Power-Rate-Slot Control Scheme for Energy Harvesting-Powered Wireless Body Area Networks

Zhiqiang Liu, *Student Member, IEEE* Bin Liu, *Member, IEEE* and Chang Wen Chen ,*Fellow, IEEE*

***Abstract*—this is abstract**

***Index Terms*—energy harvesting, resource allocation, wireless body area network (WBAN).**

I. Introduction

this is introduction

A. Related works

Some related researches

B. Motivation

C. Contributions

In this study, we investigate the resource allocation schemes in terms of the spectrum resource matching and the power allocation under a single EH-DCCN. In the EH-DCCN, D2D pairs powered by EH module are allowed to reuse the CUs' uplink spectrum resource to transmit their local data. Thus, the key contributions of this paper can be expressed as three aspects:

- Firstly, this work is the first to .
- Subsequently, two algorithms .
- As a consequence, we provide .

II. Network Model and Problem Statement

In this section,

A. Scenario, node and transmission model

$$\sum_{c_i} x_{c_i,d_j} \leq 1, (\forall d_j \in \Phi_D) \tag{1}$$

$$\sum_{d_j} x_{c_i,d_j} \leq m, (\forall c_i \in \Phi_C) \tag{2}$$

Based on the above analysis, the signal to interference plus noise ratio (SINR) of the c_i-th CU and the d_j-th D2D pair can be presented as follows:

$$R_{c_i} = \frac{p_{c_i} g_{c_i B}}{n_0 + \sum\limits_{d_j} x_{c_i,d_j} p_{d_j} g_{d_j B}}, \tag{3}$$

$$R_{d_j} = \frac{p_{d_j} g_{d_j}}{n_0 + p_{c_i} g_{c_i d_j} + \sum\limits_{\substack{d_k \neq d_j \\ d_k \in \Phi_D}} x_{c_i,d_k} p_{d_k} g_{d_k d_j}}, \tag{4}$$

where p_{c_i} and p_{d_j} are the transmission power of the c_i-th CU and the d_j-th EH-DP in a time slot, respectively. $x_{c_i,d_j} (c_i \in \Phi_C, d_j \in \Phi_D)$ is the multiplex indicator parameter. n_0 is the noise power, which equals to $B_W \cdot \rho_n$, where B_W is the uplink channel bandwidth and ρ_n is the density of noise. $g_{u_1 u_2}\,(u_1, u_2 \in \{B, \Phi_C, \Phi_D\})$, denotes the channel gain between transmitting node u_1 and receiving node u_2, which accounts for the path loss and Rayleigh fading and is expressed as

$$g_{u_1 u_2} = L_{u_1 u_2}^{-\alpha} \cdot |h_{u_1 u_2}|, \tag{5}$$

where $L_{u_1 u_2}$ is the distance between u_1 and u_2. α is the path-loss exponent between u_1 and u_2. $h_{u_1 u_2} \sim \mathcal{CN}(0,1)$ is modeled as zero-mean complex Gaussian random variables with unit variance, characterizing the Rayleigh fading.

B. Energy model

In this scenario, each EH-DP uses the harvested energy to transmit their local data. For the d_j-th EH-DP, $E_{d_j}^t$ units of energy can be harvested in the t-th time slot where $E_{d_j}^t \geq 0$. $\left\{E_{d_j}^1, E_{d_j}^2, \ldots, E_{d_j}^t, \ldots, E_{d_j}^T\right\}$ is the time sequence of harvested energy in T time slots. $E_{d_j}^t$ is also an i.i.d. sequence with Compound Poisson distribution: $E_{d_j}^t = \sum\limits_{n=1}^{N(t)} U_{d_j}^n$ [1], where $N(t)$, the number of energy packets arriving at the time slot t, is assumed to be a homogeneous Poisson process with intensity λ_{d_j}. $U_{d_j}^n$ is the size of the n-th energy packet in $N(t)$. In addition, the λ_{d_j} and $U_{d_j}^n$ are called as EH efficiency of the d_j-th EH-DP.

Let $B_{d_j}^t$ depicts the amount of available energy in the battery for transmission at the time slot t of the d_j. The transmitted power $p_{d_j}^t$ is constrained by the available energy $B_{d_j}^t$ in the battery:

$$p_{d_j}^t \leq B_{d_j}^t, \left(B_{d_j}^t = B_{d_j}^{t-1} - p_{d_j}^{t-1} + E_{d_j}^{t-1}\right).$$

We assume that the energy are only for communication purposes. Existing energy in the battery can be retrieved without any loss and the battery capacity is large enough so that every quanta of incoming energy can be stored in the battery. This assumption is practically valid for the current circumstance of the technology in which batteries have very large capacities compared to the efficiency of harvested energy flow [2]. Besides, it is assumed that the CSI of all the involved links, and the ESI of all EH-DPs in each time slot are acquired

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The authors are with the Key Laboratory of Wireless-Optical Communications, School of Information Science and Technology, University of Science and Technology of China, Hefei, Anhui, China. e-mail: (yingluo@mail.ustc.edu.cn, plhong@ustc.edu.cn, ruolinsu@mail.ustc.edu.cn, kpxue@ustc.edu.cn).

by the BS so that the BS is capable of controlling the resource allocation.

C. Mathematic model

optimization problem

D. Problem analysis

III. Algorithms design

In this section, two algorithms are explained at first, and the computational complexity of the two algorithms is elaborated in the later.

A. Outer approximation algorithm

B. Energy-aware space matching algorithm

Energy-aware Space Matching (ESM) algorithm solves the maximization problem **P1** by decomposing the problem into two steps. In the first step, the ESM implements a spectrum matching scheme to obtain the multiplex indicator parameter X; In the second step, the power allocation scheme is solved based on the first step so as to obtain the power variable sets P_C and P_D.

The first step, ESM should determine the spectrum matching indicator parameter X. As we all know, due to the fading characteristic of wireless communications, one simplest and fastest way to determine the matching parameter is based on distance constraint. But, how to set the distance and define the distance matching rules with joint consideration of available energy state and channel condition is the most important thing. In our model, according to the available power and the transmission rate constraints, the distance between CU c_i and EH-DP d_j must satisfy the following restraint if they can be matched:

$$\begin{aligned} \left|L_{c_i d_j}\right| &\geq \left(\frac{p_{d_j}\cdot\left|L_{d_j}\right|^{-\alpha} - n_0\, \hat{r}{}^{th}_{d_j}}{\hat{r}{}^{th}_{d_j}\cdot \hat{r}{}^{th}_{c_i}\left(p_{d_j}\cdot\left|L_{d_j B}\right|^{-\alpha}+n_0\right)\cdot\left|L_{c_i B}\right|^{\alpha}}\right)^{-1/\alpha} \\ &\geq \left[\left(\frac{\left|L_{d_j}\right|^{-\alpha}}{\psi}\right)\left(1-\frac{\phi\cdot\left|L_{d_j}\right|^{-\alpha}+n_0\cdot\psi\cdot \hat{r}{}^{th}_{d_j}}{\psi\cdot\left|L_{d_j}\right|^{-\alpha}\cdot p_{d_j}+\phi\cdot\left|L_{d_j}\right|^{-\alpha}}\right)\right]^{-1/\alpha} \end{aligned}$$

where ψ represents $\hat{r}{}^{th}_{d_j}\cdot \hat{r}{}^{th}_{c_i}\cdot\left|L_{d_j B}\right|^{-\alpha}\cdot\left|L_{c_i B}\right|^{\alpha}$, ϕ is $\hat{r}{}^{th}_{d_j}\cdot \hat{r}{}^{th}_{c_i}\cdot\left|L_{c_i B}\right|^{\alpha}\cdot n_0$. The relevant derivation can be seen in Appendix A. Obviously, the value of $L_{c_i d_j}$ is proportional to $L_{c_i B}$ and inversely proportional to $L_{d_j B}$ and p_{d_j}. Calculating the relevant minimum required distance for all EH-DPs is a time-consuming process. Hence, we consider to set a uniform standard. In order to let as many EH-DPs as possible access network, we must consider the worst case. According to the relationship of $L_{c_i d_j}$ between the other variables, the EH-DP $\widetilde{d}(\widetilde{d}\in\Phi_D)$, which owns the minimum available transmission power and the worst channel quality (minimum distance from base station), is chosen. Furthermore, the CU $\widetilde{c}(\widetilde{c}\in\Phi_C)$ which is farthest away from BS is chosen. Hence, we can obtain the following corollary:

Corollary 1: *In order to ensure the matched CU and EH-DPs have a feasible power allocation solution, the distance d_{EH} must satisfy a minimum value*:

$$d_{EH} = \left|L_{\widetilde{c}\widetilde{d}}\right| \geq \left(\frac{p_{\widetilde{d}}\cdot\left|L_{\widetilde{d}}\right|^{-\alpha} - n_0\, \hat{r}{}^{th}_{\widetilde{d}}}{\hat{r}{}^{th}_{\widetilde{d}}\cdot \hat{r}{}^{th}_{\widetilde{c}}\left(p_{\widetilde{d}}\cdot\left|L_{\widetilde{d}B}\right|^{-\alpha}+n_0\right)\cdot\left|L_{\widetilde{c}B}\right|^{\alpha}}\right)^{-1/\alpha}$$

Proof: The proof of this corollary is provided in Appendix A.

The d_{EH} is the minimum requisite multiplex distance, which is decided with joint consideration of the available energy and channel conditions. To solve the spectrum matching scheme in a faster and simpler way, ESM divides the cell area into two parts: Central Part (CP) and Edge Part (EP) according to d_{EH}. EH-DPs in different parts {CP or EP} can randomly reuse the CUs in the opposite part {EP or CP} to ensure the minimum distance constraint. Therefore, as shown in Fig. 1, a cellular network with R radius is divided into six 60 degree sectors [10]. The six sectors are named as 1 to 6 in counterclockwise order from north to south. Each sector is grouped into two parts: Central Part (CP) and Edge Part (EP) by d_{EH}. Moreover, to ensure the next power allocation step has a feasible solution, there are two matching rules we should be complied with:

- EH-DPs in different parts {CP or EP} can randomly reuse the CUs in the opposite part {EP or CP} of the sectors which are opposite from each EH-DP sector. For example, as Fig. 1 illustrates, the EH-DPs in the EP (yellow) or CP (blue) part of the sixth sector can randomly multiplex the spectrum resource of CUs in the CP (yellow) or EP (blue) part of the opposite sectors {2,3,4} of the sixth sector;
- EH-DPs in the same and adjacent sector can not reuse the same CU spectrum resource. As Fig. 1 shows, the spectrum resource of one CU reused by the EH-DP in the sixth sector can not be reused by EH-DPs in the sector 5 and 1 at the same time.

Based on the first rule, the division of CP and EP insures that the interference between CUs and EH-DPs is under control, which can effectively satisfy transmission rate requirements with the limitation of available energy. Likewise, the second rule makes sure that the mutual interference between EH-DPs is under control.

The second step, after obtaining the integer values of the multiplex indicator $\hat{X} = \left\{\hat{x}_{c_i,d_j}\right\}$, the proper power should be allocated between the matched CU and multiple EH-DPs to maximize the transmission rate of the whole network. Thus, the system transmission rate maximization problem can be divided into N_C subproblems due to the spectrum orthogonality of different CUs. Therefore, for any $c_i, (c_i \in \Phi_C)$, we have:

$$\max_{\{p_{c_i}, P_D\}} \log\left(1+R_{c_i}\right) + \sum_{d_j=1}^{N_D} \hat{x}_{c_i,d_j}\log\left(1+R_{d_j}\right), \quad \text{(6a)}$$

$$s.t. \quad \log\left(1+R_{c_i}\right) \geq r^{th}_{c_i}, \quad \text{(6b)}$$

$$\log\left(1+R_{d_j}\right) \geq r^{th}_{d_j}, \quad \text{(6c)}$$

$$(\textbf{??}) \sim (\textbf{??}), \quad \text{(6d)}$$

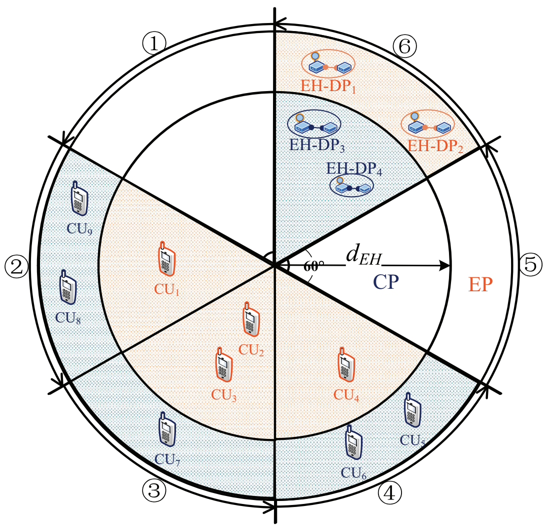

Fig. 1: Energy-aware Space Matching model

where EH-DP d_j belongs to Φ_D and reuses the spectrum resource of the CU c_i at the same time.

The above subproblem is also a non-concave maximization problem. But, we can obtain its theoretical lower bound by the approximation of (6) and the variables substitution of $p_{c_i} = e^{\widetilde{p_{c_i}}}, p_{d_j} = e^{\widetilde{p_{d_j}}}$:

$$\max_{\left\{\widetilde{p_c^i}, \widetilde{P_D}\right\}} \widetilde{f_{c_i}}\left(\hat{X}, \widetilde{p_{c_i}}, \widetilde{P_D}\right) + \sum_{d_j=1}^{N_D} \hat{x}_{c_i,d_j} \widetilde{f_{d_j}}\left(\hat{X}, \widetilde{P_C}, \widetilde{P_D}\right), \tag{7a}$$

$$s.t. \quad \widetilde{f_{c_i}}\left(\hat{X}, \widetilde{p_{c_i}}, \widetilde{P_D}\right) \geq r_{c_i}^{th}, \tag{7b}$$

$$\widetilde{f_{d_j}}\left(\hat{X}, \widetilde{P_C}, \widetilde{P_D}\right) \geq r_{d_j}^{th}, \tag{7c}$$

$$(8d) \sim (8e). \tag{7d}$$

With the convexity of *log-exp-sum*, the problem (15) can be easily proved to be a concave maximization problem about relevant power parameters of CU and EH-DPs. The pseudo code of ESM can be detailedly expressed by Algorithm 2.

C. Complexity of OAA and ESM

Hijazi et al. [11] provided an example where outer approximation takes an exponential number of iterations about 2^n, in which n is the variables that need to be solved, and equals $N_C + N_D$ in this paper. In ESM, the system only needs to implement the proper matching method for each D2D, and solve N_C sub-problems of power allocation. Thus, the complexity of ESM can be expressed as $O(N_C \cdot N_D)$ in the worst case.

IV. Simulation Results

In this section, the performance of the two proposed algorithms and the characteristics of the EH-DCCN are investigated in the performance of the average achievable system rate and the matching probability of EH-DPs. The matching

Algorithm 1: ESM

```
for  d_j = 1 to N_D do
    for  c_i = 1 to N_C do
        if c_i and d_j satisfy the two matching rules then
            x̂_{c_i,d_j} = 1;
            return;
        else
            x̂_{c_i,d_j} = 0;
        end
    end
end
for  c_i = 1 to N_C do
    {p̂_{c_i}, P̂_D} ← arg Problem(15)
end
Update: R_sum^ESM by (??):
    R_sum^ESM = R_sum(X̂, exp(P̂_C), exp(P̂_D)).
```

TABLE I: The comparison of complexity of OAA and ESM

	OAA	ESM
complexity	$O(2^{N_C+N_D})$	$O(N_C \cdot N_D)$

probability of EH-DPs represents the ratio of the matched EH-DPs in N_D. To evaluate the effectiveness of the proposed algorithms, there are two comparison schemes should be described. The first one is the exhaustive searching method, which can enumerate all possible solutions, and thus attain an optimal solution. The second one is a graph-color method [12], which is one of typical resource allocation algorithms in classical D2D communication. Besides, all of the simulation model and algorithms are coded in the MATLAB.

However, the computational complexity of the exhaustive searching method increases exponentially with the number of the users [13]. Hence, it is difficult to implement the exhaustive searching method under large-scale scenario with large number of users. Therefore, we only compare the proposed algorithms OAA and ESM with the two comparison schemes under a small-scale scenario with 5 EH-DPs and different numbers of CUs (from 2 to 6). The scenario with the similar scale is set to validate the performance of algorithms proposed in [12, 14]. Moreover, under the large-scale scenario with 100 EH-DPs and different numbers of CUs (from 30 to 100), the performance of the two proposed algorithms is also evaluated by comparing with the graph-color method. Meanwhile, the characteristics of the network are investigated.

A. Simulation setup

Above all, the detailed cellular network simulation settings should be illustrated. We consider a cellular network demonstrated by Fig. **??** with one Base Station (BS), N_C CUs and N_D EH-DPs. The BS is always located in the center of the cell, and the radius of the cellular network is 800 meters. The CUs and EH-DPs are randomly and uniformly distributed in the cell, and the position of all users is known by BS.

Furthermore, the distance between receiver and sender of each EH-DP is randomly distributed in the range of 20 meters to 50 meters.

TABLE II: EH-powered D2D simulation scenario parameters

Scenario settings		
Description		Value
BS position		at the center of the cell
CUs and EH-DPs position		uniformly random distribution
distance between sender and receiver of one EH-DP		random distribution in [20,50]m
Simulation parameters settings		
Parameter	Description	Value
R	radius of the cell	800m
N_C	sum number of CUs	large scale:[30:10:100] small scale:[2:1:6]
N_D	sum number of EH-DPs	large scale:100 small scale:5
B_W	uplink bandwidth of each orthogonal CU channel	180KHz
ρ_n	thermal noise density	-174dBm/Hz
α	path loss exponent for users	4
$P_{c_i}^{max}$	maximum transmission power constraints of CU	20dBm
$P_{d_j}^{max}$	maximum transmission power constraints of d_i-th EH-DP	17dBm
$N(t)$	the number of arriving energy packets in time slot t	Possion distribution with λ of [1:1:6]
$U_{d_i}^{n}$	average energy for each energy packet	0.0005watt
m	the maximum reusable EH-DPs of one CU	3
$r_{c_i}^{th}$	minimum transmission rate threshold of CU	1bps/Hz
$r_{d_j}^{th}$	minimum transmission rate threshold of d_i-th EH-DP	2bps/Hz

In order to study the effectiveness of the proposed algorithms and the characteristics of the EH-DCCN, we set up a small-scale scenario and a large-scale scenario. In each scenario, the energy packet arrival process for every EH-DP is supposed to be i.i.d random sample. This sample can be regarded as a statistic process obeying Poisson distribution with same parameter λ. Therefore, the energy packet arrival process, which is represented by $\lambda_{d_j}(\lambda_{d_j} = \lambda)$, is only considered as the variance of the EH efficiency. In the large-scale scenario, we define the ratio of CU and EH-DP numbers as N_C/N_D. For each simulation scenario with different ratios or EH efficiencies, for example a scenario has a ratio of 0.5, we generate the corresponding random scenario about 100 times and average the performance of transmission rate and matching probability. All of the detailed network parameters used in this paper are demonstrated by Table II.

B. The effectiveness of the proposed algorithms under small-scale scenario

Considering the high computational complexity of the exhaustive searching scheme for the scenarios with large number of users, a small-scale scenario is set to validate the effectiveness of the proposed algorithms. The small-scale scenario consists of 5 EH-DPs and different numbers of CUs (from 2 to 6). Under this small-scale scenario, the performances of the proposed algorithms and the comparison schemes in terms of average (avg.) achievable transmission rate and matching probability are demonstrated by Fig. 2 and Fig. 3, respectively. In this simulation, the EH efficiency λ is set as 2.

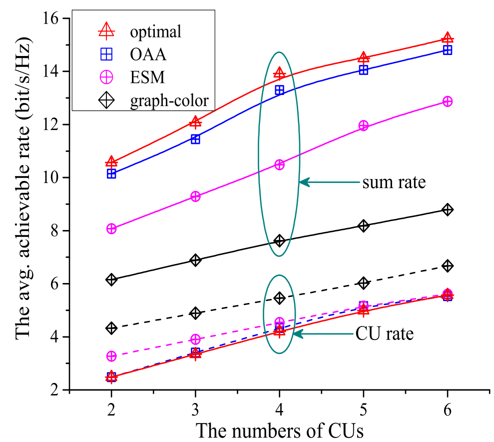

Fig. 2: The avg. achievable rate under the small-scale scenario

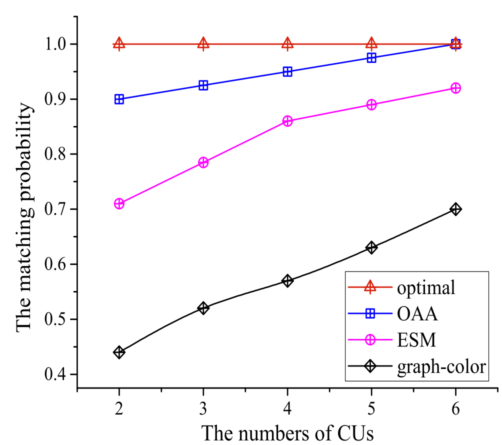

Fig. 3: The avg. matching probability under the small-scale scenario

As shown in Fig. 2 and Fig. 3, the differences of sum rate and matching probability between OAA and the optimal exhaustive searching scheme are about 0.2bit/s/Hz and 0.1, respectively. Hence, a vivid conclusion can be made that OAA can attain an approximate optimal sum rate and matching probability by comparing with the optimal exhaustive searching scheme. Simultaneously, although there is a gap about

2bit/s/Hz in sum rate between the ESM and the optimal scheme, ESM also can obtain a suboptimal performance, while owning the lowest computational complexity and satisfying the transmission rate requirements of users.

Moreover, two principle reasons can explain the poorest performance of the graph-color method. Firstly, the graph-color method randomly allocates channel resource of CU based on the constructed graph and the interference negligible distance (INS) and SIR limited area (SLA). The INS is a fixed value and the SLA is only based on channel state but ignores the energy feature. Thus, the spectrum resource matching strategy will be invalid if the available energy of D2D pairs cannot achieve their transmission rate requirements under the corresponding interference. Secondly, the graph-color method tries its best to allocate proper D2D pairs for each CU, one after the other, which will lead to unbalanced distribution of resources. In other words, some CUs share their channels with multiple D2D pairs, but some CUs are not paired with any D2D links. Finally, the unbalanced distribution of resources will result in large mutual interference among D2D links, and thus the sum transmission rate is not substantially improved.

Furthermore, the average CU rate in Fig. 2 shows the different characteristics of the above algorithms. Under the graph-color method, the CUs own the smallest interference from EH-DPs due to the unsuccessful matching, and thus CUs have the best transmission rate than other algorithms. On the contrary, the optimal exhaustive searching scheme and the OAA have the highest matching probability, which will result in that the CUs suffer the largest interference from EH-DPs. Hence, the transmission rate performance of CUs in optimal scheme and OAA is the lowest than others. Based on this, the transmission rate of the heuristic algorithm ESM is performed in the middle of all algorithms. Besides, when the node numbers of CUs are little, the number of EH-DPs reusing the same channel resource is higher. This phenomenon will result in the more interference to the CUs, and thus the avg. achievable transmission rate of CUs is smaller. Hence, the avg. achievable rate of CUs will increase with the raise of the number of CUs.

C. Simulation results in large-scale scenario

There are two principle purposes to design the large-scale scenario. The first one is to evaluate the performance of the proposed algorithms. The second one is to investigate the influence of different ratios on performance. The large-scale scenario is set with 100 EH-DPs and different numbers of CUs (from 30 to 100). In this simulation, the EH efficiency λ is also set as 2. The average achievable rate and the matching probability are illustrated in detail by Fig. 4 and 5, respectively.

There are three important phenomena can be seen in Fig. 4 and Fig. 5. The first one is that our proposed algorithms still outperform the performance of graph-color in terms of transmission rate and matching probability.

The second, the performance of ESM in sum rate gradually approaches to the optimal lower bound of OAA along with the increasing of the ratio. When the ratio is not less than 0.6,

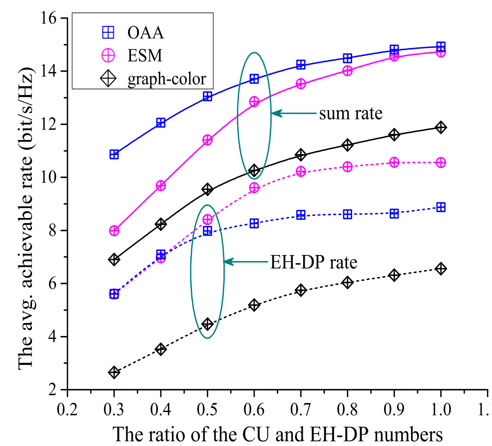

Fig. 4: The avg. achievable rate VS. different ratios of CU and EH-DP numbers under large-scale scenario

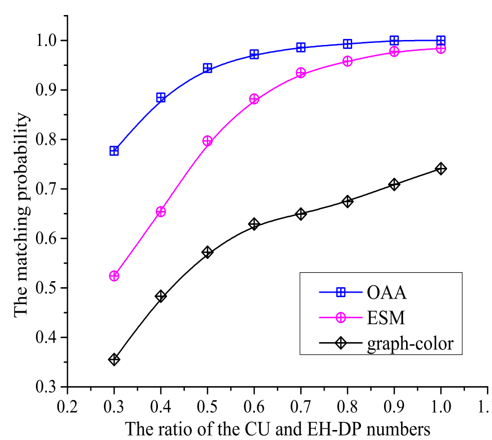

Fig. 5: The avg. matching probability VS. different ratios of CU and EH-DP numbers under large-scale scenario

the difference of sum rate between the ESM and the OAA is less than 1 bit/s/Hz. The same phenomenon can be also reflected by the matching probability of EH-DPs in Fig. 5. The average matching probability of EH-DPs in the ESM is gradually increasing to the OAA, and closing to one hundred percentage as the ratio rises. It vividly implies that the ESM can obtain the approximate performance of the theoretical tight lower bound on the original problem under the scenarios with the balanced distribution between the CUs and EH-DPs. With low computational complexity, the ESM is more suitable for the scenarios with the large scale of users and a higher ratio.

Thirdly, as demonstrated by the average achievable rate of EH-DP in Fig. 4, the ESM and the OAA are concentrated on different aspects aiming at improving the system performance. In another word, the ESM is more concerned with the rate improvement of EH-DPs. On the contrary, the OAA pays more attention to the rate improvement of CUs.

The above phenomenon can be interpreted as follows:

The OAA can acquire the optimal lower bound of the original maximization problem by the iteration process. To obtain the maximal transmission rate, the OAA will let EH-DPs match the corresponding CU as many as possible under the interference constraints. On the contrary, the maximum number of EH-DPs reusing same CU in the ESM is less than the OAA in nature. The ESM scheme only can make each CU maintain at most two EH-DPs essentially. Hence, there will be more interference for each CU in the OAA than the ESM when the ratio is low. But the number of EH-DPs multiplexing one CU in the OAA exceeds that in the ESM. Hence, the system rate and the matching probability in the OAA are still better than the ESM. This explanation is also be proved in the simulation of the variation of the average system rate in Fig. 4. As we can see in this figure, due to the matching property of the ESM, the average sum rate of the ESM is lower than the OAA when the ratio is less than 0.6. This phenomenon also explains why the ESM gets poor performance under the scenarios with lower ratio of CU and EH-DP numbers.

D. The influence of different EH efficiencies on performance

Under the same large-scale scenarios of section IV-C, the impact of EH efficiency λ on performance is also investigated. As demonstrated by Fig. 6 and Fig. 7, the matching probability is gradually increasing with the rise of λ, especially under the scenarios with lower ratio such as under 0.3. This is because the EH-DPs' ability to tolerate interference is increasing as the harvested energy rises. So, more and more EH-DPs can multiplex the spectrum resource of one CU at the same time under the control of interference. Therefore, the sum transmission rate is also growing with the rise of EH efficiency. However, as illustrated by Fig. 6 and Fig. 7, the influence of the growth of harvested energy on performance in the ESM is not more instinct than the OAA. This phenomenon can be mainly explained by the reason that although the growth of energy can make EH-DPs possible to bear more interference, the matching rules in the ESM will not be changed. In other words, the maximum tolerable EH-DP numbers of one CU in the ESM will not be changed due to the space matching property. Thus, the performance of the ESM is more stable than the OAA. But, the performance of the ESM can approach the OAA under the scenarios with the large ratio such as up to 0.8.

In addition, we can get some crucial conclusions from the performance of OAA. Due to the maximum transmission power constraints, the rise of EH efficiency cannot always increase the system performance. From the simulation results, the matching probability is close to 1 when the EH efficiency reaches 5 and the ratio is 0.3. The more distinct phenomenon can be seen in sum rate as Fig. 7 shows. The system rate is not rising when the λ equals 5. Besides, when the ratio is 0.5 or 0.8, the OAA performs stably when EH efficiency λ reaches 4 or 2 in aspects of the matching probability and sum rate, respectively. Thus, we can conclude that the ratio of CU and EH-DP numbers must be above 0.8 when EH efficiency is 2, and ratio is 0.5 or 0.3 when EH efficiency is 4 or 5, respectively. This conclusion can give an insight needed for the central controller to deploy EH-powered D2D communication underlaying cellular networks.

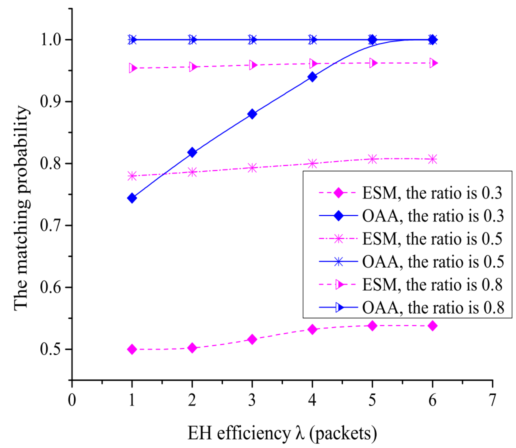

Fig. 6: The avg. matching probability VS. different EH efficiencies under large-scale scenario

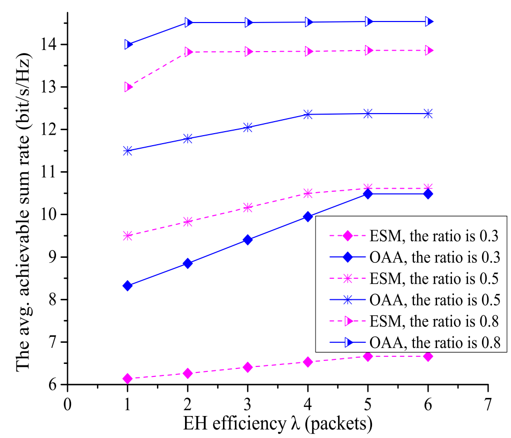

Fig. 7: The avg. achievable rate VS. different EH efficiencies under large-scale scenario

V. Conclusion

In this paper, we study the resource allocation scheme for EH-powered D2D communication underlaying cellular networks. Unlike the conventional D2D communications, the achievable energy will become another significant issue that resource allocation schemes must be considered in the EH-powered D2D communication. Thus, we investigate a sum-rate maximization problem in terms of the available energy and the transmission rate requirement under a single cellular network. Due to the optimization problem being a non-concave MINLP, we obtain the optimal lower bound of the original problem by a concave approximation and OAA algorithm. At the same time, because of the high complexity of OAA, we propose a heuristic algorithm, which is named Energy-aware Space Matching (ESM) algorithm. ESM decomposes the original problem into the spectrum matching problem and the power allocation problem. And then, ESM firstly solves the spectrum matching problem, and then allocates the proper power for the matched CU and EH-DPs. The time complexity of OAA and ESM in the worst case are $O(2^{N_C+N_D})$ and $O(N_C \cdot N_D)$, respectively. Obviously, the ESM own a lower complexity than OAA.

In the simulation, different scenarios with different ratios and EH efficiencies are set to assess the effectiveness of the two algorithms and study the characteristics of the EH-powered D2D communication. From simulations, some vivid results can be obtained. First of all, simulation results imply that our considered resource allocation strategy is more effective than the strategy only based on channel state information under EH-DCCN. Secondly, the ESM algorithm with low computational complexity is more suitable for the scenarios with higher ratio than OAA. Finally, it is better to keep the ratio above 0.8 when EH efficiency of EH-DPs is low, and the EH efficiency of EH-DPs is up to 5 if the user density of EH-DPs is larger than CUs. This results can give some insights for the central controller to deploy EH-DCCN in the future.

APPENDIX A
PROOF OF COROLLARY 1

According to the reusing rules of the ESM, the distance among EH-DPs reusing the same spectrum of one CU is enough far away from each other. Hence, the interference among EH-DPs can be approximately ignored. Based on this, the minimum reusing radius d_{EH} is approximately determined by the CU and the EH-DP reusing the same spectrum resource. Hence, according to the transmission rate requirement, the matched CU c_i and EH-DP d_j must satisfy the following constraints:

$$\begin{cases} \log\left(1+\frac{p_{c_i}\cdot\left|L_{c_iB}\right|^{-\alpha}}{n_0+p_{d_j}\cdot\left|L_{d_jB}\right|^{-\alpha}}\right)\geq r_{c_i}^{th}, \\ \log\left(1+\frac{p_{d_j}\cdot\left|L_{d_j}\right|^{-\alpha}}{n_0+p_{c_i}\cdot\left|L_{c_id_j}\right|^{-\alpha}}\right)\geq r_{d_j}^{th}. \end{cases}$$

It can be converted as follow when all variables are equal or larger than zero:

$$\begin{cases} \frac{p_{c_i}\cdot\left|L_{c_iB}\right|^{-\alpha}}{n_0+p_{d_j}\cdot\left|L_{d_jB}\right|^{-\alpha}}\geq \hat{r}_{c_i}^{th}, \\ \frac{p_{d_j}\cdot\left|L_{d_j}\right|^{-\alpha}}{n_0+p_{c_i}\cdot\left|L_{c_id_j}\right|^{-\alpha}}\geq \hat{r}_{d_j}^{th}, \end{cases}$$

where $\hat{r}_{c_i}^{th}=\exp\left(r_{c_i}^{th}\right)-1, \hat{r}_{d_j}^{th}=\exp\left(r_{d_j}^{th}\right)-1$. Thus, we can obtain the following inequality conditions:

$$\begin{cases} p_{c_i}\geq \hat{r}_{c_i}^{th}\left(p_{d_j}\cdot\left|L_{d_jB}\right|^{-\alpha}+n_0\right)\cdot\left|L_{c_iB}\right|^{\alpha}, \\ \left|L_{c_id_j}\right|\geq\left(\frac{p_{d_j}\cdot\left|L_{d_j}\right|^{-\alpha}-n_0\,\hat{r}_{d_j}^{th}}{\hat{r}_{d_j}^{th}\cdot p_{c_i}}\right)^{-1/\alpha}. \end{cases}$$

Put p_{c_i} into $\left|L_{c_id_j}\right|$:

$$\begin{aligned}\left|L_{c_id_j}\right|&\geq\left(\frac{p_{d_j}\cdot\left|L_{d_j}\right|^{-\alpha}-n_0\,\hat{r}_{d_j}^{th}}{\hat{r}_{d_j}^{th}\cdot\hat{r}_{c_i}^{th}\left(p_{d_j}\cdot\left|L_{d_jB}\right|^{-\alpha}+n_0\right)\cdot\left|L_{c_iB}\right|^{\alpha}}\right)^{-1/\alpha}\\ &\geq\left[\left(\frac{\left|L_{d_j}\right|^{-\alpha}}{\psi}\right)\left(1-\frac{\phi\cdot\left|L_{d_j}\right|^{-\alpha}+n_0\cdot\psi\cdot\hat{r}_{d_j}^{th}}{\psi\cdot\left|L_{d_j}\right|^{-\alpha}\cdot p_{d_j}+\phi\cdot\left|L_{d_j}\right|^{-\alpha}}\right)\right]^{-1/\alpha}\end{aligned}$$

where ψ represents $\hat{r}_{d_j}^{th}\cdot\hat{r}_{c_i}^{th}\cdot\left|L_{d_jB}\right|^{-\alpha}\cdot\left|L_{c_iB}\right|^{\alpha}$, ϕ is $\hat{r}_{d_j}^{th}\cdot\hat{r}_{c_i}^{th}\cdot\left|L_{c_iB}\right|^{\alpha}\cdot n_0$. As illustrated by the above inequality function, if the EH-DP d_j can reuse the CU c_i's spectrum resource to transmit, we can obtain the minimum reusing distance between the matched CU c_i and EH-DP d_j. Obviously, the value of $L_{c_id_j}$ is proportional to L_{c_iB} and inversely proportional to L_{d_jB} and p_{d_j}. In order to let as many EH-DPs as possible can multiplex CU's spectrum resource, we must consider the worst case. According to the relationship of $L_{c_id_j}$ between the other variables, the EH-DP $\tilde{d}(\tilde{d}\in\Phi_D)$, which owns the minimum available transmission power and the worst channel quality (minimum distance from base station), is chosen. Furthermore, the CU $\tilde{c}(\tilde{c}\in\Phi_C)$ which is farthest away from BS is chosen. Hence, the minimum matching radius d_{EH}, which ensures as many EH-DPs as possible can multiplex cellular spectrum resources, is shown as follow:

$$d_{EH}=\left|L_{\tilde{c}\tilde{d}}\right|\geq\left(\frac{p_{\tilde{d}}\cdot\left|L_{\tilde{d}}\right|^{-\alpha}-n_0\,\hat{r}_{\tilde{d}}^{th}}{\hat{r}_{\tilde{d}}^{th}\cdot\hat{r}_{\tilde{c}}^{th}\left(p_{\tilde{d}}\cdot\left|L_{\tilde{d}B}\right|^{-\alpha}+n_0\right)\cdot\left|L_{\tilde{c}B}\right|^{\alpha}}\right)^{-1/\alpha}.$$

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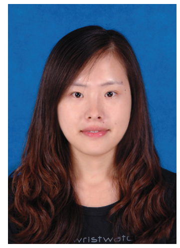

Ying Luo received the B.S. and M.S. degree from the department of Information Engineering, South West University of Science and Technology (SWUST), in 2012 and 2015. She is currently working toward the Ph.D. degree in Information and Communication Engineering from the Department of Electronic Engineering and Information Science (EEIS), University of Science and Technology of China (USTC). Her research interests has focused on the analysis of heterogeneous cellular networks.

Peilin Hong received her B.S. and M.S. degrees from the Department of Electronic Engineering and Information Science (EEIS), University of Science and Technology of China (USTC), in 1983 and 1986. Currently, she is a Professor and Advisor for Ph.D. candidates in the Department of EEIS, USTC. Her research interests include next-generation Internet, policy control, IP QoS, and information security. She has published 2 books and over 150 academic papers in several journals and conference proceedings.

Ruolin Su received the B.S. degree from the Department of Communications Engineering, Harbin Institute of Technology, China, in 2016. Currently, she is pursuing the M.S. degree at the Department of Electronic Engineering and Information Science, University of Science and Technology of China. Her current research interest is resource allocation in device-to-device communication.

Kaiping Xue was born in 1980. He graduated with a B.S. degree from the Department of Information Security, University of Science and Technology of China (USTC), in 2003 and received a Ph.D. degree from the Department of Electronic Engineering and Information Science (EEIS), USTC, in 2007. Currently, he is an Associate Professor in the Department of Information Security and Department of EEIS, USTC. His research interests include next-generation Internet, distributed networks and network security.