Energy-efficient Power Allocation in SWIPT Based on a Non-linear Energy Harvesting Model

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***Abstract*—The technology of simultaneous wireless information and power transfer (SWIPT) has been proposed to solve issues of low energy efficiency (EE) in the Internet of things (IOT) systems such as device-to-device(D2D) network. A lot of work has been done in this field using SWIPT based on linear energy harvesting models, where the nonlinearity of the energy harvester was totally ignored. This project focus on maximizing the EE of each D2D link by proposing a power allocation scheme based on a nonlinear EH model. A pre-matching algorithm is first proposed to find those D2D links which can be used to perform SWIPT and those which are not able to meet the requirement of EH sensitivity (non-EH). Afterwards, a two-layer iterative algorithm is proposed to optimize the power splitting ratio and D2D power transmission power. Based on its result, two preference lists are built for all D2D links and cellular user equipment (CUE) and one stable-matching algorithm with constraints is proposed to further optimize the matching process. Finally, the sum EE of all non-EH D2D links are also maximized using similar matching methodologies. The results from the simulation show that higher EE of each D2D link was achieved using proposed algorithms utilizing power allocation scheme and SWIPT based on a non-EH model than that in the existing work.**

***Index Terms*—Cellular user equipment, device-to-device, energy harvesting, energy efficiency, power allocation, radio frequency, simultaneous wireless information and power transfer**

I. Introduction

WITH the rapid development of wireless communications, we are now entering the era of the Internet of things (IOT), where there are numerous mobile devices connected to each other. With the aid of IOT, we are heading towards a world where everyone and everything can communicate with each other, it can be used in a lot of applications like architecture, enabling technology and so on [1]. Although, IOT has brought a lot of convenience to our life, the system is still suffering from a lot of issues, where low EE is the most serious one, which is mainly caused by limited lifetime and capacity of built-in batteries of mobile devices in the IOT network [2]. It is predicted that there will be over 75 billion IOT devices in the future, which imposes significant pressure on improving EE in IOT network. There are a lot of wireless technologies such as Bluetooth and Wi-Fi which have been exploited to support IOT. However, the main drawback of the foregoing techniques is that most of them are used in unlicensed bands, which can lead to interference and hence the quality of service in IOT network can not be guaranteed. [3]. Fortunately, this issue can be coped with by using cellular networks, which has numerous advantages such as supporting large-scale and offering reduced power consumption [4]. However, there are also some other issues such as the traffic congestion and power consumption caused by the communication through the base stations (BSs) in cellular networks.

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Device-to-device (D2D) communication system is one of the promising models which can be used to solve the foregoing issues. In the D2D system, the users are in proximity to communicate with each other directly and the communication between each D2D user doesn't need to pass through the base stations (BSs). It has been put in widespread use to solve issues such as offloading traffic congestion of base station and reduce the energy consumption from base station which therefore can be used to support for IOT [5]-[6] and it is used as a basic system model in this project.

The mutual interference between each D2D user link and each cellular user equipment (CUE) is the main reason for large energy consumption, which is one of the most serious issues in IOT network [7].

To solve the issues of large energy consumption in the D2D network, Energy harvesting (EH) was introduced with which we can capture and convert those unwanted energy resources such as thermal energy for specific requirements [8]. The energy source from ambient environment is high-quality compared with normal batteries and capacitors, which are usually used in the EH model. However, it is not quite energy efficient as expected since we cannot predict most of the ambient resources that we want to use when the EH models utilize the natural resources.

WPT is a typical EH technologie whose nodes can be charged from the radiant electromagnetic field [9]. There are two types of WPT that are usually used in EH model: near-field and far field, and they can be both used to harvest energy either from ambient environment and or base station. However, they also have some drawbacks. For instance, it is difficult to keep the field strengths stable when using the near-field WPT. To mitigate the drawbacks of WPT, a promising solution: SWIPT was mentioned in [10], where the concept of transmitting energy and information simultaneously was first introduced. It is a technology which can transfer information and energy simultaneously, which is very useful especially for notable gain of spectral efficiency and Interference Exploitation [1], making this technology become the basis of energy supply and exchange of information in the era of IOT.

The energy efficiency (EE) is defined based on the whole D2D link, and it includes the harvested energy from D2D receiver, which can be used to check if a D2D communication is green communication [6]. A lot of work has been done to improve EE in D2D communication system. In [11], an idea of optimally coordinating users to redistribute the traffic in D2D communication system was implemented to maximize EE. A joint subchannel and power resource allocation have been modified to maximize the weighted energy-efficiency in [12]. Neither of the cases considered using SWIPT and the results were still affected by mutual interference.

When it comes to the optimization problem of EE in IOT network, resource allocation is always a significant topic, since there are different varieties of resources in the communication system such as power, frequency, and time. Optimizing the utilization of those resources is an important direction of improving EE. In [13], the power resource allocation problem has been solved by generating a power allocation model using game theory with the utility defined for each SWIPT-Supported D2D link. In [14], an optimization problem with power and spectrum resource reusing constraints was first formulated, after which an energy-efficient stable matching algorithm based on EH model was proposed to address it.

All the work above did succeed in improving EE in D2D communication system to some extent. However, the results were still not very practical since the EH model they used was a simplified linear model, where the harvested energy is linearly proportional to the input RF energy. Moreover, in [13]-[14], the value of power splitting ratio of SWIPT was fixed, which means that the opportunity of maximizing EE in aspect of power splitting was totally ignored.

In this project, the aim of the experiment is mainly focused on maximizing EE of all D2D links in a D2D communication system underlaying a cellular network based on a nonlinear EH model. The contributions of this project can be summarized as follows:

1. An understanding of relevant theory and concept of technology such as SWIPT and optimization theory is obtained.
2. Considering the the fact that each D2D receiver, transmitter and CUE must be randomly distributed for the sake of not losing generality, a system model is constructed.
3. A pre-matching algorithm is implemented to separate those D2D links which can perform SWIPT from those non-EH D2D links.
4. A two-layer iterative algorithm is devised based on the results in [7] to help each pair of D2D link and CUE find the best power segment in the non-linear EH model that can achieve the maximum EE and these two algorithms succeeded in optimizing two parameters: transmission power and power splitting ratio jointly which is the hard core in the objective function of the formulated optimization problem in this project.
5. Based on the results of foregoing algorithms, two types of preference list for D2D links and CUEs are established based on specific constraints.
6. To further optimize the matching process, a stable matching algorithm with constraints is proposed to help each D2D link find its best partner CUE to match, which can help it achieve the highest EE among all the CUEs in the preference list.
7. Similar matching-based algorithms are implemented to help those D2D links which can not perform SWIPT find their best partners that can help them maximize EE.
8. Several simulations are performed to evaluate the robustness of the implemented algorithms in a lot of aspects such as EE performance and convergence. To compare with the obtained results, one linear EH model, similar matching-based algorithms and one heuristic algorithm where each D2D link are randomly matched with maximum transmission power of D2D links are implemented.

II. Economic, legal, social, ethical and environmental context

Nowadays, energy loss is becoming a serious issue in IOT network, and with increasing number of IOT devices, a little improvement can make a huge difference especially for some countaries which are experiencing energy crisis. The improvement of EE is also important in economy since increased EE can reduce the cost of individuals and create more new jobs.

III. Methodology

This section demonstrates the methodology which is used to generate the system model and some corresponding mathematical concepts which is used to clarify the optimization problem and implement the algorithms.

A. System model

As shown in Fig. 1, in the system model, a base station (BS) in located at the center of the cell which is surrounded by D2D transmitters (TXs), D2D receivers (RXs) and CUEs. Each D2D link i can be defined as the communication link between each D2D TX i and RX i. The communication will be established when each D2D link i shares the spectrum resources with a CUE.

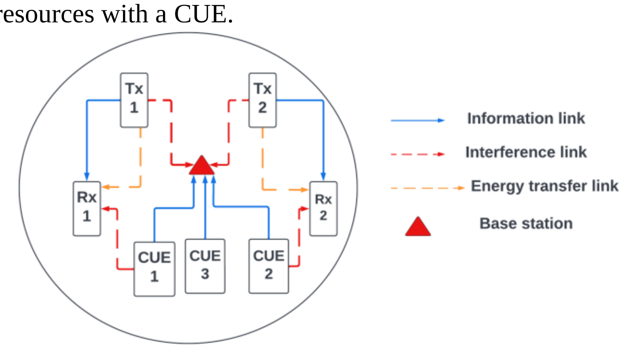

Fig. 1 Standard D2D communication cellular network

There is a D2D link set and CUE set which is denoted as $D = \{1,2,3\ \dots\ i,\ \dots\ N\}$ and $C = \{1,2,3,\ \dots\ k,\ \dots\ M\}$, where in this project, $M \leq N$. Each D2D transmitter is paired with only one corresponding D2D Receiver. In this D2D cellular network, for the sake of not losing generality, each D2D transmitter and Receiver should be distributed randomly and they should not be distributed out of the system following the radius of the cellular network which is set as 250 m in this project, to achieve that, the coordinates of each D2D transmitter and receiver will be randomly generated and cantered around the base station.

B. SWIPT-Supported D2D links

Since SWIPT is quite sensitive to the communication distance, not all the D2D links are able to perform SWIPT and the EH model can be activated only when the minimum energy requirement is satisfied, which is known as the EH sensitivity [15].So, to maximize EE of each SWIPT-Supported D2D link, it is necessary to separate all the SWIPT-Supported D2D links in the D2D link set.

SWIPT can be implemented using two types of schemes [1]: power splitting (PS) and time switching (TS). In this project, SWIPT is implemented in power splitting mode as it has proved to perform better compared to being implemented in time switching mode [16] especially in aspect of EE performance and throughput. The power splitting mode model is implemented as shown in Fig. 2, where the input RF signal is divided into two parts through the power splitter, and it allows the system to harvest energy and decode the information at the same time, where θ is the power splitting ratio.

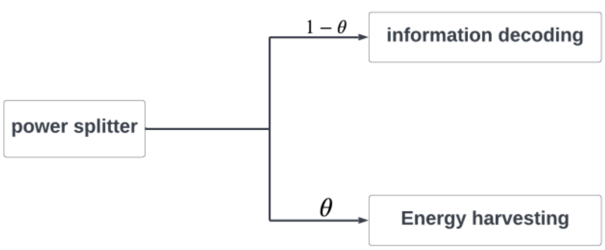

Fig. 2 Power splitting model of SWIPT

For each SWIPT-Supported D2D link i, the throughput can be expressed as follows:

$$T_i^D = log2\left(1 + \frac{(1-\theta_i)P_i^D h_i^D}{(1-\theta_i)\left(P_k^c h_{k,i} + N_0\right) + N_1}\right), (1)$$

where θ_i is denoted as the power splitting ratio of each D2D link i, P_i^D is the transmission power of each D2D link i, P_k^c is the transmission power of CUE k, N_0 and N_1 are additive white Gaussian noise and noise power caused by RF signal, h_i^D and $h_{k,i}$ are the channel response of each D2D link i and interference link from each D2D link i to CUE k, since both of them are multiplied by transmission power, so they are thought of as channel power gain which can be calculated as:

$$h = \frac{e^1}{d^a}, (2)$$

where e^1 is the independent unit-mean exponential distribution, d is the communication distance and interference distance, a is the pass loss exponent which was set as 3 to model that of urban city [17].

In this project, the received power for the EH model when D2D receiver i is sharing resource block with CUE k can be denoted as P_i^R and it can be calculated as:

$$P_i^R = \theta_i\left(P_i^D h_i^D + P_k^c h_{k,i} + N_0\right) \quad (3)$$

C. Piecewise linear EH model

To calculate the harvested energy for each D2D link i , a piecewise linear EH model in [18] is proposed and it is employed as:

$$EH_i^D = \begin{cases} 0, & P_i^R \in [P_{thresold}^0, P_{thresold}^1] \\ k_j P_i^R + b_j, & P_i^R \in [P_{thresold}^j, P_{thresold}^{j+1}] \\ P_{max}^{harvested}, & P_i^R \in [P_{thresold}^L, P_{thresold}^{L+1}] \end{cases}, (4)$$

where $P_{thresold} = \{P_{thresold}^j | 1 \le j \le L+1\}$ is a set of power segments, which shows the stage of the EH model where the current energy harvester is working at, k_j and b_j are the coefficients of the received power and intersect, respectively in the j_{th} segment of the piecewise linear EH model. $P_{max}^{harvested}$ is the maximum harvested energy in the EH model, and as shown in function (4), when the received power is greater than $P_{thresold}^0$ and smaller than $P_{thresold}^1$, the EH model will not be activated, where $P_{thresold}^1$ is the minimum received power for activating the EH model. And when the received power is within a range of certain power segment j, the model will be like a linear function. The harvested energy will reach the maximum value when the received power is greater than all the power segments. The piecewise linear EH model has proved to be more energy efficient and has lower complexity than traditional linear EH model [19] and it has proved to improve more accuracy with increasing number of power segment [20].

D. EE of each D2D link

Another important parameter for calculating EE of each D2D link i is the energy consumption, which is denoted as EC_i^D and expressed as:

$$EC_i^D = P_i^D + 2P_{circuit} - EH_i^D \quad (5)$$

Then the EE of each D2D link i can be calculated as a fraction:

$$EE_i^D = \frac{T_i^D}{EC_i^D} = \frac{log2\left(1 + \frac{(1-\theta_i)P_i^D h_i^D}{(1-\theta_i)\left(P_k^c h_{k,i} + N_0\right) + N_1}\right)}{P_i^D + 2P_{circuit} - EH_i^D} \quad (6)$$

E. Pre-matching Algorithm

As mentioned in the Section III-B, SWIPT is a distance-sensitive technique. So, the whole D2D link set will be divided into two groups, one for those D2D links which can perform SWIPT, which is denoted as $EnaD$, the other for those which can not activate EH model (Non-EH) is denoted as $InfD$.

A pre-matching algorithm is proposed to obtain the two groups. Two factors that can be used as the standard for the current D2D link i to perform SWIPT are the minimum power splitting ratio θ^i_{min} and maximum throughput $T^D_{i,max}$. $T^D_{i,max}$ can be calculated based on equation (1):

$$T^D_{i,max} = \frac{P_i^D h_i^D}{P_k^C h_{k,i} + N_0 + \frac{N_1}{1-\theta_{i,min}}} \quad (7)$$

The θ^i_{min} can be expressed as:

$$\theta_{i,min} = \frac{P^1_{thresold}}{P_{max} h_i^D + P_k^c h_{k,i} + N_0} \quad (8)$$

For each SWIPT-Supported D2D link i, two constraints are established, which can be expressed as:

$$\theta^i_{min} < 1 \,, T^D_{i,max} \geq T^D_{min} \,, (9)$$

where T^D_{min} is the minimum throughput D2D link i.

As shown in Algorithm 1, for each SWIPT-Supported D2D link i, a partner selection is established and assigned to CUE set first. A CUE k will be removed from the partner selection of i if the requirement of the minimum power splitting ratio and maximum throughput of the current D2D link i are not satisfied. At the end of each matching process of each D2D link i, it will be regarded as a SWIPT-Supported link if it has at least one CUE k in its partner selection and it will be put into the SWIPT-Supported gropu($EnaD$),otherwise, it will be regarded as a link which can not perform SWIPT and put into a non-EH group ($InfD$).

ALGORITHM 1: PRE-MATCHING ALGORITHM

Algorithm 1 Pre-Matching Algorithm

```
Input  : D, C, P_k^C, P_thresold^1, P_max, T_min^D
Output : PS, InfD, EnaD
Initialize EnaD = ∅, InfD = ∅
for i ∈ D do
    PS_i^D = C
    for k ∈ C do
        obtain θ_i,min using (8), obtain T_i,max^D using (7)
        if θ_i,min ≥ 1 or T_i,max^D ≤ T_min^D then
            Remove current k from PS_i^D
        end if
    end for
    if PS_i^D = ∅ then
        add i to InfD
    elseif PS_i^D ≠ ∅ then
        add i to EnaD
    end if
    add PS_i^D to PS
end for
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F. Formulation of EE optimization problem

As shown in Fig. 3, after using the pre-matching algorithm, it is noted that each SWIPT-Supported D2D link i is matched with more than one CUE k in its partner selection where the x axis is the numbering label of each link. To optimize the results from the per-matching algorithm, the next target is to help each D2D link i find its best partner CUE k based on the established partner selection.

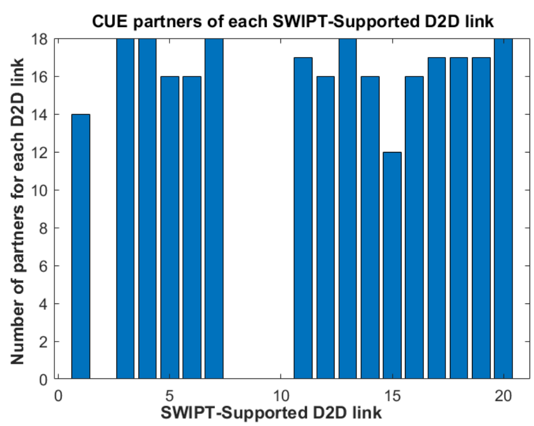

Fig. 3 The number of CUE partners at different SWIPT-Supported D2D link

According to equation (6), the optimization problem of EE is formulated as:

$$\boldsymbol{C1}: \max_{\{\theta_i, P_i^D\}} EE_i^D, i \in EnaD$$
$$\begin{aligned} &N1: 0 < P_i^D < P_{max} \\ &N2: 0 \leq \theta_i \leq 1 \\ &N3: T_i^D \geq T_{min}^D \\ &N4: T_k^C \geq T_{min}^C \\ &N5: P_i^R \geq P_{thresold}^1 \\ &N6: P_{thresold}^j \leq P_i^R \leq P_{thresold}^{j+1} \end{aligned} \quad ,(10)$$

where the optimization problem of EE is transformed to a constrained optimization problem of power splitting ratio θ_i and transmission power P_i^D of each D2D link i. ***N1-N6*** are the constrains of this optimization problem, where ***N1*** shows that the transmission power can not exceed the established maximum transmission power, ***N2*** defines the range for the power splitting ratio, ***N3*** and ***N4*** set the minimum Throughput which is required for each SWIPT-Supported D2D link i and CUE k respectively. ***N5*** shows that the EH model will be activated by receiving minimum value of energy and ***N6*** shows that each D2D link i will work at different power segments of EH model based on the received power.

However, equation (6) is a fractional function which is hard to solve directly. According to [21], a maximization problem like $\max\{\mathrm{N(x)/D(x)}\}$ can be transformed to another non-fractional maximization problem $\max\{\mathrm{N(x)} - \mathrm{qD(x)}\}$ where q is the solution of the former maximization problem. So $\mathbf{C1}$ can be similarly transformed to a simpler non-fractional function $\mathbf{C2}$:

$$\boldsymbol{C2}: \max_{\{\theta_i, P_i^D\}} T_i^D - G_i^D EC_i^D, i \in EnaD \quad (11)$$
$$\boldsymbol{s.t. N1 - N6}$$

Based on [21], there is a theorem which can be used to achieve G_i^D:

Theorem 1: The optimal G_i^{D*} can be achieved only when $T_i^{D*} - G_i^{D*} EC_i^{D*} = 0$, where G_i^{D*} is the solution of $\boldsymbol{C1}$, and T_i^{D*}, EC_i^{D*} are the optimal values of Throughput and total energy consumption of each SWIPT-Supported D2D link i.

Now the fractional function ***C1*** can be solved by addressing ***C2. C2*** can be regarded as an optimization problem with multiple inequality constraints, so, the corresponding Lagrange function is given as:

$$\begin{aligned} &L(P_i^D, \theta_i, \alpha, \beta, \gamma, \delta, \sigma) \\ &= T_i^D - G_i^D EC_i^D - \alpha(P_i^D - P_{max}) \\ &- \beta(\theta_i - 1) + \gamma(T_i^D - T_{min}^D) \\ &+ \delta(T_i^C - T_{min}^C) + \sigma(P_i^R - P_{thresold}^1) \end{aligned} \quad (12)$$

Where $\alpha, \beta, \gamma, \delta$ and σ are the Lagrange multipliers. According to the duality of Lagrange functions, Dual function can be defined as the infimum of the Lagrange function:

$$\begin{aligned} \boldsymbol{Propostion\ 1}: &g(\alpha, \beta, \gamma, \delta, \sigma) \\ &= \inf_{\{\theta_i, P_i^D\}} L(P_i^D, \theta_i, \alpha, \beta, \gamma, \delta, \sigma) \\ &= \max_{\{P_i^D, \theta_i\}} L(P_i^D, \theta_i, \alpha, \beta, \gamma, \delta, \sigma) \end{aligned}$$

Then the Lagrange dual problem can be defined as:

$$\begin{aligned} &\boldsymbol{C3}: \min g(\alpha, \beta, \gamma, \delta, \sigma) \\ &= \min_{\alpha,\beta,\gamma,\delta,\sigma \geq 0} \max_{\{P_i^D, \theta_i\}} L(P_i^D, \theta_i, \alpha, \beta, \gamma, \delta, \sigma) \quad (13) \\ &i \in EnaD \end{aligned}$$

Before we start wo solve $\boldsymbol{C3}$**,** here is a proposition to use first:

$\boldsymbol{Propostion\ 2}$: $\boldsymbol{C3}$ is convex with respect to θ_i and with respect to P_i^D when the value of θ_i and P_i^D are fixed, respectively.

Proof: At Appendix B

Then based on $\boldsymbol{Proposition\ 2}$, the local optimal value of θ_i and P_i^D can be obtained by using block coordinate descent (BCD) method. According to Karush– Kuhn–Tucker (KKT) conditions, the power splitting ratio θ_i and transmission power P_i^D of each SWIPT-Supported D2D i can be expressed as (14) and (15) respectively:

$$\frac{L(P_i^D, \theta_i, \alpha, \beta, \gamma, \delta, \sigma)}{\partial \theta_i} = 0 \quad (14)$$
$$\frac{L(P_i^D, \theta_i, \alpha, \beta, \gamma, \delta, \sigma)}{\partial P_i^D} = 0 \quad (15)$$

Since equation (14) and (15) are complicated and hard to solve directly, gradient method can be used to optimize all the Lagrange multipliers for each D2D link i. The process can be expressed as:

$$\begin{aligned} \alpha &= \{\alpha + s_1(P_i^D - P_{max})\}^+ \\ \beta &= \{\beta + s_2(\theta_i - 1)\}^+ \\ \gamma &= \{\gamma + s_3(T_i^D - T_{min}^D)\}^+ \\ \delta &= \{\delta + s_4(T_i^C - T_{min}^C)\}^+ \\ \sigma &= \{\sigma + s_5(P_i^R - P_{thresold}^1)\}^+ \end{aligned} \quad ,(16)$$

where symbol $\{M\}^+$ means $\max\{0, M\}$, and $s_1 - s_5$ are the step size, which will be used to update the corresponding Lagrange multipliers and they are all set to 10^{-5} in this project.

G. Inner-Loop Algorithm

In equation (4), the power segments of the EH model are set in ascending order, as mentioned in Section III-F, each D2D receiver works at different power segment of the EH model. So, for each D2D link i paired with a CUE k, the maximum number N_{max} of power segment can be obtained by calculating maximum received power of i, which is expressed as:

$$P_{i,max}^R = P_{max} h_i^D + P_k^c h_{k,i} + N_0 \quad (17)$$

ALGORITHM 2: INNER LOOP ALGORITHM

Algorithm 2 Inner loop algorithm

Input : $EnaD, PS$

Output : $\theta_{i,j}, P_{i,j}^D, EE_{i,j}^D$

$for\ i \in EnaD\ do$
  $for\ k \in PS_i^D\ do$
  Calculate $P_{i,max}^R$ using (5), and obtain N_{max} using function A
    $for\ j = 1{:}\,N_{max}\ do$
      Initialize P_i^D as $P_i^D(0), G_i^D$ as $G_i^D(0)$
      Initialize t=0, I, ϕ
      obtain $\theta_i(t)$ by calculating (14) using $P_i^D(0)$
      $while\ t < I$
        Obtain $P_i^D(t+1)$ using $\theta_i(t)$ to calculate (15
        Obtain $\theta_i(t+1)$ using $P_i^D(t+1)$ to calculate (
        $if\ T_i^D - G_i^D(t)EC_i^D < \phi\ then$
          $\theta_{i,j} = \theta_i(t+1), P_{i,j}^D = P_i^D(t+1), EE_{i,j}^D = G_i^D(t)$
            $break\ iteration$
        $else$
          Update all the Lagrange multipliers using (
          $G_i^D(t+1) = \frac{T_i^D\left(\theta_i(t+1), P_i^D(t+1)\right)}{EC_i^D\left(\theta_i(t+1), P_i^D(t+1)\right)}$, $continue$
        $endif$
          $t = t+1$
      $end\ while$
    $end\ for$
  $end\ for$
$end\ for$

To solve $\boldsymbol{C3}$, an inner loop algorithm is proposed. As shown in Algorithm 2, after the N_{max} is obtained, for each pair of D2D link i and CUE k, the obtained value of the transmission power, power splitting ratio and EE at different power segment will be checked if they meet the requirement based on $\boldsymbol{Theorem\ 1}$. If so, the value of transmission power $\{P_{i,1}^D, P_{i,2}^D, \dots, P_{i.j}^D, \dots P_{i,Nmax}^D$,power splitting ratio $\{\theta_{i,1}, \theta_{i,2}, \dots, \theta_{i,j}, \dots, \theta_{i,N_{max}}\}$ and EE $\{EE_{i,1}, \dots EE_{i,N_{max}}\}$ at different power segment can be obtained, otherwise, the iteration will continue for each iteration step t until the maximum iteration number I or the requirement Φ is reached.

H. Outer-Loop Algorithm

According to the results of the inner-loop Algorithm, for each D2D i paired with CUE k, it has different EE at multiple power segments of the EH model. To further optimize the matching process, an outer-loop algorithm is proposed to help each pair of D2D i and CUE k find the best power segment that can help it achieve the highest EE. As shown in Algorithm 3, the optimal power segment of each pair can be expressed as:

$$j^* = argmax_j\{EE_{i,1,}EE_{i,2}, \dots, EE_{i,j}, \dots EE_{i,N_{max}}\} \quad (18)$$

Then the optimal value of the power splitting ratio and D2D transmission power can be obtained at the optimal power segment, which are denoted as θ_{i,j^*} and P_{i,j^*}^D, respectively.

ALGORITHM 3: OUTER LOOP ALGORITHM

Algorithm 3 Outer loop Algorithm

Input : $EnaD, PS, \theta_{i,j}, P_{i,j}^D, EE_{i,j}^D$

Output : $P_i^{D*}, \theta_i^*, EE_i^{D*}$

$for\ i \in EnaD$
  $for\ k \in PS_i^D$
    Obtain $P_{i,max}^R$ using (5), and obtain N_{max}
    $for\ j = 1{:}\,N_{max}$
      $j^* = \arg\max\{EE_{i,1}^D, EE_{i,2}^D, \dots, EE_{i,j}^D, \dots EE_{i,N_{max}}^D\}$
      Assign $P_i^{D*} = P_{i,j^*}^D$, $EE_i^{D*} = EE_{i,j^*}^D, \theta_i^* = \theta_{i,j^*}$
    $end\ for$
  $end\ for$
$end\ for$

I. Preference Lists

Based on the results of the inner loop and outer loop algorithm, each pair of D2D i and CUE k has the highest EE at the specific power segment of the EH model. Then two preference lists are built for each D2D link i and CUE k, respectively. As shown in Algorithm 4, the preference list for all D2D links is built by setting each CUE partner in descending order of EE while the preference list for CUE is built by setting each D2D link in ascending order of interference power, where the interference power can be expressed as:

$$P_{interference} = P_i^D * h_i^B \quad (19)$$

Where h_i^B is the channel response from a D2D link i to base station.

ALGORITHM 4: PREFERENCE LIST

Algorithm 4 Preference list

Input :$P_i^{D*}, EE_i^{D*}, \theta_i^*, EnaD, C, PS$

Output :Ω_i^D, Ω_k^C

$for\ i \in EnaD\ do$
  $for\ k \in PS_i^D\ do$
    $get\ EE_i^{D*}$ and place k into Ω_i^D in descending order of EE_i^{D*}
  $endfor$
$endfor$

$for\ k \in PS_i^D\ do$
  $for\ i \in EnaD\ do$
    obtain $P_{interference}$ caused by i using (17), and place i into Ω_k^c in ascending order of $P_{interference}$
  $endfor$
$endfor$

J. *One-to-one stable matching with constraints*

After building the preference list for each D2D link i and CUE k, a perfect match will be called, if each SWIPT-Supported D2D link i can find their own partner CUE k. However, it is very difficult to achieve that since the channel condition can not be totally ideal under some circumstances and the communication distance can be very long, while SWIPT is quite sensitive to communication distance. Also, as mentioned in section III-F, each SWIPT-Supported link i selected limited number of CUE partners after using the pre-matching algorithm, which means that some SWIPT-Supported D2D links have limited number of CUE partners in its partner selection. What is more, each CUE k has its own preference list, which means CUE k may not accept the proposal of matching from a D2D link i. All the situations may cause a D2D link i to fail to find a CUE partner.

A one-to-one stable matching algorithm with constraints is proposed to solve aforementioned issues. According to [22], stable matching will support a group which sends a proposal to the other group. As shown in algorithm 5, for each D2D link i, it will try to match with its best preferred CUE k based on its preference list. If the current CUE k receives only one proposal from i, then they will be matched immediately. If the current CUE k also has some other proposals from some other SWIPT-Supported D2D links, then the best partner selection will be determined by checking if one of the D2D links has only one preference in its list, if so, then it will be matched with the CUE k immediately. If there is no such a SWIPT-Supported D2D link i which has only one preferred CUE in its list, then the CUE k will match one of them based on its own preference list. For each iteration, those D2D links which already find a partner will be removed from the SWIPT-Supported group and this matching process will end until all the D2D links find its CUE partner.

ALGORITHM 5: ONE-TO-ONE STABLE MATCHING

Algorithm 5: One-to-one Stable Matching Algorithm

Input : $\Omega_i^D, \Omega_k^C, EnaD, C, PS$

Output : ϕ, ϕ^R

$while\ EnaD \neq \phi\ do$
  $for\ i \in EnaD\ do$
    Let i propose its most preferred CUE Ω_i^D which should be the first CUE in Ω_i^D
    $for\ k \in PS$
      if k is the most preferred CUE for i $then$
        $if\ k$ receives only one proposal from D2D link i then
          i will be matched with $k, \phi = (i, k)$
          The matched i will be removed form $EnaD$
          $break$
        $elseif\ k$ receives not only one proposal from different D2D links $then$
          if one of the D2D links α has only one preferred CUE in its preference list $then$
          α will be matched with k, $\phi = (i, k)$, it will be removed from $EnaD$
          $elseif$ all the D2D links have more than one preferred CUE in their preference lists $then$
            The CUE k will be matched with its most preferred D2D link i' from its preference list Ω_k^C, and the matched D2D link will be removed form $EnaD$
          $end\ if$
        $end\ if$
      $elseif\ \ k\ is\ the\ most\ preferred\ CUE\ for\ i\ \ then$
        $continue$
      $end\ if$
    $end\ for$
    i deletes its most preferred CUE from Ω_i^D
  $end\ for$
$end\ while$
Gather all the unmatched CUEs in ϕ_R

K. *EE for Non-EH group*

As mentioned in Section III-E, all the D2D links that can not perform SWIPT are put into a group denoted as $InfD$. Since these links are not able to perform SWIPT, we do not need to think about the EH sensitivity and power splitting ratio anymore. So, only one parameter we need to consider is the transmission power P_i^D, which means that the original optimization problem of EE was transformed to an optimization problem of P_i^D, where the optimal value of it can be expressed as:

$$P_i^{D*} = \left\{ \frac{(1+\beta')\log_2 e}{\alpha' + Q_i^{D*}} - \frac{P_k^C h_k^i + N0 + N1}{h_i^D} \right\}^+ (18)$$

And the corresponding interference power used in preference list establishment is given by:

$$P_{interference} = P_k^C * h_{k,i} \ (19)$$

IV. Discussion

This section will demonstrate the results of all the proposed algorithms mentioned in the previous section based on the non-linear EH model in [7]. A similar matching-based algorithm in [14], a linear EH model and a heuristic algorithm where each SWIPT-Supported D2D link i is randomly matched with the maximum transmission power were employed to compare with the obtained results.

A. Simulation setup

The simulation set up follows system model given in section III-A as shown in Table 1, for the sake of not losing generality, the number of D2D and CUE are assumed to be the same for each generation of the system model. All the data listed in Table 1 are from [7].

TABLE 1: SIMULATION PARAMETER [7]

Simulation parameter	Value
Radius of Cellular Network	250m
Number of D2D links N	$10 \sim 70$
Number of CUE links M	$10 \sim 70$
D2D communication distance	$10 \sim 70m$
Path loss exponent	3
EH power segment $[Pth_1\ Pth_2\ Pth_3\ Pth_4]$	[10 100 230.06 57368] uw
EH linear function coefficient $[k_1\ k_2\ k_3\ k_4]$	[0 0.3899 0.6967 0.1427]
EH linear function intercept $[b_1\ b_2\ b_3\ b_4]$	[0 -1.6613 -19.1737 108.2778]
Maximum harvested power $P_{max}^{harvested}$	250uw
Max transmission power P_{max}	23dBm
Circuit power consumption P_{cir}	20dBm
CUE transmission power P_k^C	23dBm
Initial Lagrange multipliers $\alpha, \beta, \gamma, \delta, \sigma$	0.1
Noise power N_0, N_1	-100dBm
Throughput requirement of D2D link i T_{min}^D	2bits/Hz
Throughput requirement of CUE k T_{min}^C	1bit/Hz

B. Pre-matching failure rate

Fig. 4 and Fig. 5 plot the pre-matching failure rate (PFMR) which is defined as the ratio of the number of Non-EH D2D links to the total number of D2D users. Two factors: the number of D2D links and the communication distance are considered to measure the performance of the pre-matching algorithm.

As shown in Fig. 4 , the PFMR decreased from 14% when the number of D2D user is 10 to approximately 12.7% when the number is 70, which is what we expect since the bigger the number of the user is in the system, there will be more CUE trying to match each D2D link i, which makes it more possible for each D2D link to have at least one CUE in its partner selection and hence decreases the PFMR.

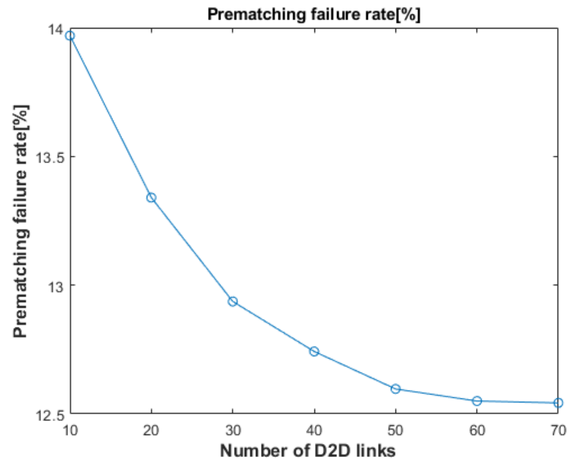

Fig. 4 Pre-matching failure rate versus the number of D2D links

As we can see from Fig. 5, when we change the communication distance, which is defined as the distance between each D2D transmitter and D2D receiver, the PFMR increased from around 8% to 100% with the communication increasing from 10m to 70m. The reason for that is because SWIPT is supposed to work under short distance as mentioned in Section I, and when the communication distance increases, the transmission power of each D2D transmitter needs to be increased to achieve the constraints of EH model to activate it and if the transmission power exceeds the established value of maximum transmission power, it can not perform SWIPT and hence increases PFMR. This also indicates that the pre-matching algorithm and SWIPT are very sensitive to the communication distance when the pass loss is large.

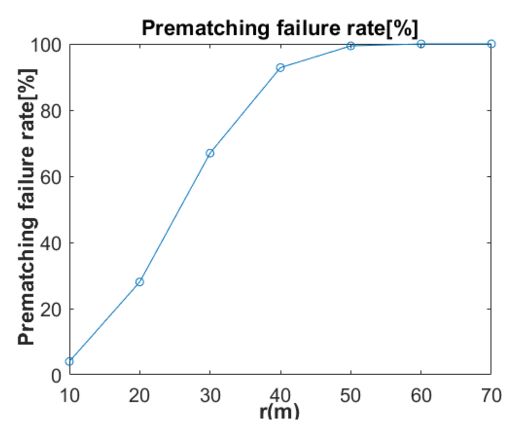

Fig. 5 Pre-matching failure rate versus D2D communication distance.

It is also noticed that the PFMR can be affected significantly by the established minimum threshold power

$P^1_{threshold}$. As shown in Fig. 6, when $P^1_{threshold}$ increases, the value of the PFMR increases at different number of D2D users. The reason for that is because $P^1_{threshold}$ is the minimum power requirement to activate the EH model, when $P^1_{threshold}$ increases, it also makes it more difficult for each D2D link i to perform SWIPT.

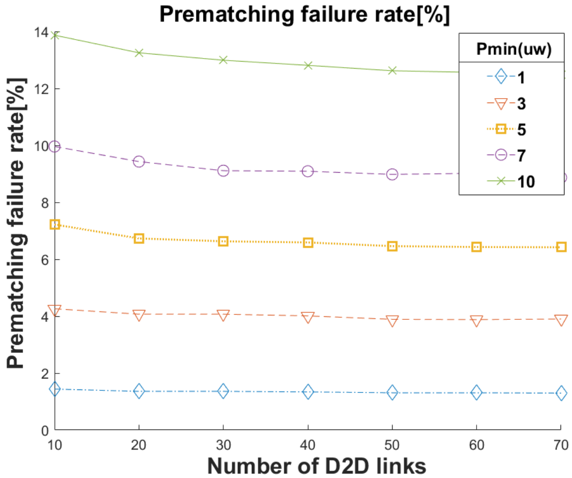

Fig. 6 Pre-matching failure rate with different minimum power segment at different D2D users.

Similarly, as shown in Fig. 7, when increasing the minimum power segment $P^1_{thresold}$ at different communication distance, the PFMR increases as well since it increases the difficulty of activating the EH model and hence increases the PFMR.

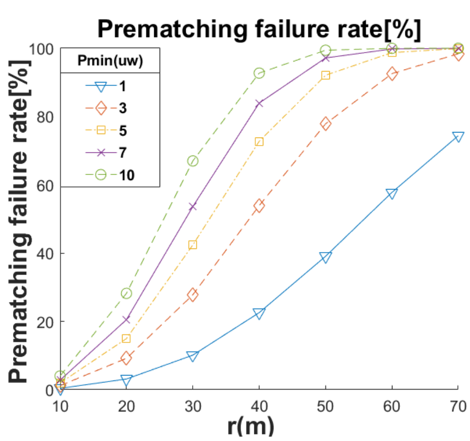

Fig. 7 Pre-matching failure rate with different minimum power segment at different D2D communication distance

C. Convergence of inner loop Algorithm

Fig. 8 plots the EE at different iteration step of a D2D link i matched with two different value of maximum transmission power P_{max}. The EE of the of D2D link i converges at iteration step 3 and iteration step 4 when P_{max} is 23dBm and 20dBm, respectively. The result indicates that this iterative algorithm is quite efficient for addressing the target optimization problem and it also shows that with higher maximum transmission power established, each D2D link i can achieve higher EE since higher transmission power limit allows for more optimal value of P^D_i.

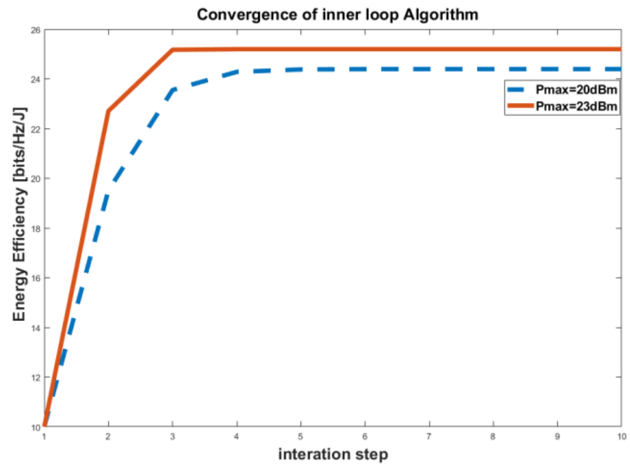

Fig. 8 Pre-matching failure rate with different minimum power segment at different D2D users.

D. Sum EE

In this section, the sum EE of all D2D links has been plotted at different number of D2D users, communication distance and CUE transmission power. Three other different different models are added to compare with the obtained results, including a linear EH model, a stable matching algorithm in [14] and a heuristic algorithm where all the D2D links are randomly matched with maximum transmission power. The linear EH model were employed by fixing the value of coefficient of the received power P^R_i and intercept in equation (4). The main difference between the stable matching-based algorithm in [14] and algorithms mentioned in Section III E-J is that the Non-EH D2D links were not considered, which means that all the D2D links were not pre-matched with any CUE partners before optimizing EE of each D2D link i. The heuristic algorithm was proposed by fixing the value of transmission power P^D_i to P_{max}, where the parameter that need to be optimized in $\boldsymbol{C1}$ is only power splitting ratio θ_i.

Fig. 9 demonstrates the sum EE of all D2D links at different D2D users using four different types of models. As we can see from the figure, the proposed algorithms in this project achieved the highest sum EE. The gap between the EE performance of linear EH model and the proposed algorithms indicates that the linear EH model might cause some mismatches for power allocation, and it tolerates some degradation of EE performance from the piecewise linear EH model. The bigger difference between the piecewise linear EH model and that in [14] shows that pre-matching process and the proposed one-to-one stable matching algorithm make more SWIPT-Supported D2D links to find their best CUE partners and hence achieve better EE performance. In Fig. 9, the improvement of the EE performance mainly results from the continuous optimization of power splitting ratio and D2D transmission power in the inner loop algorithm. It is also noticed that the gap between the proposed algorithms and [14] is not very large and the reason for that is because the communication distance is set as 20 m, which is not very long, and as shown in Fig. 9, under this circumstance, the PFMR is quite low, which means that the number of SWIPT-Supported D2D links quite close to that in [14].

It is noticed that in Fig. 9, the heuristic algorithm gives the worst sum EE. The result can be attributed to higher EE loss, which is mainly caused by energy consumption, although this algorithm has totally ignored the issues of power consumption and aimed to increased EE by improving the throughput of each D2D link i.

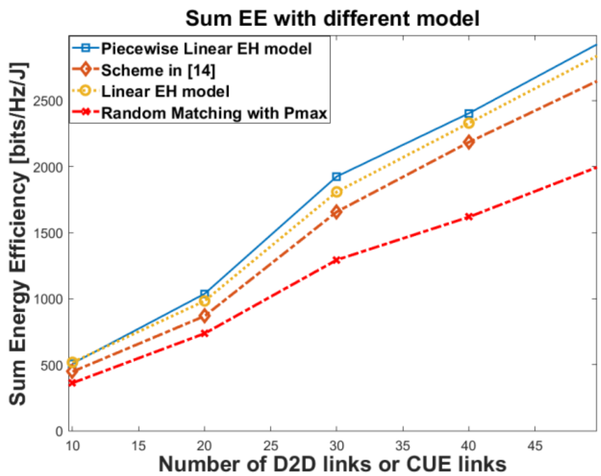

Fig. 9 Sum EE at different number of D2D users or CUEs

Fig. 10 shows the sum EE of all D2D links using different algorithms at different communication distance r.As described in Fig. 7, the PFMR increases significantly with communication distance increasing and hence causes the sum EE to decrease sharply, while the proposed algorithms still give the best EE performance compared with all the other algorithms, where the heuristic algorithm still gives the worst EE performance. The reason why there is huge EE reduction as the communication increases is that larger transmission power will be needed to meet the constraints $\boldsymbol{N3}$ and $\boldsymbol{N5}$ when increasing the communication distance, which will also cause more energy consumption.

It is noticed that when the communication distance is around 20m, the sum EE of [14] is still quite close to the proposed algorithms as the PFMR is quite low where each D2D link i can always find their CUE partner and we still can see that small gap still exists since the power splitting ratio and transmission power are optimized. As the communication distance becomes larger, the gap becomes larger since PFMR becomes higher and more D2D can not communicate in [14] due to pass loss and Rayleigh fading and hence leads to lower sum EE. The little gap between the EH model and piece wise linear EH model proves that the linear EH model causes some mismatches for power allocation, which leads to EE degradation.

The huge gap between proposed algorithms and the heuristic algorithm indicates that this heuristic algorithm suffers from huge EE degradation due to large energy consumption.

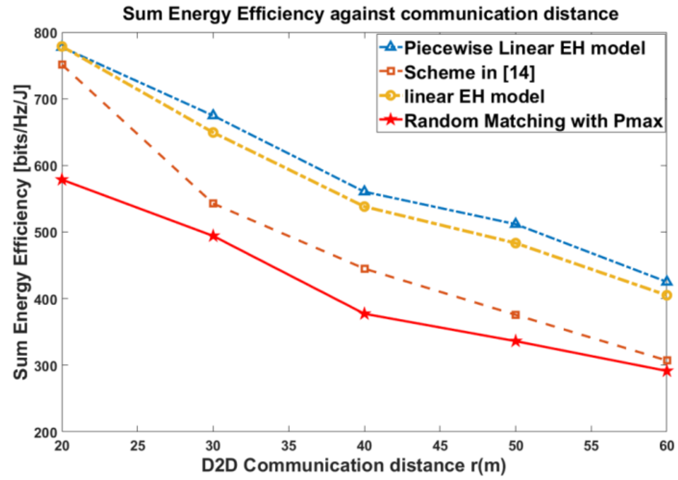

Fig. 10 Sum EE at different D2D communication distance

Fig. 11 plots the sum EE of all D2D links at different CUE transmission power. As we can see from the figure, the sum EE increases from approximately 1680 bits/Hz/J to a peak of 1840 bits/Hz/J with the CUE transmission power increasing from -20dBm to 0 dBm, after which it decreased continuously when the CUE transmission power is further increased. The reason for this case is that more energy is provided when the CUE transmission power is higher, which can let each D2D receiver harvest more energy according to equation (3) and (4). However, as the CUE power increases to a certain value (in this Fig. 11 is 0dBm), sum EE will start to decrease. The reason for that is because the increasing value of CUE power also causes interference power to increase according to equation (19), which causes the EE loss and can not be compensated by more harvested energy.

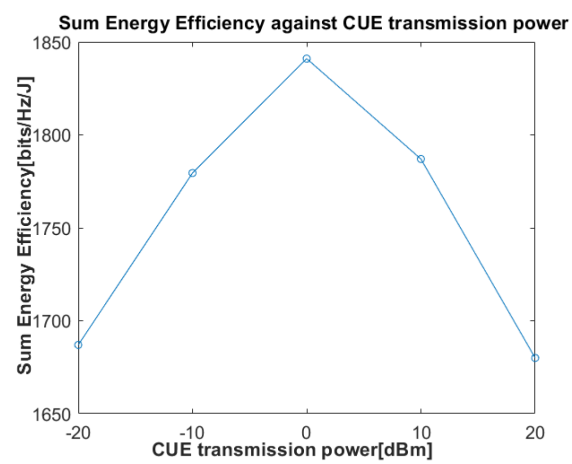

Fig. 11 Sum EE at different CUE transmission power.

V. CONCLUSIONS

In this project, it aims to optimize the sum EE of all D2D links by optimizing the transmission power of each SWIPT-Supported D2D link and power splitting ratio based on a piecewise linear EH model. Particularly, fist we proposed a pre-matching algorithm to separate those SWIPT-Supported links from the D2D link sets. Then an inner loop and outer loop iterative algorithm are proposed to optimize the transmission power and power splitting ratio of each SWIPT-Supported D2D link. To further optimize the matching process, a one-to-one stable matching algorithm is proposed to help each SWIPT-Supported D2D link find their best CUE partner based on the established preference lists for D2D group and CUE group. The sum EE of Non-EH D2D group is also optimized using the similar matching process. The simulation results show that the sum EE is higher when the number of D2D users is bigger and the communication distance is shorter, which indicates that the technology of SWIPT is sensitive to distance. The proposed algorithms proved to be more energy efficient than some of the existing work.

VI. Future Work

Although the proposed algorithms in this project have proved to achieve higher EE than some existing work, it is also noticed that the simulation works very slowly, as we can see from the description of convergence analysis in Appendix-A, the time complexity is still high in this algorithm, and it would be an issue if the input data is big. So, in the future, the optimization target of this project will be focused on optimizing the proposed algorithms. What is more, the sum EE of each D2D link can also be further optimized by further optimizing the power splitting ratio, transmission power of each D2D link i.

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APPENDIX

A. Convergence Analysis of Algorithms

In the pre-matching algorithm, the complexity is determined by the number of all the D2D uers and CUEs in the generated system. If set the number of D2D links in the system as M and that of CUE as N. Then the computational complexity can be expressed as $O(MN)$.

To calculate the complexity of the inner loop algorithm, first the number of SWIPT-Supported D2D links is set as M' and the number of the number of the CUE partners in the partner selection of each D2D link i is N'. For each SWIPT-Supported D2D link i paired with a CUE k, we set the maximum number of the power segment is N_{max}. We assume that the "while loop" needs δ_1 iteration step to converge and to optimize each Lagrange multipliers, the gradient methods need δ_2 iteration steps to converge and since the number of the Lagrange multipliers is 5, so the total number of iteration steps to converge is $5\delta_2$. So, the computational complexity can be calculated as: $O(M'N'5\delta_2\delta_1N_{max})$.

Similarly, the corresponding complexity of the outer loop algorithm is $O(M'N'N_{max})$.

As for the complexity of the one-to-one stable matching algorithm with constraints, since each D2D link i only proposed to its most preferred CUE k once for each iteration, then the computational complexity of Algorithm 5 can be expressed as $O(M^{2''}N'')$, where M'' and N'' are the number of SWIPT-Supported D2D links and CUEs in the proposed system, respectively.

B. Convexity of Proposition 3

To find the convexity of $\boldsymbol{P3}$, the second order partial derivative of the Lagrange function with respect to θ_i and P_i^D need to be achieved, which can be expressed as:

$$\frac{L^2(P_i^D,\theta_i,\alpha,\beta,\gamma,\delta,\sigma)}{\partial\theta_i^2} = \frac{-Clog_2^e X\left((P_i^D+X)(1-\theta_i)+N1\right)}{(X(1-\theta_i)+N_1)^2\left((P_i^D+X)(1-\theta_i)+N1\right)^2} + \frac{-Clog_2^e(X(1-\theta_i)+N_1)(P_i^D h_i^D +)}{(X(1-\theta_i)+N_1)^2\left((P_i^D+X)(1-\theta_i)+N1\right)^2}, (20)$$

where $C = P_i^D h_i^D N_1$, $X = P_k^C h_k^i + N_0$

$$\frac{L^2(P_i^D,\theta_i,\alpha,\beta,\gamma,\delta,\sigma)}{\partial {P_i^D}^2} = -\frac{-({h_i^D}^2 \log_2^e)(1+A)}{(P_i^D h_i^D + P_k^C h_{k,i} + N_0 + \frac{N_1}{1-\theta_i})} - \frac{\left(P_k^c h_{k,c} h_i^B log_2^e\right)Y}{G\left(P_i^D h_i^D + P_k^C h_{k,i} + N_0 + N_1\right)^2}, (21)$$

where $A = h_{k,i}h_i^B$, $G = (N_1 + N_0 + P_i^D h_i^D)^2$, $Y = [(2P_i^D 2h_i^B + 2N_0 + 2N_1)h_i^B + P_k^C h_k^C]^2$

It is clear that both (20) and (21) are negative, so the Lagrange optimization problem is convex, which proves the ***Proposition 3.***