In this section, we focus on the reduction of system energy consumption while ensuring the users’ service requirements. We formulate the optimization problem for process-oriented user scheduling. Moreover, we proposed an efficient 3-step iterative algorithm with polynomial time complexity to solve the NP-hard problem.

1. Problem formulation

To fully utilize the slow time-varying characteristic of the large-scale channel fading, we divide the total service time into  time slots, each lasts . The value  is carefully chosen so that  remains constant in each time slot . Thus, we make it possible to estimate  for  based on shipping lanes and timetable. With the large-scale channel fading known beforehand, we can further design and implement a process-oriented scheme foe user scheduling.

The total energy consumption of the system consists of cellular transmission power (BS) and D2D transmission power. Our objective is to minimize the system energy consumption by means of user scheduling in cellular transmission and D2D transmission. We further denote the transmission link from BS/user  ( means BS,  means user relay) to user  at time slot  by . For the transmission link , we denote the ratio of the used transmission speed to max transmission speed by .  means no subcarrier is scheduled for the transmission , while  means a subcarrier is scheduled and the transmission uses  of its max speed. By  we denote the total data volume user  have by time slot . Since the system has no D2D data reuse, user  must have enough  in order to transmit to  at .

Denote the transmission power for  by . We formulate the optimization problem as

 (1a)

*s.t.*  (1b)

 (1c)

 (1d)

 (1e)

 (1f)

 (1g)

Where  represent the maximum transmission power of BS and users, and . Constraint in (1b) guarantees that users can only receive from one source since they have single antenna. Constraint in (1c) guarantees that at most  users can be severed simultaneously in the system, cellular or D2D, since there is only  subcarriers. (1f) and (1g) make sure that the QoS constraint is met and relays can only transmit all they have at most. From (1d) we have

 (2)

We can use (2) to get the transmission power based on ,  and CSI.

1. Algorithm

The problem in (1) is a discrete non-convex optimization problem and is NP-hard. Therefore, conventional method for solving linear or convex optimization problems are no longer applicable. We decompose the problem into three simpler sub-problems. First, we ignore the subcarrier constraint and only consider the cellular transmission. Second, we use an iterative algorithm to make sure the cellular transmission uses no more than  subcarriers. Last, we use another iterative algorithm to substitute part of the cellular transmission links for D2D transmission links for less energy consumption.

For the first two sub-problems, we consider a cellular-only system. We fix  since users can only receive data from BS.

 (3a)

*s.t.*  (3b)

 (3c)

 (3d)

 (3e)

 (3f)

Here in (3a)  and  since the system here is cellular only and don’t need to transmit at power less than maximum. However, in the third sub-problem, we use a substitution set of D2D links consist of exact one cellular link  and one D2D relay transmission link . Two links (one cellular and one D2D) in the substitution set must use less power combined than the original cellular one for improvement energy-wise. This results in that the speed of the two links in the substitution set must be less than their max speed, and therefore  and . Thus, in (1a) we have .  represents maximum transmission power of BS. Constraint in (1b) is not necessary here since users can only receive data from one source, namely BS.

1. Sub-problem 1

For the first sub-problem, we optimize  with constraint (3c)-(3f), ignoring the subcarrier constraint. This means we assume that the BS is omnipotent: that is, BS can serve infinite number of users. In this case, the optimization variables of different users in no longer correlated, and the optimal solution of this problem can be obtained by scheduling each user separately. The problem can be reduced to . Note that  is a monotone increasing function of , therefore we can obtain the optimal solution for each user by assigning time slots with best CSI.

Define  as the set of chosen transmission link at a specific time slot, i.e.,  if  is a chosen transmission link at time slot . We propose Algorithm 1 to solve the first sub-problem.

Algorithm 1

**for** each user  :

**while**  not met :

find 

set 

update , update , update  .

1. Sub-problem 2

After Algorithm 1,  is not a feasible solution for the cellular-only system in (3a)-(3f), since we haven’t take (3b) into account. Here at sub-problem 2, we further check the feasibility of  and design an effectively method to make it approach the optimal feasible solution iteratively.

As  is the optimal solution for (3c)-(3f), the original problem in (3a)-(3f) is equivalent to minimizing the energy consumption gap between  and the result  in sub-problem 2, and the second sub-problem can be expressed as

 (4a)

*s.t.*  (4b)

 (4c)

 (4d)

 (4e)

 (4f)

Note that solving this sub-problem is a process of adjusting the user scheduling result in . We propose an iterative method as shown in Algorithm 2.

Algorithm 2

initial 

**while**  not met :

find , where , 

set , 

**while**  not met :

find , where 

set 

update , update , update  .

1. Sub-problem 3

After the first two problems, we have already claimed an approximation of the optimal solution for the cellular-only system in a  subspace. In sub-problem 3, we change part of the cellular transmission links into D2D transmission links for better energy efficiency, and optimize in a  subspace. Given that  is only based on constraint (3a)-(3f), the original problem in (1a)-(1g) is equivalent to maximizing the energy consumption reduction between  and the result  in sub-problem 2, and the third sub-problem can be expressed as

 (5a)

*s.t.*  (5b)

 (5c)

 (5d)

 (5e)

 (5f)

 (5g)

Here . For simplicity, by  we denote the cellular transmission link in  that is to be replaced by a set of D2D links in sub-problem 3, and this link has max transmission speed . Whereas the substitution set of D2D links in this paper consist of exact one cellular link  and one D2D relay transmission link . Two links (one cellular and one D2D) in the substitution set must use less power combined than the original cellular one. Accordingly, the speed of the two links in the substitution set must be less than their max speed, and therefore  and . Note that solving this sub-problem has to be solved in a larger subspace . We propose another iterative method as shown in Algorithm 3.

Algorithm 3

initial 

**for** all user  :

set  as temporary set for all possible d2d link sets to user ,

**for** all time slot  :

**for** all relay  :

**if**  and  :

**for** all time slot  where  and  and :

**if** :

set 

**while**  :

update 

**if**  and  where  and  and :



**else**:



**if** :



set 

update , update , update 

set 

**else** :

**break**

Here  means that



and 

and 

And  means that



and 

Therefore the system constraint in (1b) and (1c) is met.