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 (BS) transmission part and D2D transmission part. 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 . We assume BS/user always use their max power  for transmission  and therefore the transmission speed is always at its maximum. For the transmission link , we denote the ratio of the used transmission time to time slot’s duration by .  means no subcarrier is scheduled for the transmission , whereas  means a subcarrier is scheduled at time slot  and the transmission uses  of the time slot’s duration. 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 .

We formulate the optimization problem as

 (2a)

*s.t.*  (2b)

 (2c)

 (2d)

 ,  (2e)

 (2f)

 (2g)

where  represents the maximum transmission power of BS and users, and  since we have to consider transmissions from  sources to  targets at  time slots dimension. Constraint in (2b) guarantees that users can only receive from one source since they have single antenna. Constraint in (2c) guarantees that at most  users can be severed simultaneously in the system, cellular or D2D, since there is only  subcarriers. In (2e) we create two denotations  and  for simplicity in (2a) and (2g). (2f) and (2g) make sure that the QoS constraint is met and relays can only transmit all they have at most.

1. Algorithm

The problem in (1) is a discrete non-convex optimization problem and is NP-hard. Therefore, conventional methods 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 and get a suboptimal solution for the cellular-only system. Last, we use another iterative algorithm to substitute part of the cellular transmission links for D2D transmission link sets for less energy consumption. Each of the substitution D2D link sets consists 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 energy combined than the original cellular-only link for improvement energy-wise. This results in that the transmission time of the two links in the substitution set must be less than time slot duration .

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)

 represents the maximum transmission power of BS. Here  since the optimization is currently in a  subspace (only one source BS) in the first two cellular-only sub problems. Constraint in (1b) is not necessary here since users can only receive data from one source, namely BS.

1. Sub-problem 1 - optimal user scheduling for cellular system regardless of subcarrier count

For the first sub-problem, we optimize  with constraint (3c)-(3f), ignoring the subcarrier constraint in (3b). 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  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 optimal user scheduling for cellular system regardless of subcarrier count

**for** each user  :

**while**  not met :

find 

set 

update , update , update  .

1. Sub-problem 2 - suboptimal user scheduling for cellular system

The solution  returned by Algorithm 1 is not a feasible one for the cellular-only system in (3a)-(3f) since (3b) has not been taken into account. We design an effective method to approach the suboptimal 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)

 ,  (3d)

 (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 suboptimal user scheduling for cellular system

initialize 

**while**  not met :

find , where , 

set , 

**while**  not met :

find , where 

set 

update , update , update  .

1. Sub-problem 3 - suboptimal user scheduling for D2D underlying cellular system

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  since the optimization is now in a  subspace since there are  sources (BS/users),  targets and  time slots. 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. 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 energy combined than the original cellular one. Accordingly, the transmission time of the two links in the substitution set must be less than time slot duration , and therefore  and . We propose another iterative method as shown in Algorithm 3.

Algorithm 3 suboptimal user scheduling for D2D underlying cellular system

initialize 

**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 (2b) and (2c) is met.