Energy Efficient Caching and Sharing Policy in Multihop Device-to-Device Networks

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Abstract. Caching content at the user device and sharing files via multihop Device-to-Device link can offload the traffic from the Base Station, which is inevitable to consume the user's energy. But most works usually assume that the battery capacity is implicitly infinite and rarely consider the impact of the user's remaining battery energy on the file transmission. In fact, the user device has limited battery capacity and the transmission may be not completed due to the insufficient battery energy. So it is important to utilize the limited battery energy to ensure more successful transmission and traffic offloading. In this paper, we firstly optimize the caching policy and obtain the minimum energy cost of cache-enabled multihop D2D communications. For this purpose, we classify users into different clusters and use a weighted undirected graph to represent the topological relationship of users in one cluster. Then, we propose a novel algorithm to find the optimal path to transmit files via multihop D2D link. Finally, we obtain the minimum energy cost and optimal caching policy. Simulation results show that the proposed caching policy performs better than other general caching strategies in terms of energy conservation.

Keywords: Caching policy · Energy cost · Multihop D2D
Undirected graph

1 Introduction

With the development and popularization of mobile devices, such as smartphones and tablets, the demand for mobile data is increasing rapidly [7]. At the same time, research shows that the majority of users' requests for content are often asynchronous and duplicated [2], which increases the load on base stations heavily. Therefore, caching content at the edge of the network and sharing content via D2D link become a trend of content distribution, which not only can offload traffic from the base station, but also can provide lower latency and higher quality user experience [1].

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Recent researches about D2D cache network are almost focus on the performance of caching policy. In [9], the probabilistic caching policy was proved to outperform the universal caching strategy due to its promising performance and feasibility in practical use. However, the authors of [8] showed that the optimal caching scheme for D2D content distribution was similar to the demand distribution, which can be modeled as a Zipf distribution. In fact, sharing content has to consume transmitter's energy, nevertheless, the user device has limited battery capacity and may be not willing to consume its power to transmit files to other users. The authors of [12] proposed an energy-aware incentive mechanism to motivate mobile users to participate in D2D content sharing. In addition, taking the user's battery capacity into account contributes to a reduction in the possibility of offloading traffic. In [4], the author investigated the relationship between offloading gain and energy cost of each helper user and introduced a user centric protocol to control the energy cost for a helper user to transmit the file. In [10], a new definition, energy-consumption-ratio was proposed, which was used to measure the energy efficiency that caching scheme can achieve. In these previous research [4,8,10,12], users obtained the required file from other users only via one-hop transmission, not consider multihop transmission. Therefore, in [6], the author extended the one-hop D2D network and considered multihop transmission, and in [5] a sequence of adjacent nodes were modeled as a linear topology to investigate the performances of both local and distributed cooperative caching policies. In practice, however, the users are randomly distributed and not always be represented by linear topology.

In the previous researches for caching in D2D network [8–10], for simplicity, the user device is assumed to have enough battery energy to transmit files. However, in fact, the user device has the limited battery energy. There are few papers consider the impact of the user's remaining battery energy on content delivery via multihop D2D link. Once the transmission fails, the energy consumed is wasted. In this paper, we take the user's battery capacity into account to make sure successful transmission. In addition, in order to better reflect the users location in practice, we consider a weighted undirected graph to represent the topology among users in a cluster. We aim to optimize caching policy to minimize the energy consumption by helper users via multihop D2D link. To acquire the minimum energy cost, we first derive the expression of successful transmission probability, defined as the probability that user's battery power and transmission rate are no less than the predicted threshold. Then, we proposed a novel algorithm to calculate the optimal transmission path between any two users via multihop D2D link and obtain the optimal caching scheme. Finally, The proposed caching policy is proved to outperform other general caching strategies in terms of energy conservation by simulation results.

The remainder of the paper is organized as follows. The Sect. 2 elaborates the system model and problem formulation. In Sect. 3, we introduce the energy efficient caching and sharing policy. Simulation results and discussions are given in Sect. 4. Finally, we conclude this paper in Sect. 5.

2 System Model and Problem Formulation

We consider a single cell cellular network with numberable user devices, which are modeled as homogeneous Poisson point process (PPP) with density λ_u denoted as Φ_u. According to their physical location, users are clustered with M users in one cluster. The topological relationship among users in each cluster is represented by a random geometric graph $G = (V, E)$, where V is the users set and E represents the relationship among users. When the distance between two users is no more than the D2D communication distance R_c, there is one edge between this two users, facilitating a one-hop D2D link. Each user is equipped with a cache memory. For the sake of simplicity, assume that each user can only cache one file. Users can download the file to their devices during the off-peak time, such as midnight. When a user requests the file, users cached the file within communication distance R_c denoted as D2D transmitter can transmit the file to the D2D receiver via one-hop D2D link, otherwise, via multi-hop D2D link. When a user is not connected to any user in the cluster, it can request the file from the BS. Assume that Each cache-enabled user is equipped with one transmit antenna with the same transmission power and each requester has one receive antenna. The BS is aware of the files cached in user devices and D2D communication.

2.1 Content Popularity and Caching Placement

We consider a finite file library $F = [f_1, f_2, ...f_N]$ in one cluster, where N is the library size and f_k is sorted in descending order of the files' popularity. Each content has the same size of S bits, assuming that the large files can be divided into several the same size files. Then, the probability that the kth most popular file is requested follows the Zipf distribution:

$$p_k = \frac{1/k^{\beta}}{\sum\limits_{t=1}^{N} 1/t^{\beta}} \tag{1}$$

where β is the Zipf parameter reflecting how skewed the popularity distribution is. Large β means that a few files are responsible for the majority of requests [3].

We consider the probability caching strategy which each user randomly caches file f_k according to probability c_k, where c_k is the probability that user caches the file f_k. Then, the users caching the file f_k follow a PPP Φ_c with density $\lambda_c = \lambda_u c_k$. Since each user only caches one file, so c_k must meet the following conditions:

$$0 \le c_k \le 1, k = 1, 2, ...N \tag{2}$$

$$\sum_{k=1}^{N} c_k = 1 \tag{3}$$

2.2 Channel Model and Energy Analysis

In this paper, we consider that D2D users work in Underlay Mode and reuse uplink resource of cellular network, because battery supplies energy for transmitter, which is of great significance for improving energy efficiency. Assume that each cellular user can only be reused by one D2D user. In this way, there is no interference between D2D users, as shown in Fig. 1.

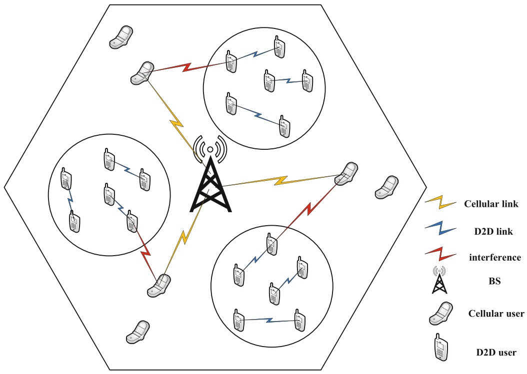


Fig. 1. System model of cellular and D2D network

The general channel model considers large-scale fading channels and small-scale fading channels. Large-scale fading channels are generally modeled by the standard path loss propagation model $r^{-\alpha}$, where r is the communication distance and α is the path loss exponent. Small-scale fading channels are usually modeled by Rayleigh fading channels whose channel gain h follows the exponential distribution with unit mean. In this paper, we consider D2D users reuse the cellular users which frequency is orthogonal and a cellular user is assumed to only be reused by one D2D user. Thus, when user i transmits a file to user j through one-hop D2D, the signal to interference plus noise ratio (SINR) is

$$SINR_{ij} = \frac{P_d h r_{ij}^{-\alpha}}{P_u h_u r_u^{-\alpha} + \sigma^2} \tag{4}$$

where P_d and P_u is respectively the transmit power at each D2D user and each cellular user. h and h_u is respectively the Rayleigh fading channel gain of D2D user and cellular user. r_{ij} is the distance between user i and user j. σ^2 is the variance of Gaussian white noise.

Therefore,the transmission rate between user i and user j is $R_{ij} = B\log_2(1+SINR_{ij})$. The energy consumed by D2D transmitter which transmits file f_k to D2D receiver through one-hop D2D link directly is:

$$W_{ij} = Pt = \frac{P_d S}{R_{ij}} = \frac{P_d S}{B\log_2(1+SINR_{ij})} \tag{5}$$

Here, we don't consider the circuit power.

2.3 Problem Formulation

We assume that each device have the same battery capacity of C, and only a fraction η of what can be used to transmit a file requested by other user devices. We make this assumption according to the following reasons: on one hand, when a user device transmits the file, it may do other communication businesses, which also consume energy; on the other hand, we must make sure that the user device has so much battery power to transmit a file on the basis of normal communication. Denote the operating voltage of the user device as V. To complete the one-hop D2D transmission, the battery capacity of D2D transmitter must meet $W_{ij} \leq \eta CV$. Meanwhile, in order to ensure that the D2D transmission is completed within the tolerable delay, the transmit rate must meet $R_{ij} \geq R_0$, where R_0 is the given transmission rate threshold. So the probability of one-hop D2D successful transmission is expressed as:

$$\begin{aligned} p_{ts} &= P(W_{ij} \leq \eta CV, R_{ij} \geq R_0) \\ &= P(SINR_{ij} \geq \tau) \\ &= e^{\frac{-\tau\sigma^2 r_{ij}^{\alpha}}{P_d}} \times \frac{1}{bP_u r_u^{-\alpha} + 1} \end{aligned} \tag{6}$$

where $\tau = e^{\max(\frac{P_d S \ln 2}{\eta CVB}, \frac{R_0 \ln 2}{B})} - 1$ and $b = \frac{\tau r_{ij}^{\alpha}}{P_d}$. According to the expression in (6), when $\eta \leq \frac{P_d S}{R_0 CV}$, p_{ts} is related to the remaining battery ratio η. That is, when the remaining power is too low, the user device's battery capacity limits p_{ts}. while $\eta \geq \frac{P_d S}{R_0 CV}$, that is, user has enough power, p_{ts} is limited by the data rate threshold R_0.

According to the above analysis, the total energy cost that the request user j get the desired file f_k from the cache user i in cluster (one-hop D2D or multihop D2D) is:

$$E = \sum_{i=1}^{M}\sum_{j=1}^{M} P_{ts}E_{ij} \tag{7}$$

where E_{ij} denotes the total energy consumed by user i to transmit file f_k to user j via multihop D2D link, and it is the sum of W_{ij} in (5). P_{ts} is the probability that user i transmit file f_k to user j successfully and is product of several p_{ts}.

Due to the user's limited battery capacity, we must minimize the energy cost for transmitting file via multihop D2D link in (7). At the same time, reducing the energy cost for the network should not compromise the hit probability denoted as the requested file is cached by at least one user in the cluster. Therefore, we optimize the caching policy to maximize the hit probability firstly. Then, we minimize the energy cost for a given optimal caching policy. Because the users caching the file f_k follow a PPP Φ_c with density $\lambda_c = \lambda_u c_k$, So the probability that the requested file f_k is cached in the cluster with radius R_{clu} is:

$$P_{ck} = 1 - e^{-\lambda_c \pi R_{clu}^2} \tag{8}$$

then, the hit probability can be expressed as:

$$P_{hit} = \sum_{k=1}^{N} P_k P_{ck} \tag{9}$$

According to the above analysis, we firstly maximize the hit probability for the optimal caching policy. Then, based on the acquired caching policy, we can minimize the total energy cost E for transmitting the file via multihop D2D link in (7) by solve the following problem:

$$\min E = \sum_{i=1}^{M} \sum_{j=1}^{M} P_{ts} E_{ij} \tag{10}$$

3 The Optimization Algorithm for Minimum Energy Cost

To solve the optimization problem (10), we must evaluate the E_{ij} and P_{ts} in expression (7) at first. Since E_{ij} denotes the energy consumed by user i to transmit file f_k to user j via multihop D2D link, it is of great significance to find the optimal path between user i and user j in graph $G = (V, E)$. Once we obtain the optimal path, the E_{ij} and P_{ts} can be calculated. To find the optimal path for transmitting files, we propose a novel algorithm to evaluate the minimum E_{ij} based on the Dijkstra algorithm in undirected graph. The algorithm includes the following two steps:

(1) Initialization:
   - (a) Determine the number of users M in one cluster, define the mark-matrix $final_{M\times M}$ to judge $E(i,j)$ need be updated or not.
   - (b) Calculate the distance d_{ij} between user i and user i, initialize the energy cost matrix $E_{M\times M}$ and $P_{tsM\times M}$. When $d_{ij} < R_c$, we consider that user i and user j can transmit files via one-hop D2D link directly and the default $E(i,j)$ is minimum. We don't consider the situation that the energy cost of multihop D2D link is less than that of one-hop D2D link. So we can calculate the $E(i,j)$ and $P_{ts}(i,j)$ according to (5) and (6) directly, also set $final(i,j) = 1$. when $d_{ij} > R_c$, we suppose the user i and user j are unreachable and set $E(i,j) = infinite$, $P_{ts}(i,j) = 0$ and $final(i,j) = 0$.

(2) Find the shortest path:
   - (a) when $d_{ij} > R_c$, for user i, we find the user mid who consume the least energy among the users connected to user i. Similarly, for user mid, we find the the user who consume the least energy among the users connected to user mid, and so forth until to user j.
   - (b) If there is no path between user i and user j, we set $E(i,j) = infinite$, $P_{ts}(i,j) = 0$ and $final(i,j) = 1$. For each user, we perform the above process to find the shortest path to other users. If a user is not connected to any other users, it can get the required files from the Base Station. The detailed process is shown in Algorithm 1.

4 Simulation Results and Discussions

In this section, some simulation results are presented to illustrate the performance of the proposed algorithm and caching scheme. We consider a single cellular cell with only one base station and radius of 500 m. The location of users follows the PPP with $\lambda_u = 0.01$. There are 15 users randomly distributed in one cluster, that is square region with side length of 100 m, as shown in Fig. 3. The other simulation parameter setting are showed in Table 1. The variance of

Algorithm 1. Shortest Path for Minimum Energy Based on Dijkstra Algorithm

Initialization:
(a)The number of users M in one cluster and mark-matrix $final_{M\times M}$ to judge $E(i,j)$ be updated or not.
(b)Calculate d_{ij}, if $i=j$, then $d_{ij}=0$.
for $i=1,\cdots,M$ **do**
  for $j=1,\cdots,M$ **do**
    if $i=j$ **then**
      $E(i,j)=0$, $P_{ts}(i,j)=1$ and $final(i,j)=1$
    else
      if $d_{ij}\le R_c$ **then**
        Calculate $E(i,j)$ according to (5) and $P_{ts}(i,j)$ according to (6), set $final(i,j)=1$
      else
        $E(i,j)=\inf$ and $P_{ts}(i,j)=0$
      end if
    end if
  end for
end for
for $k=1,\cdots,M$ **do**
  for $i=1,\cdots,M$ **do**
    for $j=1,\cdots,M$ **do**
      Find the minimum value min of the ith row of matrix E and record the $P_{ts}(k,j)$ and j
      $min = E(k,j)$
      $pmin = P_{ts}(k,j)$
      $minnum = j$
    end for
    $final(k, minnum) = 1$
    for $w=1,\cdots,M$ **do**
      if $final(k,w)=0$ && $(min + E(minnum,w)) < E(k,w)$ **then**
        Update $E(k,w) = min + E(minnum,w)$
        Update $P_{ts}(k,w) = pmin * P_{ts}(minnum,w)$
      end if
    end for
  end for
end for
Output the matrix E and matrix P_{ts}

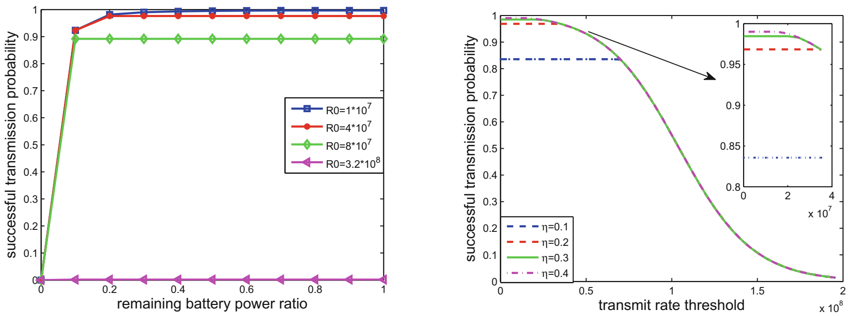
Gaussian white noise is adopted from [11]. We compare the performance of the following caching policy with the proposed caching policy in this simulation:

- Uniform caching policy: Each user caches any file of the file library according to uniform probability
- Popularity based caching policy: Each user caches the file of the file library according to content popularity.

Table 1. The simulation parameters

Simulation parameters	Value
The size of the file library in one cluster N	500
The size of each file S	50 MBytes
The exponent of file popularity distribution β	0.7
The communication distance of D2D link R_c	30 m
The transmit power of D2D user P_d and P_u	200 mw
The variance of Gaussian white noise σ^2	-174 dBm
The path loss exponent α	4
The bandwidth of D2D B	20 MHz
The battery capacity C	3000 mAh
The operating voltage of the user device V	4 V

In Fig. 2, we show the probability of transmission successful for different transmission rate threshold R_0 and remaining battery power ratio η. In Fig. 2(a), it can be observed that at the beginning, as the remaining power increases, the probability of successful transmission gradually increases. When the remaining



(a) (b)

Fig. 2. Impact of remaining battery power ratio and transmission rate threshold on successful transmission probability

power is greater than a certain value, the probability of successful transmission almost keeps constant. At the same time, there are different constant values for different R_0. This is because when the user's battery power is poor, the probability of successful transmission is mainly influenced by the the user's battery power. whereas the battery power is so much to transmit a file completely, the transmission rate threshold is limiting factor. Also, in Fig. 2(b), when the transmission rate threshold is small, it is easy to transmit a file successfully. So the probability of successful transmission is limited by the battery power. However, when the transmission rate threshold is too large, it is difficult to transmit completely. These simulation results are consistent with the analysis of (6) in the above.

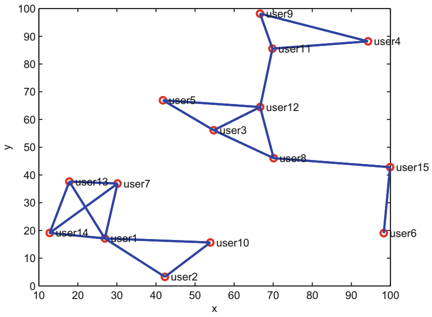


Fig. 3. The topology of users in one cluster

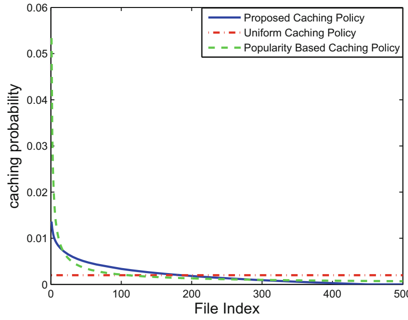


Fig. 4. Comparison of different cache policies

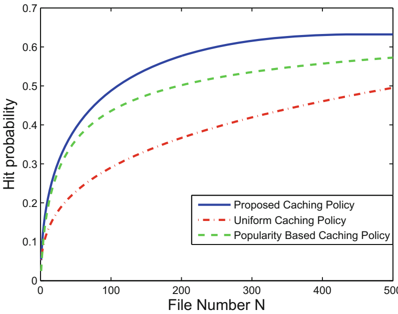


Fig. 5. The hit probability of different cache policies

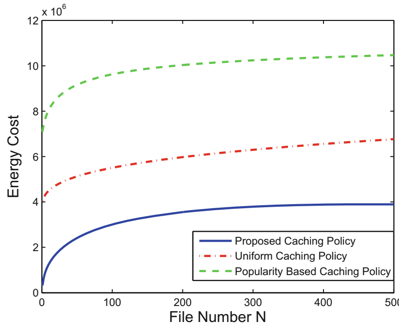


Fig. 6. Energy cost under different cache policies

Figure 4 illustrates the comparison of different caching policy. The proposed caching scheme is a compromise between popularity based caching policy and uniform caching policy, and when the file's popularity is too low, the caching probability of file is almost zero. In Fig. 5, it is showed that the proposed caching policy has higher hit probability than other two caching scheme. Figure 6 reflects the energy cost under different caching policy and it is obvious that the proposed caching policy can reduce energy cost, compared with uniform caching policy and popularity based caching policy.

5 Conclusion

In this paper, we consider the impact of users' battery energy on the content transmission in the caching network with D2D communication. We focus on obtaining minimize the energy cost of delivering a file via multihop D2D link. In addition, reducing the energy cost should not compromise the caching hit probability. To solve this problem, we classify users into different clusters and model users' topology relation as an undirected weighted graph in one cluster. Then, we determine the caching policy for making sure the hit probability. Based on the caching policy, to obtain the minimum energy cost, a novel algorithm is proposed to find the optimal path between any two users to transmit files. Moreover, we also take the battery capacity into account to make sure successful transmission. Simulation results show that the proposed caching policy outperforms other general caching strategies for less energy cost.

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