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Research Article

Device-to-Device Users Clustering Based on Physical and Social Characteristics

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This paper proposes a novel method for device-to-device (D2D) user clustering that allows wireless users in proximity to share common resources to save both system bandwidth and energy resources. The idea at the basis of our proposed cluster formation is to incorporate both social interactions and physical relationships among D2D terminals. Towards this goal, we propose two clustering approaches. The first one is based on the Chinese restaurant process (CRP), whereas the second one enhances the traditional CRP by defining a "distance-dependent Chinese restaurant process" (namely, DCRP). Numerical simulation results demonstrate superiority of our proposed clustering schemes in terms of system throughput, energy consumption, and energy efficiency over the existing schemes that rely only on physical distance.

1. Introduction

Given the explosive growth of online social networking activities, social interactions among mobile users and people's social behaviors can be significantly impacted by the advent of D2D communications. On the other hand, social interaction profiles of mobile users can also have strong impact on the efficacy and efficiency of D2D clustering communications. The concept of D2D communication is widely used for hot-spot services, whereas D2D user equipments (DUEs) in close proximity usually can form *D2D clusters* to collaboratively communicate and/or share resources. By letting multiple DUEs collaboratively form user clusters, it becomes possible to better utilize their collective resources, coordinate intracommunications, manage interferences, and improve their social interactions.

D2D communications can offer a number of advantages including better spectrum efficiency, higher energy efficiency, shorter latency, and improved social interactive experience. A number of existing works have studied various D2D perspectives, such as selecting a mode between cellular and D2D [1], spectrum resource allocation [2, 3], and interference management [4]. In terms of spectrum efficiency, D2D communications allow cellular user equipments (CUEs) to directly send and receive without having to go through the base stations (BSs) as relays, thereby improving spectrum utility. D2D underlay links [5, 6] can also share other cellular user equipment (CUE) channels through interference management to further improve network spectrum efficiency. With respect to energy efficiency [7], shorter distance D2D communications allow DUEs to expend significantly less transmission power than in cellular mode. Furthermore, D2D communications can substantially reduce latency in local content (file) sharing and social media interaction [8, 9]. D2D communications also facilitate the formation of self-organizing networks in time of disaster or emergency relief [10, 11].

In this work, we investigate novel approaches to form D2D clusters. D2D clustering exploits the proximity property of D2D communications. Because of wireless channel diversity, cluster members with good channel conditions can assist DUEs under poor channel conditions to avoid link failure through means such as content (file) sharing or relaying [12, 13]. There already exist a number of works on

D2D clustering. For example, D2D clustering can improve multicast performance in cellular networks, as shown in [14, 15], by balancing multichannel diversity and multicast gain, and can improve the effectiveness of D2D cellular links with respect to noncellular short-range technologies [16]. Further, cluster heads (CH) can assist cluster members [17], by letting them retransmit the store information in the event of initial transmission failures. Finally, for supporting traffic safety applications, [18] proposes a cluster with a multihop relay chain of devices in order to maximize the dissemination distance and minimize the dissemination delay.

In this work, we take advantage of user behavioral information in terms of DUE social interaction to form more effective DUE clusters. Clearly, more and more people are actively involved in online social interactions with the explosive growth of online social media. Wireless networking can potentially benefit from exploiting such social interactions [19]. The work in [20] exploited such social ties to enhance cooperative D2D communications among devices by leveraging social trust and social reciprocity. The work in [21] presented a social-aware approach for the optimization of D2D communications by exploiting the social ties and influence among individuals. The work in [22] studied joint precoding strategy of D2D and cochannel cellular transmission in clustered D2D underlaying cellular network, whereas [14] introduced intracluster D2D retransmission scheme. Nevertheless, these works focus on D2D clusters formed by exploiting only information on distance among DUEs. Our work advances the state of the art on D2D cluster formation by adopting a novel approach that exploits social interactive information in addition to user proximity.

To the best of the authors' knowledge, there exists no work on specific performance analysis of social-oriented D2D clustering based on CRP. With this aim, we propose new approaches to D2D clustering based on the Chinese restaurant process (CRP). Specifically, we integrate the social interaction of DUEs in the CRP-based clustering methods by considering both the basic CRP and a distance-dependent CRP (namely, DCRP). Both can integrate physical distances and social interaction metrics among DUEs in their clustering process. Through performance analysis, we shall show that CRP- and DCRP-based clustering can take advantage of both the physical and social distances directly to achieve better user experience including file sharing.

We discuss socially oriented clustering approaches based on CRP in two scenarios, that is, (i) underlay and (ii) overlay. For D2D underlay, we first extend the work in [9] by proposing an efficient D2D clustering admission policy designed to increase the system rate. By analyzing the interplay between D2D clusters and the arrival rate of DUEs intending to join a D2D cluster, we present two attraction functions describing the mutual suitability by considering (i) social interaction, (ii) energy balance, and (iii) location. Further, we formulate the probability of the arrival user joining a certain D2D cluster based on CRP and utilize a matching function to assign an optimal D2D cluster for each arrival user.

For D2D overlay, we propose a novel clustering scheme by incorporating both social and physical relationships among DUEs. We exploit the CRP to characterize the formation of our D2D-based clusters by taking into account both the physical distance and the social relationship among nodes. We present a performance analysis of our proposed scheme in comparison with clustering schemes in literature based on physical distance only.

The organization of this paper is as follows. Section 2 provides the preliminary concepts, notations, and problem formulations in this work. Section 3 briefly introduces the classic CRP and delineates the application of CRP in D2D clustering. Section 4 presents a distance-based CRP (DCRP) and also provides D2D clustering algorithms based on DCRP. Further, Section 5 elaborates in detail on social interaction oriented D2D clustering. Section 6 analyzes the performance of D2D clusters before the conclusions in Section 7.

2. Preliminaries and Problem Description

2.1. Preliminary and Scenario Description. D2D communications represent a novel transmission paradigm that enhances the traditional cellular communications by allowing user equipment (UE) to directly send to or receive data from another peer UE without having to route traffic through the basestations (BSs). As shown in Figure 1, D2D links can exploit the system resources in underlay (i.e., D2D and cellular links share the overall resources in the cell) or in overlay (i.e., D2D links are given their dedicated resources assigned by the BS) modes. In this paper, we propose novel clustering schemes that are suitable to both underlay and overlay modes.

Clustering is the process of forming different DUE groups, where group members effectively collaborate to improve the perceived quality of services such as content (file) sharing, spectrum sharing [23], distributed transmission, and multihop connection. As shown in Figure 1, a D2D cluster should consist of DUEs typically in close proximity with twofold benefits: reduced transmission power for DUE cluster members and reduced interference to users external to the cluster. To take full advantage of user collaboration and file sharing, DUEs in a cluster should share as much common interest as possible. In addition, a number of DUE members in a cluster cannot be too large, since too many DUEs sharing the same bandwidth in a cluster will lead to excessive delays in intraclustering communications. It is worth noting that different D2D clusters can lead to different content and resource sharing performance that are important measures of D2D communications.

In addition to physical distance limitation, social interaction is really a critical factor for D2D communication. Thus, we will consider the impact of social interaction on users' behaviors to form D2D clusters. In fact, for D2D cluster communications, whether a user is willing to share files owned or not with another user in the same cluster depends in part on their social relationship. Since the degree of trust and willingness among different users for content resource sharing is different, how to divide the users into D2D clusters to enhance the performance is very important. Thus, we present an efficient D2D clustering scheme by jointly considering the social interaction and physical distance factors.

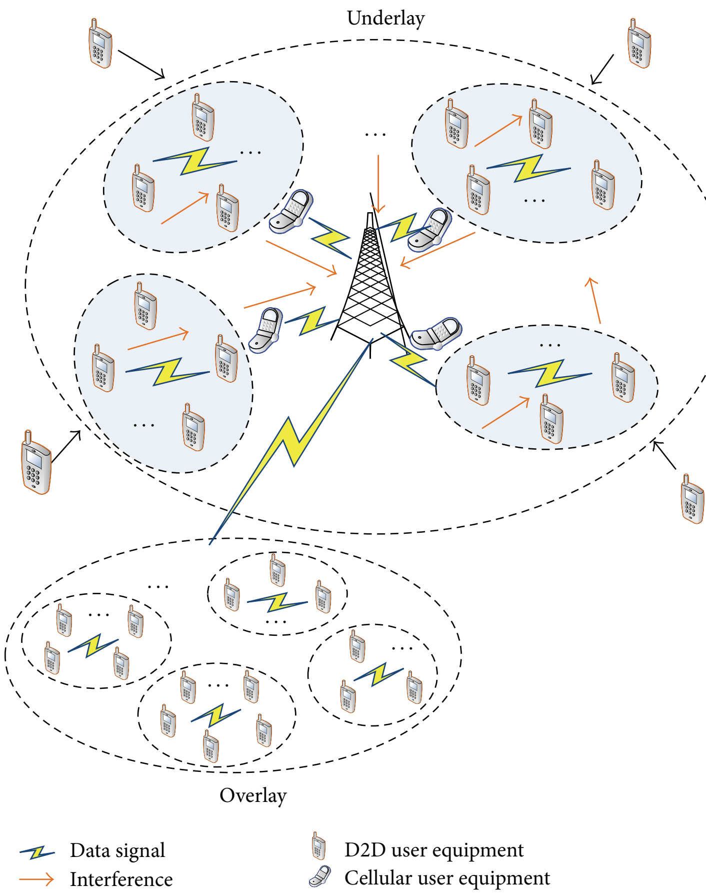

Figure 1: D2D communication in cellular networks.

Assume a number of D2D users with subscription to different types of shared resources in a given area and each D2D user is itself an initial D2D cluster. More users may arrive and join an existing D2D cluster. According to our proposed approach, when a new user arrives, the selection of the relevant cluster will be performed by taking into account information such as user locations, user preference, and also user social interaction (such as the number of users in clusters and the social tie of the user with other existing cluster users). These arriving users have opportunities either to join existing clusters with which they share common interest and are close in distance or to start their own clusters. Such decisions should not be deterministic. In particular, the Chinese restaurant process provides a very natural model for this clustering decision process.

2.2. CRP in D2D Clustering with Social Interaction. CRP studied in nonparametric modeling due to its flexibility and extensibility [24, 25] is a stochastic process through generating an exchangeable partition of data points. CRP has been extended to deal with distances and sequential data, such as the distance-dependent CRP (DCRP), which has been introduced in [26] to model random partitions of nonexchangeable data (which is a feature of many applications). In DCRP, each data point is more likely to be clustered with other data that are nearby.

Since CRP is an efficient tool to model data partitions, here we adopt the CRP to model the formation of D2D clusters. We will present our multiple objective oriented schemes in CRP-based clustering and analyze D2D clustering performance by evaluating the benefits from content sharing. Without unnecessary repetition, we shall focus on traditional CRP-based clustering scheme in D2D underlay in Section 3 and illustrate DCRP-based clustering approach in D2D overlay in Sections 4 and 5, though the proposed general principles of clustering apply to both cases of underlay and overlay.

2.3. Assumptions and Notations. We denote the channel response between nodes m and n by h_{mn}, the threshold indicating the maximum number of users in each D2D cluster by $N_{\max}$ and the maximum D2D communication distance by $d_{\max}$. K is the number of D2D clusters, $\mathcal{N}_i$ is the set of users in the ith cluster (with $i = 1, \ldots, K$), and $N_i = |\mathcal{N}_i|$ is the number of users in such a cluster. Finally, let P_B and P_D be the transmit powers of BS and D2D users, respectively.

We assume that the channels from BS to users follow a large-scale path loss model [27], and the D2D user channels are independent and identically distributed (i.i.d.) and are in flat fading. We assume channel noise to be additive white Gaussian (AWG) with zero mean and variance σ^2. We also assume that the content sharing between two D2D users requires little (i.e., limited) bandwidth overhead or does not consume bandwidth overhead at all. Without loss of generality, the user locations are uniformly distributed within a cell.

3. Our Proposed CRP-Based Clustering

In this section, we describe an admission policy for D2D clustering that utilizes the CRP. The proposed admission policy is suitable for both D2D underlay and overlay. However, in order to avoid the overlapped explanation, we will take D2D underlay, for example, to elaborate the clustering policy.

3.1. System Model. As shown in Figure 1, we consider a single cell environment where the users can work in two modes, which are cellular mode (cellular user) and D2D mode (D2D user). Each user is equipped with a single omnidirectional antenna and any two users in D2D clusters communicate in pairs consisting of one transmitter and one receiver. We focus on the uplink period of the system where K orthogonal channels are occupied by K corresponding cellular users. At the beginning of the network, there are K D2D users owning K types of resources and each of them shares the channel with a certain cellular user. The K D2D users can be considered as K initial D2D clusters, and the set of D2D clusters is denoted by $\mathcal{C} = \{c_1, c_2, \ldots, c_K\}$. There will be more users arriving at the network, and they will join an optimal D2D cluster. We assume that any channel occupied by the ith ($i = 1, 2, \ldots, K$) cellular user can be shared with members of the ith D2D cluster [28]. D2D communication session setup procedures can be found in [29].

As depicted in Figure 1, when the cellular UEs need to communicate with BS to access required service or data in D2D underlay, the BS suffers interference caused by the D2D transmitters sharing the cell resources. On the other hand, the D2D receivers are exposed to interference from the corresponding cellular user and the other D2D transmitters in the same cluster. Since D2D communications are aimed at improving the overall system capacity, in this paper, we utilize the system sum rate to evaluate the performance of our clustering scheme.

3.2. Description of CRP. Let us consider a Chinese restaurant with an infinite number of tables, and the customers will come in and choose to sit in one of the tables. The first customer sits down at a table. The nth customer sits at a table (which is previously chosen by some customers) with a probability proportional to the number of customers sitting at that table or the nth customer sits at a new table with a probability proportional to the scalar parameter α. Thus, for the nth customer, the distribution over customer assignments conditioned on $\mathbf{z}_{-n}$ (other customers' assignments except for the nth customer) can be described as

$$P\left(z_n = k \mid \mathbf{z}_{-n}, \alpha\right) = \begin{cases} \dfrac{m_k}{n-1+\alpha}, & \text{if } k \leq k_0, \\[2ex] \dfrac{\alpha}{n-1+\alpha}, & \text{if } k = k_0 + 1, \end{cases} \tag{1}$$

where k_0 is the number of tables with customers and m_k is the number of customers sitting at the kth table.

If we consider the adoption of CRP for D2D cluster formation, the clustering process is totally based on CRP without considering the factors that affect the optimal cluster of a new D2D user. For the nth D2D user, we can define a distribution over cluster assignments conditioned on $\mathbf{z}_{-n}$ (other users' cluster assignments except for the nth user):

$$P\left(z_n = c_i \mid \mathbf{z}_{-n}, \alpha\right) = \begin{cases} \dfrac{m_i}{n-1+\alpha}, & c_i \in \mathcal{C}_n, \\[2ex] \dfrac{\alpha}{n-1+\alpha}, & c_i \notin \mathcal{C}_n, \end{cases} \tag{2}$$

where $\mathcal{C}_n$ is the current set of D2D clusters with arrival D2D users, m_i is the number of users in cluster c_i, and $c_i \notin \mathcal{C}_{-n}$ means that the nth user starts a new cluster.

To make the clustering results more practical, we will take several factors into account, including users' behavior, social interaction, social relationship, and their preference as well. Indeed, one related literature [30] proposed a dynamic multirelational CRP to study the interplay of world-wide, geographic, network, and user specific influences and their dynamics in generation of social media. In this paper, we propose two new different D2D clustering schemes based on CRP jointly considering the factors affecting the clustering process.

3.3. Generalized Cluster Formulation with Multiple Objectives. To evaluate the mutual suitability between the nth D2D user and D2D cluster c_i, we first present two attraction functions, $f_u(n, c_i)$ describing the attraction of D2D cluster c_i to nth D2D user and $f_c(c_i, n)$ indicating the attraction of nth D2D user to D2D cluster c_i.

We can jointly consider multiple factors to formulate the attraction function $f_u(n, c_i)$ and $f_c(c_i, n)$ according to multiple objectives. We considered four main factors in literature [31] including interest, distance, energy, and social interaction to design $f_u(n, c_i)$. Interest factor indicates the matching degree between the nth D2D user's interest and the resource owned by cluster c_i. Distance factor represents the position impact for the nth D2D user to join cluster c_i. Energy factor represents the energy state of D2D cluster c_i, and social interaction factor illustrates the joint impact of the number of D2D users in cluster c_i and the social trust between the nth D2D user and these D2D users.

Based on the above description, we can formulate the attraction function $f_u(n, c_i)$ as

$$f_u\left(n, c_i\right) = \sum_{j=1}^{m} w_{R_j} f_{R_j}\left(n, c_i\right), \tag{3}$$

where m indicates the number of considered component factors. $f_{R_j}(n, c_i)$ denotes the factor function and w_{R_j} is the corresponding weight for each factor while satisfying the constraint that $\sum_{j=1}^{m} w_{R_j} = 1$. It is worth noticing that $d_i(n)$ is the minimum distance between the nth D2D user and D2D users in ith cluster c_i. Therefore, considering the maximum D2D communication distance ($d_{\max}$) and the maximum number of D2D users ($N_{\max}$) in a cluster, we can recast $f_u(n, c_i)$ as

$$f_u(n, c_i) = \begin{cases} \sum_{j=1}^{m} w_{R_j} f_{R_j}(n, c_i), & m_i < N_{\max}, \text{and } d_i(n) \le d_{\max}, \\ 0, & m_i = N_{\max}, \text{or } d_i(n) > d_{\max}. \end{cases} \quad (4)$$

On the other hand, we can also formulate attraction function $f_c(c_i, n)$ for cluster c_i by taking a couple of factors into consideration, such as reliability and contribution from each D2D user similarly.

Reliability describes the trust level of the nth D2D user for cluster c_i; it considers not only the history of the user's behavior but also the social trust between the considered user and other users in cluster c_i. Contribution factor jointly considers the nth user's power and the interest matching degree between the resource owned by the nth user and the resource owned by cluster c_i.

Therefore, considering a minimum distance threshold $d^{\min}(c_i)$ to avoid serious interference between cellular user and D2D links, we can rewrite $f_c(c_i, n)$ as

$$f_c(c_i, n) = \begin{cases} \sum_{j=1}^{m} w_{R_j} f_{R_j}(c_i, n), & d_1(c_{0,i}, n) \ge d^{\min}(c_i), \\ 0, & d_1(c_{0,i}, n) < d^{\min}(c_i), \end{cases} \quad (5)$$

where $d_1(c_{0,i}, n)$ is the distance between the nth D2D user and the cellular user $c_{0,i}$ that shares channel with underlay cluster c_i. So far, we have formulated the mutual attraction functions $f_u(n, c_i)$ and $f_c(c_i, n)$. Next, we will specifically describe the admission policy based D2D clustering scheme utilizing CRP.

3.4. Admission Policy Based D2D Clustering Scheme. Taking the attraction function $f_u(n, c_i)$ into account, we can formulate the probability that the nth D2D user joins the D2D cluster c_i based on CRP as

$$P(z_n = c_i \mid \mathbf{z}_{-n}, \alpha) = \begin{cases} \dfrac{(m_i/(n-1+\alpha)) f_u(n, c_i)}{\sum_{c_i \in \mathscr{C}_n} (m_i/(n-1+\alpha)) f_u(n, c_i) + (\alpha/(n-1+\alpha)) f_u(n, c_i)}, & c_i \in \mathscr{C}_n, \\ \dfrac{(\alpha/(n-1+\alpha)) f_u(n, c_i)}{\sum_{c_i \in \mathscr{C}_n} (m_i/(n-1+\alpha)) f_u(n, c_i) + (\alpha/(n-1+\alpha)) f_u(n, c_i)}, & c_i \notin \mathscr{C}_n. \end{cases} \quad (6)$$

When the D2D cluster c_i evaluates the performance of the nth D2D user by the attraction function $f_c(c_i, n)$, we predefine a threshold f_{th} to determine whether the nth D2D user is admitted to join. When $f_c(c_i, n) \ge f_{\text{th}}$, the nth D2D user is admitted to join in cluster c_i and vice versa. Thus, we introduce a decision function $D_i(n)$ to represent this selection process, and $D_i(n)$ is written as

$$D_i(n) = \begin{cases} 1, & \text{if } f_c(c_i, n) \ge f_{\text{th}}, \\ 0, & \text{if } f_c(c_i, n) < f_{\text{th}}. \end{cases} \quad (7)$$

Thus, a user n is admitted into cluster c_i randomly based on probability $P(z_n = c_i \mid \mathbf{z}_{-n}, \alpha)$ if $D_i(n) = 1$. Therefore, we obtain the D2D cluster $c_{i_0}(n)$ for the nth D2D user. For convenience, we assume that any arrival D2D user can join an existing D2D cluster. We now summarize our clustering algorithm in Algorithm 1.

We have assessed this CRP-based clustering approach by evaluating the system sum rate during the uplink period in D2D underlay in [31], where achieved results demonstrated the effectiveness of this approach.

4. DCRP and Social Interaction Oriented Clustering

Definitely, we can consider multiple factors to form cluster as mentioned before. However, to make the treatment simpler, we only consider the joint use of distance and social interaction in this section, and we will present the performance analysis of D2D clustering by evaluating the benefits from content sharing. Since we already discussed traditional CRP and its application in D2D clustering, next we will investigate DCRP based D2D clustering.

4.1. P-DCRP Clustering Scheme. Refer to the distance-dependent CRP proposed in [26]; we exploit a physical distance-dependent D2D clustering scheme utilizing CRP (P-DCRP), which considers the physical distance between D2D users. The P-DCRP clustering scheme is summarized in Algorithm 2. The probability of user n selecting user ℓ as its partner to form a D2D link can be calculated as

$$P(\text{link}(n, \ell) \mid D, \alpha) = \begin{cases} \dfrac{f_1(d(n, \ell))}{\sum_{\ell \ne n} f_1(d(n, \ell)) + \alpha}, & \text{if } n \ne \ell, \\ \dfrac{\alpha}{\sum_{\ell \ne n} f_1(d(n, \ell)) + \alpha} & \text{if } n = \ell, \end{cases} \quad (8)$$

where D is the physical distance matrix of potential (or established) D2D links between D2D users, $d(n, \ell)$ is the distance between user n and user ℓ, and α is the parameter of CRP, indicating the willingness for each arrival D2D user to stay alone and create a new cluster.

In addition, the physical distance-based function $f_1(d(n, \ell))$ is defined as

$$f_1(d(n, \ell)) = \begin{cases} \dfrac{1}{d(n, \ell)}, & \text{if } d(n, \ell) \le d_{\max}, \\ 0, & \text{if } d(n, \ell) > d_{\max}. \end{cases} \quad (9)$$

Based on the probabilities of pairing user n to other users, user n will select one user as its partner or stay alone randomly.

For each arrival D2D user n
for $c_i \in \mathscr{C}_n$ **do**
  calculate $P_i(n) = P(z_n = c_i \mid \mathbf{z}_{-n}, \alpha)$ from (6)
  compute $D_i(n)$ according to (7).
  if $D_i(n) = 1$ **then**
    Randomly select cluster c_i with probability $P_i(n)$
  end if
end for

Algorithm 1: Finding a cluster c_i for D2D user n.

For each arrival D2D user n
for $c_i \in \mathscr{C}_n$ **do**
  calculate $P_i(n)$ from (10)
  compute $D_i(n)$ according to (7).
  if $D_i(n) = 1$ **then**
    Randomly select cluster c_i with probability $P_i(n)$
  end if
end for

Algorithm 2: P-DCRP clustering.

The direct application of P-DCRP for clustering is straightforward. In particular, define the mutual physical distance between two DUEs as $p(n, \ell)$. For each new D2D user n, determine whether user n should join user ℓ and hence its cluster randomly based on the probability of (8). Notice that each cluster c_i may already have multiple users. Then, user n will compute the probability of user n joining cluster c_i as

$$P_i(n) = \sum_{\text{user } \ell \in c_i} \frac{f_1(d(n,\ell))}{\sum_{\ell \neq n} f_1(d(n,\ell)) + \alpha}. \tag{10}$$

4.2. Our Proposed S-DCRP Clustering Scheme. We present (see Algorithm 3) a novel social oriented and CRP-based D2D clustering scheme by considering social interaction and physical distance simultaneously, and we denote this by S-DCRP. Specifically, we formulate the social distance between two users to evaluate the effect of their social interaction on D2D clustering. Thus, we calculate the social distance based on the social trust [20] as

$$s(n,\ell) = -\log_2(p(n,\ell)), \tag{11}$$

where $p(n,\ell) \in [0,1]$ is the social trust between users n and ℓ.

Notice that larger value of $p(n,\ell)$ leads to smaller $s(n,\ell)$; that is, the shorter the social distance between two users is, the larger the probability of file (resource) sharing between D2D users achieves. Thus, by jointly considering both social and physical distance, we can formulate the probability that user n selects user ℓ as its partner for D2D communication as

For each arrival D2D user n
for $c_i \in \mathscr{C}_n$ **do**
  calculate $P_i(n)$ from (14)
  compute $D_i(n)$ according to (7).
  if $D_i(n) = 1$ **then**
    Randomly select cluster c_i with probability $P_i(n)$
  end if
end for

Algorithm 3: S-DCRP clustering.

$$P(\text{link}(n,\ell) \mid S, D, \alpha) = \begin{cases} \dfrac{f_2(s(n,\ell))}{\sum_{\ell \neq n} f_2(s(n,\ell)) + \alpha}, & \text{if } n \neq \ell, \\ \dfrac{\alpha}{\sum_{\ell \neq n} f_2(s(n,\ell)) + \alpha}, & \text{if } n = \ell, \end{cases} \tag{12}$$

where S is the social distance matrix of D2D users, and the social distance-based function $f_2(s(n,\ell))$ is defined as

$$f_2(s(n,\ell)) = \begin{cases} \dfrac{1}{s(n,\ell)}, & d(n,\ell) \leq d_{\max}, \\ 0, & d(n,\ell) > d_{\max}. \end{cases} \tag{13}$$

Similarly, based on the probabilities of user n selecting other users, user n selects one user as its partner and cluster randomly (otherwise, it remains alone):

$$P_i(n) = \sum_{\text{user } \ell \in c_i} \frac{f_2(s(n,\ell))}{\sum_{\ell \neq n} f_s(s(n,\ell)) + \alpha}. \tag{14}$$

4.3. Merits of S-DCRP Clustering Scheme. Different from the traditional CRP, P-DCRP and S-DCRP schemes generalize the ideas in [26] to model the users' D2D clustering, which is nonexchangeable. By jointly considering social and physical distance to form clusters, our scheme can boost the benefits from both the social and physical information of the users.

In our proposed S-DCRP scheme, we take the social distance into account in addition to the physical distance. Under the maximum D2D communication distance constraint, for a certain user, our proposed S-DCRP scheme can effectively obtain a higher probability of selecting a partner who prefers to share its file with the considered user. Therefore, for our scheme, users belonging to the same D2D cluster can more efficiently share their files with each other rather than obtaining the files from BS, which can undoubtedly enhance system performance in terms of lower energy consumption and higher system throughput by involving D2D clustering.

5. Performance Analysis for S-DCRP Clustering

In this section, we will discuss the benefits of file sharing in D2D clusters in two separate modes, which are request mode and delivery mode. In request mode, D2D user will act as a request node to ask for resource file from BS or other neighbouring nodes who own the requested file. In delivery mode, we assume a D2D user already obtained a file from BS and can share it with other neighbouring users in the same cluster who acquire the same file.

5.1. Delivery Mode. In this subsection, we analyze the system performance by evaluating the benefits from file sharing in D2D clusters. Note that we assume that a user can request and get a desired file from BS first, with whom other members (DUEs) within the same cluster may ask for sharing the acquired file. Thus, we can assess the resulting system gain from file sharing in clusters, including throughput, energy consumption, and energy efficiency. We utilize the social trust between two users in the same cluster as the probability of their file sharing. The social trust between two users varies according to their relationship.

Let $\mathscr{D} = \{1, 2, \ldots, N\}$ be the DUEs in all clusters under consideration. Let the integer set $\mathscr{N}_i = \{v_1^i, v_2^i, \ldots, v_{N_i}^i\}$ of cardinality N_i denote the set of nodes within cluster-i where $\mathscr{N}_i \subset \mathscr{D}$. Consider a node v_k^i in cluster-i. Recall the definition of probability $p(i, j)$. It is clear that $p(v_k^i, v_k^i) = 1$.

If node v_k^i obtains a file from BS, then the probability that n distinct nodes $\{j_1, \ldots, j_n\} \subset \mathscr{N}_i \setminus \{v_k^i\}$ wishing to share the same file is given by

$$P\left(v_k^i; \{j_1, \ldots, j_n\}\right) = \prod_{\ell=1}^{n} p\left(v_k^i, j_\ell\right) \prod_{m=n+1}^{N_i-1} \left[1 - p\left(v_k^i, j_m\right)\right], \quad j_{m_1} \neq j_{m_2}, \quad \{j_1, \ldots, j_n\} \subset \mathscr{N}_i \setminus \left\{v_k^i\right\}. \tag{15}$$

Then, the probability that there are exactly n additional users within the cluster also wishing to share this file can be calculated as

$$P_i\left(v_k^i, n\right) = \sum_{\substack{j_1 \in \mathscr{N}_i \setminus \{v_k^i\}, \\ j_2 \in \mathscr{N}_i \setminus \{v_k^i, j_1\}, \ldots, \\ j_n \in \mathscr{N}_i \setminus \{v_k^i, j_1, \ldots, j_{n-1}\}}} \cdots \sum P\left(v_k^i; \{j_1, \ldots, j_n\}\right), \quad n = 0, \ldots, N_i. \tag{16}$$

Note that

$$P_i\left(v_k^i, 0\right) = \prod_{\substack{m=1 \\ j_{m_1} \neq j_{m_2} \\ j_m \in \mathscr{N}_i \setminus \{v_k^i\}}}^{N_i-1} \left[1 - p\left(v_k^i, j_m\right)\right]. \tag{17}$$

Let $|h_{Bv_k^i}|^2$ be the channel power gain between node v_k^i and BS. Then, the unit bandwidth rate for v_k^i to retrieve a data file from BS can be written as

$$R_{B,v_k^i} = \log_2\left(1 + \frac{P_B \left|h_{Bv_k^i}\right|^2}{\sigma^2}\right), \tag{18}$$

where P_B is the transmit power of BS. Let the channel power gain between node v_k^i and node $j_\ell \in \mathscr{N}_i \setminus \{v_k^i\}$ be $|h_{v_k^i j_\ell}|^2$. Recall that P_D is the DUE transmit power. Then, the rate of file sharing between the two nodes becomes

$$R_{v_k^i, j_\ell} = \log_2\left(1 + \frac{P_D \left|h_{v_k^i j_\ell}\right|^2}{\sigma^2}\right), \quad j_\ell \in \mathscr{N}_i \setminus \left\{v_k^i\right\}. \tag{19}$$

Therefore, the overall throughput from BS delivery and clustering communications between v_k^i with $n = 1, \ldots, N_i - 1$ additional users in the ith D2D cluster can be tallied as

$$R_k^i = R_{B,v_k^i} + \sum_{n=1}^{N_i-1} \sum_{\substack{j_1 \in \mathscr{N}_i \setminus \{v_k^i\}, \\ j_2 \in \mathscr{N}_i \setminus \{v_k^i, j_1\}, \ldots, \\ j_n \in \mathscr{N}_i \setminus \{v_k^i, j_1, \ldots, j_{n-1}\}}} \cdots \sum \left[P\left(v_k^i; \{j_1, \ldots, j_n\}\right) \sum_{\ell=1}^{n} R_{v_k^i, j_\ell}\right]. \tag{20}$$

For all users in the ith D2D cluster, the throughput brought by the file transmission from BS to members in the cluster can be written as

$$R^i = \sum_{k=1}^{N_i} R_k^i. \tag{21}$$

Considering the K total D2D clusters, the total throughput is hence

$$R_t = \sum_{i=1}^{K} R^i. \tag{22}$$

We assume that data files from BS have the same length (L), and each D2D cluster is assigned the same bandwidth (W). Thus, for node v_k^i, the transmission time (delay) and the energy consumption to obtain the file from BS, respectively, are

$$D_{B,v_k^i} = \frac{L}{W R_{B,v_k^i}}, \qquad E_{B,v_k^i} = P_B D_{B,v_k^i}. \tag{23}$$

When n users in the cluster want to get this file through file sharing, the average transmission time and the energy consumption for node v_k^i to transmit this file can be calculated, respectively, as

$$D_{d,v_k^i} = \sum_{n=1}^{N_i-1} \sum_{\substack{j_1 \in \mathscr{N}_i \setminus \{v_k^i\}, \\ j_2 \in \mathscr{N}_i \setminus \{v_k^i, j_1\}, \ldots, \\ j_n \in \mathscr{N}_i \setminus \{v_k^i, j_1, \ldots, j_{n-1}\}}} \cdots \sum \frac{P\left(v_k^i; \{j_1, \ldots, j_n\}\right) \cdot L}{W \cdot \min_{\ell=1,\ldots,n} R_{v_k^i, j_\ell}}, \quad E_{d,v_k^i} = P_D D_{d,v_k^i}, \tag{24}$$

where $n = 0$ is not included as there is no file sharing.

Thus, we can calculate the average cluster energy consumption corresponding to the cluster file sharing throughput as

$$E_t = \sum_{i=1}^{K}\left(\sum_{k=1}^{N_i}\left(E_{B,v_k^i} + E_{d,v_k^i}\right)\right). \tag{25}$$

It is clear that file sharing in D2D clusters can lead to a higher throughput but also requires additional energy consumption in D2D communications. Therefore, we utilize its energy efficiency to evaluate the performance advantage of D2D clustering schemes, which is defined as

$$\eta = \frac{R_t}{E_t}. \tag{26}$$

Without loss of generality, when D2D clustering is not used, that is, in the nonclustering case, all users obtain the files from BS. Thus, we can find the ith cluster throughput and the total throughput for all users, respectively, as

$$\begin{aligned} R^i &= \sum_{k=1}^{N_i} \Bigg(R_{B,v_k^i} + \sum_{n=1}^{N_i-1} \sum_{\substack{j_1 \in \mathcal{N}_i \setminus \{v_k^i\}, \\ j_2 \in \mathcal{N}_i \setminus \{v_k^i, j_1\}, \dots, \\ j_n \in \mathcal{N}_i \setminus \{v_k^i, j_1, \dots, j_{n-1}\}}} \cdots \sum \Bigg[P\left(v_k^i; \{j_1, \dots, j_n\}\right) \cdot \sum_{\ell=1}^{n} R_{B,j_\ell} \Bigg] \Bigg), \\ R_t &= \sum_{i=1}^{K} R^i. \end{aligned} \tag{27}$$

For nonclustering D2D users, we can also determine the total energy consumption as

$$E_t = \sum_{i=1}^{K} \sum_{k=1}^{N_i} \Bigg(E_{B,v_k^i} + \sum_{n=1}^{N_i-1} \sum_{\substack{j_1 \in \mathcal{N}_i \setminus \{v_k^i\}, \\ j_2 \in \mathcal{N}_i \setminus \{v_k^i, j_1\}, \dots, \\ j_n \in \mathcal{N}_i \setminus \{v_k^i, j_1, \dots, j_{n-1}\}}} \cdots \sum \Bigg[P\left(v_k^i; \{j_1, \dots, j_n\}\right) \cdot \sum_{\ell=1}^{n} \frac{P_B \cdot L}{W \cdot R_{B,j_\ell}} \Bigg] \Bigg). \tag{28}$$

5.2. Request Mode. In this scenario, the users request files from BS or from neighbouring users who own the files in the same cluster. For a certain user, when there are cluster members who have a file and are willing to share such a file, it can obtain the file from file sharing. Otherwise, it needs to request the file from BS.

For node v_k^i, the probability that n users in the cluster have and are willing to share this file with it can be calculated as $P_i(v_k^i, n)$ where $n = 1, \dots, N_i - 1$. If $n = 0$, the probability that node v_k^i obtains the file directly from BS equals $P_i(v_k^i, 0)$.

For node v_k^i belonging to the ith D2D cluster, the rate for it to obtain a file from B is simply given by

$$R_{B,v_k^i} = \log_2 \left(1 + \frac{P_B \left| h_{Bv_k^i} \right|^2}{\sigma^2} \right). \tag{29}$$

When there are n users in the cluster who have and are willing to share this file with the kth user, we select a user j_ℓ with the best channel gain as an optimal user for file sharing. Thus, the mean (expected) rate for node v_k^i for obtaining the file from the optimal user j_ℓ or the BS B can be written as

$$\begin{aligned} R_k^i &= P_i\left(v_k^i, 0\right) R_{B,v_k^i} \\ &+ \sum_{n=1}^{N_i-1} \sum_{\substack{j_1 \in \mathcal{N}_i \setminus \{v_k^i\}, \\ j_2 \in \mathcal{N}_i \setminus \{v_k^i, j_1\}, \dots, \\ j_n \in \mathcal{N}_i \setminus \{v_k^i, j_1, \dots, j_{n-1}\}}} \cdots \sum P\left(v_k^i; \{j_1, \dots, j_n\}\right) \\ &\cdot \max_{\ell=1,\dots,n} R_{v_k^i, j_\ell}. \end{aligned} \tag{30}$$

Similarly, by considering all users in all D2D clusters, the total throughput can be calculated as

$$R_t = \sum_{i=1}^{K} \sum_{k=1}^{N_i} R_k^i. \tag{31}$$

We assume that the requested files have the same length (L), the total bandwidth is W_0, and each user has the same bandwidth (W_0/N). Note that N is the number of users in our scenario. Thus, for the kth user, the transmission time to obtain the file from BS is written as

$$D_{B,v_k^i} = \frac{L}{(W_0/N) R_{B,v_k^i}}. \tag{32}$$

When n users in the cluster have a certain file and are willing to share such a file with the kth user, the average transmission time to obtain this file can be calculated as

$$D_{d,v_k^i} = \sum_{n=1}^{N_i-1} \sum_{\substack{j_1 \in \mathcal{N}_i \setminus \{v_k^i\}, \\ j_2 \in \mathcal{N}_i \setminus \{v_k^i, j_1\}, \dots, \\ j_n \in \mathcal{N}_i \setminus \{v_k^i, j_1, \dots, j_{n-1}\}}} \cdots \sum \frac{P_i\left(v_k^i; \{j_1, \dots, j_n\}\right) \cdot L}{(W_0/N) \max_{\ell=1,\dots,n} R_{v_k^i, j_\ell}}. \tag{33}$$

Including the possibility of obtaining the file from B, the average transmission time to obtain this file is simply

$$D_k^i = D_{d,v_k^i} + P_i\left(v_k^i, 0\right) D_{B,v_k^i}. \tag{34}$$

Similarly, the total energy consumption for the users in all D2D clusters can be written as

$$E_t = \sum_{i=1}^{K} \left(\sum_{k=1}^{N_i} \left(P_i\left(v_k^i, 0\right) P_B D_{B,v_k^i} + P_D D_{d,v_k^i} \right) \right), \tag{35}$$

and we also utilize energy efficiency $\eta = R_t/E_t$ to evaluate the performance of D2D clustering schemes.

When D2D clustering is not utilized, that is, in the nonclustering case, the users obtain the files from BS with probability 1, and we calculate the total throughput for all users in (31) as

$$R_t = \sum_{i=1}^{K} \left(\sum_{k=1}^{N_i} \left(\log_2 \left(1 + \frac{P_B \left| h_{Bk}^i \right|^2}{\sigma^2} \right) \right) \right). \quad (36)$$

We can also calculate the total energy consumption for all users in (35) as

$$E_t = \sum_{i=1}^{K} \left(\sum_{k=1}^{N_i} \left(P_B \frac{L}{(W_0/N)\, R_{B,v_k^i}} \right) \right). \quad (37)$$

6. Numerical Results for DCRP Clustering

In this section, we present numerical results to demonstrate the performance of our proposed DCRP clustering scheme in D2D communications. The random clustering scheme and the nonclustering scheme are also used for comparison. In the simulation test, we consider a special case by taking three social trust levels into account for, respectively, friends, acquaintances, and strangers, denoted as q_1, q_2, and q_3. In other words, the social trust $p(i, j)$ between nodes i and j can be equal to q_1, q_2, or q_3.

In our test scenario, the DUEs are uniformly distributed within a circular region of 100 m radius centered at (100 m, 0). We fix the BS at (300 m, 0). The large-scale path loss exponent between the BS and users is $\beta = 3.5$ and that of D2D users is $\beta = 4$. The parameter of CRP is $\alpha = 0.1$ and we set $\sigma^2 = -90$ dBm. $P_B = 0.2$ mW and $P_D = 0.1$ mW.

6.1. Cluster Delivery Mode. In this simulation scenario, we let $L = 1$ Mbit and $W = 1$ MHz. We test the performance of different schemes for various values of $d_{\max}$ and $N_{\max}$. Figure 2 shows that the throughput for all schemes grows with increasing number of users. However, the S-DCRP scheme achieves a higher throughput than other schemes for different values of $d_{\max}$ and $N_{\max}$. Furthermore, the variation of $d_{\max}$ has a greater impact on the throughput than that of $N_{\max}$. When the number of users is small, larger value of $d_{\max}$ or smaller value of $N_{\max}$ can improve the throughput for S-DCRP and P-DCRP schemes and vice versa.

It may be misleading to see that clusters formed by our scheme consume more energy because of more active participation in this *cluster delivery mode*. Indeed, extra energy consumption is used for more file sharing in socially well connected clusters. Therefore, to tell a more balanced story, Figure 3 plots the energy efficiency for all schemes, in which our scheme results in a higher energy efficiency than other schemes.

Next, we consider different schemes for different social trust values of q_1, q_2, and q_3. As shown in Figure 4, the S-DCRP scheme exhibits a higher throughput than other schemes under two groups of q_1, q_2, and q_3 values. Larger values of q_1, q_2, and q_3 have a positive impact on the throughput for all schemes.

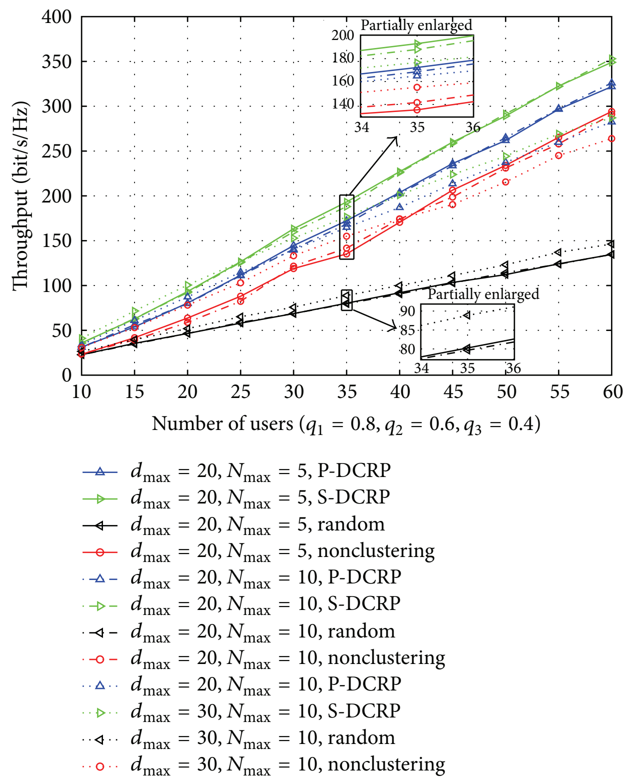

FIGURE 2: Throughput versus N with different values of $d_{\max}$ and $N_{\max}$.

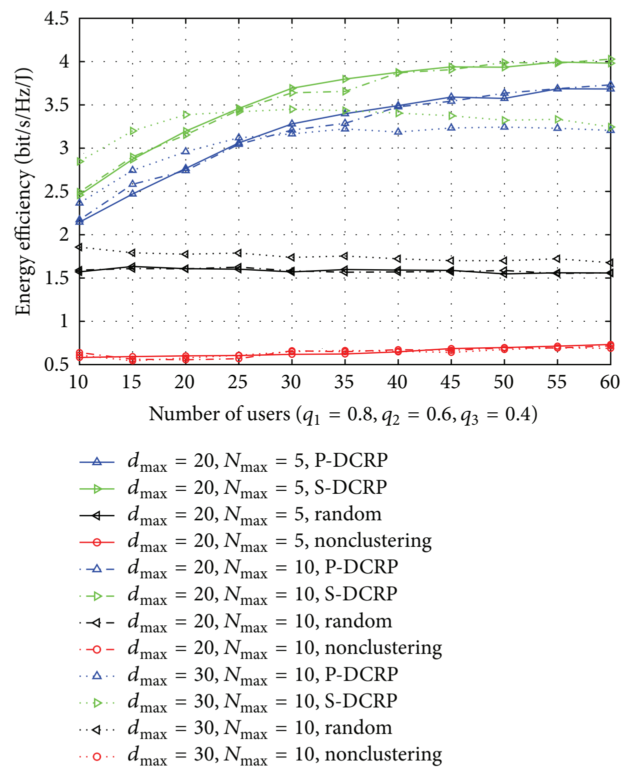

FIGURE 3: Energy efficiency versus N with different values of $d_{\max}$ and $N_{\max}$.

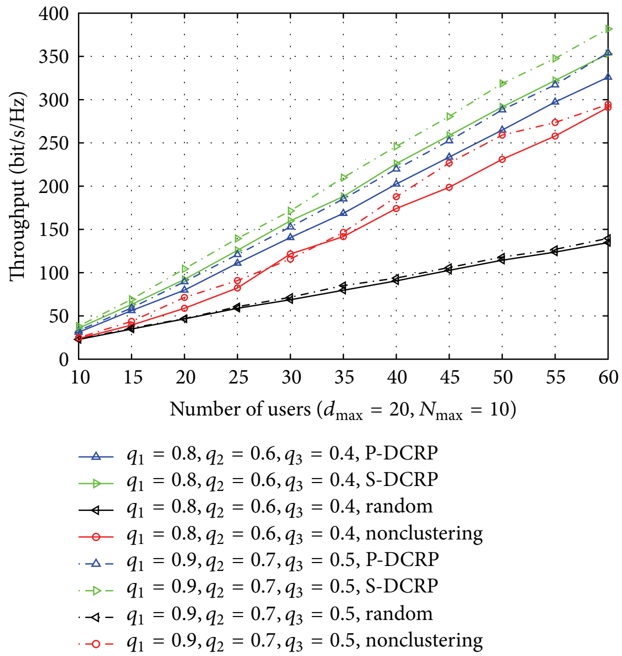

FIGURE 4: Throughput versus N with different values of q_1, q_2, and q_3.

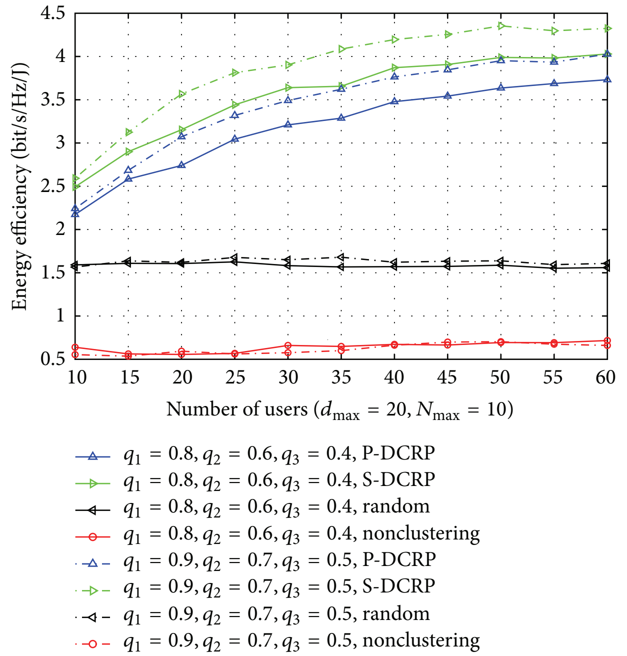

FIGURE 5: Energy efficiency versus N with different values of q_1, q_2, and q_3.

Comparing clusters formed by different methods, Figure 5 demonstrates energy efficiency from different solutions. We find that larger values for q_1, q_2, and q_3 lead to higher energy efficiency for S-DCRP and P-DCRP schemes. This confirms that our novel proposed scheme has better performance in terms of the energy efficiency than other schemes.

We also examine the performance of different schemes with different values of N. From Figure 6, we can see that more nodes lead to higher system throughput for all schemes. Among algorithms in comparison, for moderate value of d_{max}, our proposed S-DCRP scheme exhibits superior performance in throughput. Figure 7 indicates the performance on energy efficiency for all schemes under comparison. For moderate d_{max}, our proposed SD-CRP scheme can achieve better energy efficiency than other schemes.

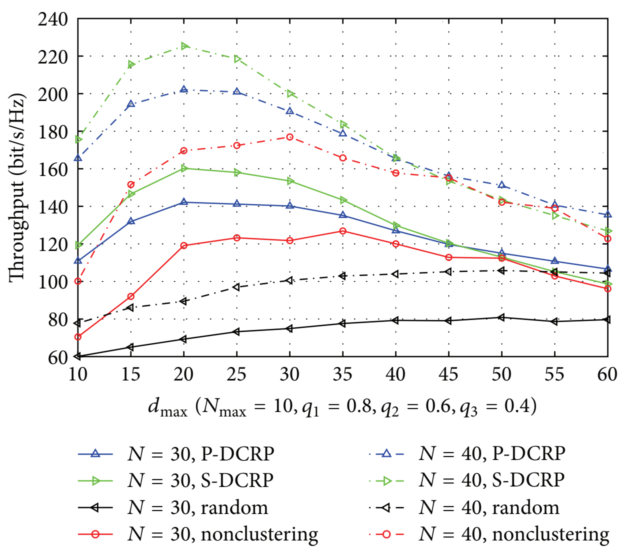

FIGURE 6: Throughput versus d_{max} with different values of N.

6.2. Request Mode in Clusters. In this simulation scenario, we fix $L = 1$ Mbit and $W_0 = 10$ MHz. We examine the performance of different schemes for various values of d_{max} and N_{max}. From Figure 8, the S-DCRP scheme has a higher throughput than other schemes as N_{max} varies. Further, the throughput for all schemes becomes larger when the number of users increase. Figure 9 shows that clusters from our scheme consumes less energy than others, since we allow file sharing for the optimal user with the best channel gain. In addition, our consideration of social distance increases the probability of file sharing, and this involves an overall energy consumption reduction. Figure 10 provides the energy efficiency for all schemes, showing higher energy efficiency for clusters formed by the proposed scheme. Because of the reduced bandwidth per user in this fixed bandwidth scenario, the energy efficiency for all schemes worsens when the number of users becomes larger.

We then illustrate the cluster performance from different clustering schemes for different q_1, q_2, and q_3. Figure 11 shows that clusters from the S-DCRP scheme achieve higher throughput than others. As we increase q_1, q_2, and q_3, the throughput of clusters also improves. From the energy consumption of this request mode, clusters created by our scheme also consume less energy when compared with other schemes and achieve higher energy efficiency as shown in Figure 12.

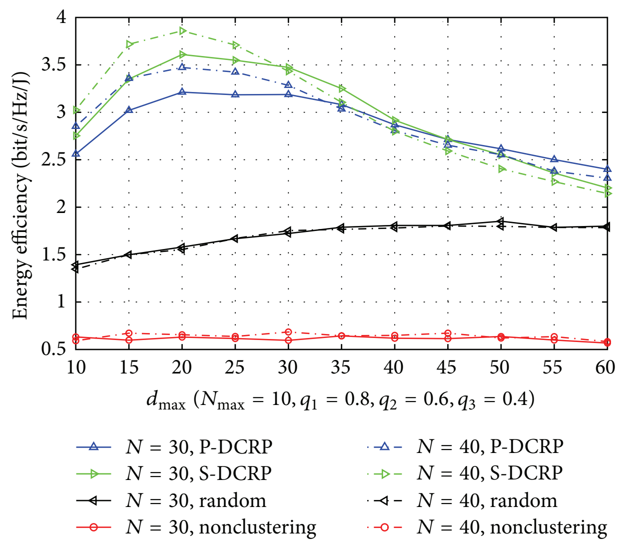

FIGURE 7: Energy efficiency versus d_{max} with different values of N.

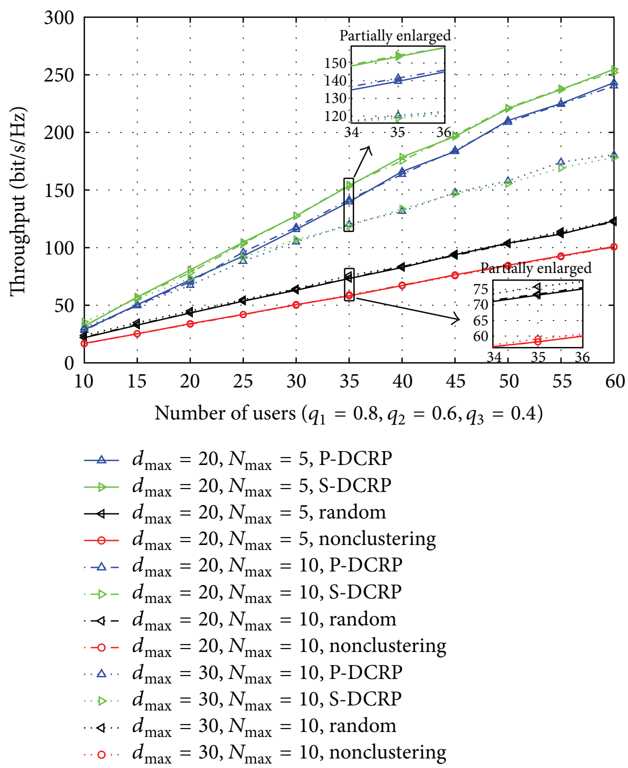

FIGURE 8: Throughput versus N with different values of d_{max} and N_{max}.

Finally, we demonstrate the clustering performance of different schemes for different values of N. As shown in Figure 13, with moderate d_{max}, the throughput for clusters decreases with increasing d_{max}. Also, the throughput for S-DCRP scheme is below that of P-DCRP scheme when d_{max} is large. When N becomes larger, throughput worsens for all schemes. Figure 14 shows that our clustering scheme

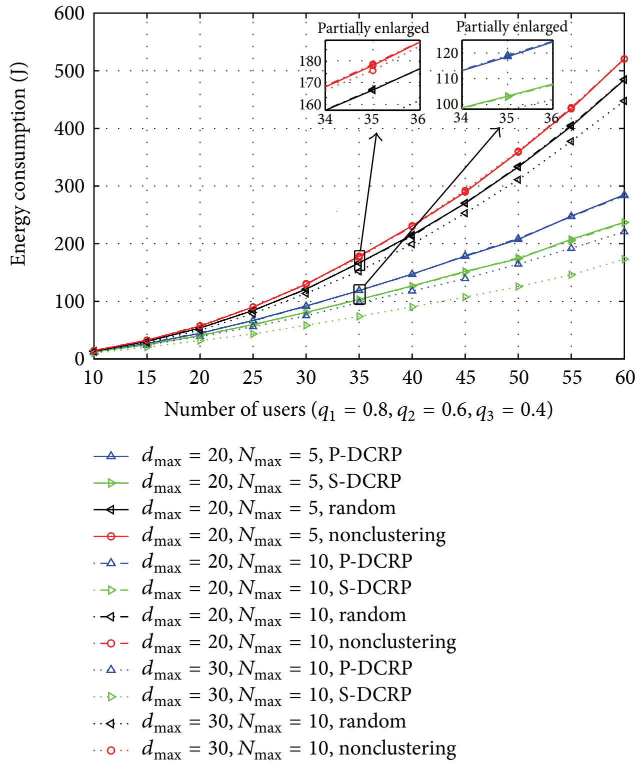

FIGURE 9: Energy consumption versus N with different values of d_{max} and N_{max}.

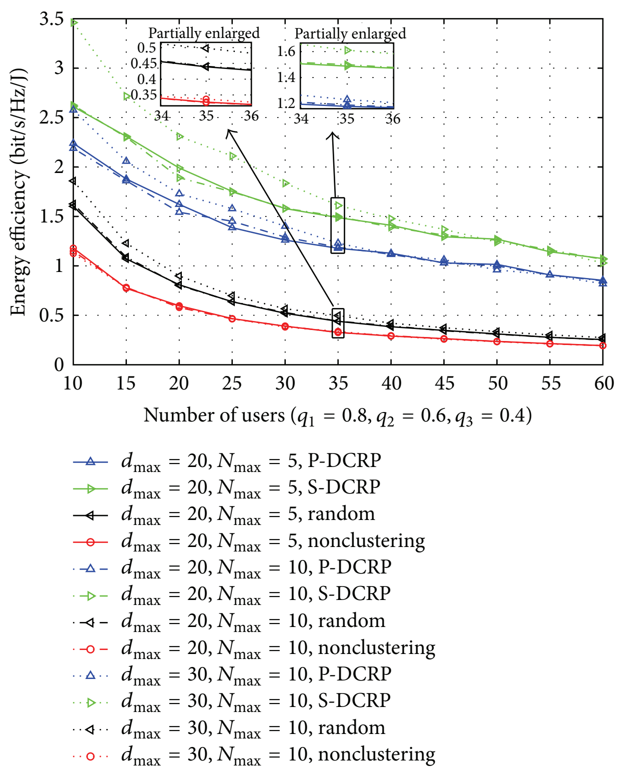

FIGURE 10: Energy efficiency versus N with different values of d_{max} and N_{max}.

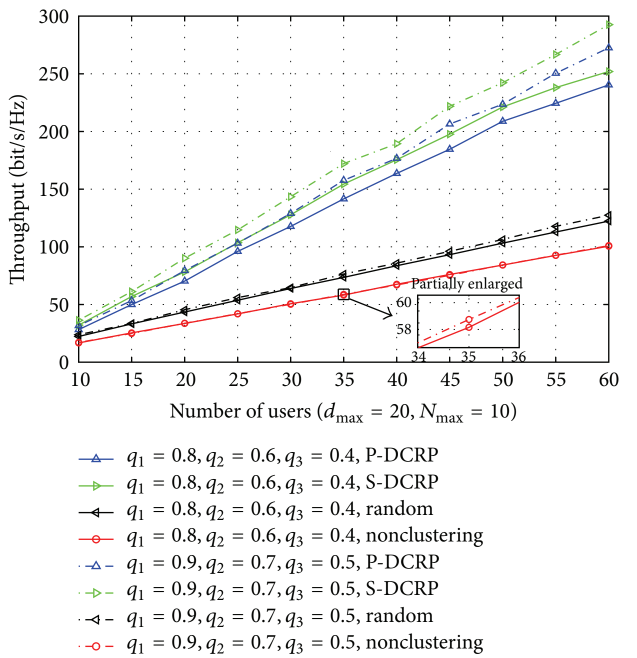

FIGURE 11: Throughput versus N with different values of q_1, q_2, and q_3.

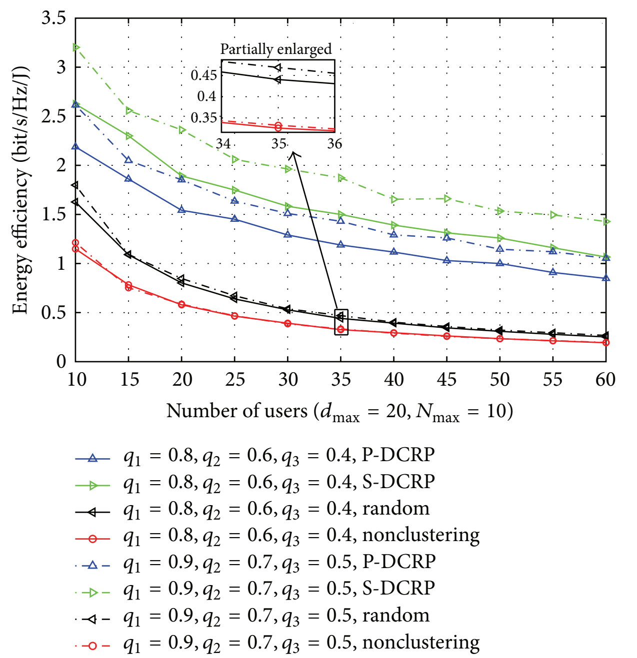

FIGURE 12: Energy efficiency versus N with different values of q_1, q_2, and q_3.

leads to higher energy efficiency than other schemes under comparison.

7. Conclusion

This paper studies D2D clustering based on CRP and DCRP. We propose a multiobjective clustering approach based on

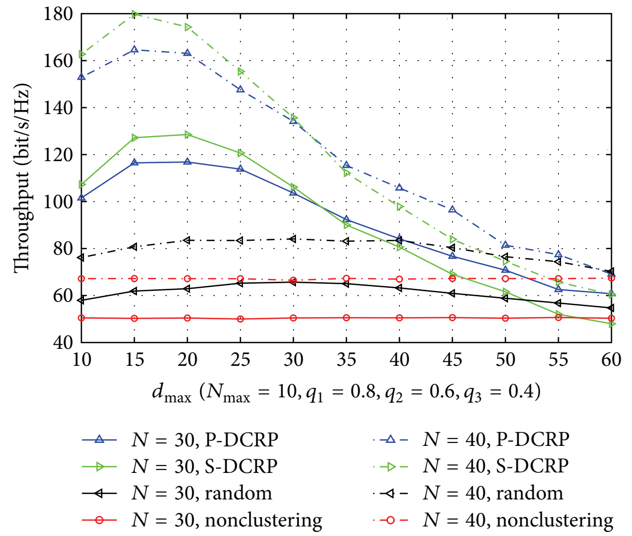

FIGURE 13: Throughput versus d_{max} with different values of N.

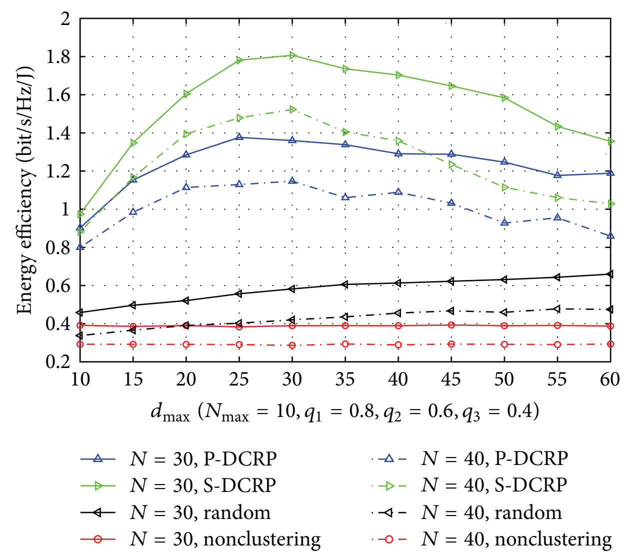

FIGURE 14: Energy efficiency versus d_{max} with different values of N.

CRP that allows each new device to select a cluster for improving link rate for D2D underlay in cellular networks. For D2D overlay, we propose a novel clustering scheme by incorporating both social and physical relationships among D2D users. Furthermore, we present performance analysis of D2D clusters in different content sharing modes. Our results demonstrate the advantages of our proposed scheme in terms of system throughput and energy consumption, as well as energy efficiency.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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