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A Scheme of Ad-hoc-Based D2D Communication in Cellular Networks

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Device-to-Device (D2D) communication is a novel communication technology which has been confirmed in ad hoc networks as a new direction. It allows mobile terminals communicate with each other directly by using the licensed frequency resources under the control of cellular networks. This paper first conducts an empirical study based on usage detail records in a city of China to evaluate the probability of D2D communication in different scenarios. Based on the results, to improve the probability of D2D communication, a scheme of ad-hoc-based D2D communication is proposed by incorporating the Delay Tolerant Networks (DTN), since DTN enables communication in sparse mobile ad-hoc networks. Simulation results show that the ad-hoc-based D2D communication can greatly increase the connection ratio of user pairs.

Keywords: Device-to-device (D2D) communication, ad hoc, delay tolerant network (DTN), data forwarding, cellular networks, data analysis.

1 INTRODUCTION

With the rapid development of mobile communication technique and cellular networks as well as the popularity of intelligent terminals such as mobile phones and tablets, mobile users are showing explosive growth. Cellular networks are developing toward higher data rates, greater utilization of network

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resources and larger network capacity, which will put forward higher requirements on the radio spectrum resources. Due to the limited spectrum in mobile communication networks, the growing traffic will inevitably lead to congestion in the network. Therefore, how to achieve high data rate and large capacity in mobile communication networks with limited bandwidth resources has become the focus of related researches [1, 6, 11, 14 and 18].

In current cellular networks, services are provided to User Equipment (UE) through Base Stations (BSs). That means data must first go through base stations and the core network, and then can be forwarded to the destination UE. But this communication mode results in an enormous waste of spectrum resources for UEs close with each other. Recently, Device-to-Device (D2D) communication has received much attention due to its potential to improve local service performance. In D2D communication, UEs transmit data to each other over a direct link instead of through the base station. Compared with other short-range wireless communication technique, D2D communication can improve the system's spectrum resource utilization, reduce the load of base stations and core networks and the power consumption of UEs, as well as enhance the robustness of network infrastructures [1-3]. In D2D communication, it must ensure that there are session overlaps between user pairs in the same base station. In this condition, whether D2D communication can be established remains a question. While current researches pay little attention on this. In this case, this paper aims to study the probability of achieving D2D communication between user pairs based on an empirical data set.

The data set in this paper are data usage detail records (UDRs) provided by a telecommunication operator. Based on these records, we first define three performance metrics: connection ratio (CR), communication probability (CP) and communication duration (CD). Then we investigate the probability of D2D communication according to statistical analysis of these metrics in six different scenarios. Based on the results, we proposed a novel scheme called ad-hoc-based D2D communication by introducing the Delay Tolerant Networks (DTN) to improve the probability of D2D communication. In ad hoc networks, the network disconnection phenomenon often appears [19, 20, 23, 24, 27, 28, 29]. In this case, the DTN is increasing applied to enable communication in mobile ad-hoc networks. The main contributions of this paper are two folds.

- *Statistical analysis of the performance metrics illustrates the probability of D2D communication.*
- *We propose a scheme of ad-hoc-based D2D communication, which is achieved by adding intermediate UEs as data forwarding nodes. Simulation results demonstrate that the ad-hoc-based D2D communication can significantly improve the probability of D2D communication between user pairs.*

The remainder of this paper is organized as follows: Section two briefly reviews the related work on D2D communication. In Section 3, we conduct an empirical study on statistical analysis of the performance metrics in D2D communication. Section 4 introduces the scheme of ad-hoc-based D2D communication and conduct a simulation study. Section 5 concludes the work.

2 RELATED WORK

Most of current research on D2D communication focuses on technological problems such as the wireless spectrum resource management strategies, D2D transmission power control, and optimization of system transmission capacity, etc. Different resource management programs against wireless spectrum resource management issues for D2D communication were proposed in literature [4-7]. Pei Y and Liang Y C [4] adopted a new spectrum sharing protocol, which allows the D2D users to communicate bi-directionally with each other while assisting the two-way communication between the cellular base station (BS) and the cellular user (CU) over the same time and frequency resources. This protocol is effective to improve the sum rate for both the D2D and cellular users. With the aim of optimizing resource sharing for D2D communication to better utilize uplink resources in a multiuser cellular system, Wang J, *et al.* [5] proposed an analytical characterization of the globally optimal resource sharing strategy, and furthermore propose two suboptimal strategies with less complexity. Literature [6] studied orthogonal and non-orthogonal distribution models against spectrum resource allocation problem in communications between base stations and D2D. It mainly analyzed the power control and efficient resource allocation in restriction of frequency and power to optimize the transmission rate. In literature [7], cellular network which supports D2D communication was seen as a Stackelberg Game Model, while the base station acted as a leader and each user device was a subsidiary. Based on this model, a novel distributed united spectrum sharing and power allocation scheme was designed to improve local services and reduce the limited signaling overhead of the underlying cellular model network.

In the aspect of power control research, Cheng Y, *et al.* [8] proposed a combined power control and link selection algorithm with temporary removal based on power control structure of a conventional cellular networks and proved that the proposed algorithm converged to the optimal power and link selection vector in all feasible systems. In the literature [9], a method was introduced to dynamically adjusts D2D's transmit power by measuring the channel quality information in real-time. A D2D power control mechanism with fuzzy logic in TD-LTE-A system was proposed in literature [10]. Teng F, *et al.* [11] proposed a new power control mechanism for a cellular system that support D2D communication through the uplink resource. This mechanism allocated power among D2D users locally rather than through a central controller, while power of cellular subscriber was still controlled by the receiving station.

In order to enhance the transmission capacity of the system, Literature [12] conducted a comprehensive analysis the transmission capacity of relay assisted D2D network, confirmed that the relay assistance will effectively enhance system capacity and power efficiency. Literature [13] proved that MIMO relay technology can enhance the transmission capacity of D2D communication system. Literature [14] enhanced overall capacity of cellular network and D2D communication system by adopting new interference management strategies. In addition, many methods have been discussed and proposed to solve the problem of how to detect neighbor equipment and establish D2D link timely [15]. In literature [16, 17], a distributed mechanism for application-aware proximity services in (D2D) communications is presented. This mechanism not only enables neighbor discovery and service discovery simultaneously, but achieves synchronization in physical communication timing and service interests in the meanwhile.

Major efforts so far have been put to demonstrate the technical research of D2D communication under the assumption that the D2D communication is feasible. But whether the D2D communication is really feasible has rarely been demonstrated. The precondition for achieving D2D communication is that the communication time of user pairs has overlaps. So in this article we analyze the feasibility of D2D communication by the user data extracted from mobile Internet. These data contains users' related session information of connecting and disconnecting to the mobile Internet, which is a true reflection of user behavior. And the performance indicates such as user pair's connection, the communication probability and the communication duration are determined to evaluate the feasibility of D2D communication.

3 EMPIRICAL STUDY

To gain further insight of D2D communication, we conduct an empirical research. For the sake of simplicity, we make the following definitions:

- **Connection ratio (CR) of UE** A is defined as:

$$CR_{D2D} = \frac{M_0}{M-1} \tag{1}$$

where M_0 is the number of users with whom A can establish communication in the same base station. M is the total number of users in the base

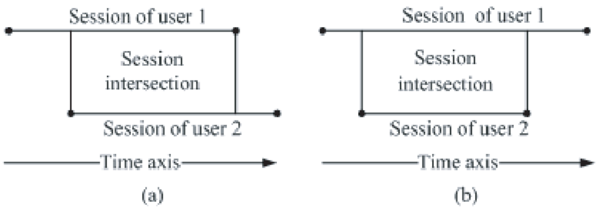

FIGURE 1
Session time relationships of two users in D2D communication

station. The higher the connection ratio of a UE is, the more UEs it can establish D2D communication with.

- **Communication probability (CP) between UE A and UE B** is defined as:

$$CP_{D2D,A,B} = \frac{C_{A,B}}{a \times b} \tag{2}$$

where a, b is the number of sessions of A and B, respectively. $C_{A,B}$ is the number of D2D communication times between A and B. The communication probability identifies the probability two users can establish D2D communication with each other.

- **Communication duration (CD)** is defined as the session overlap length of a user pair in D2D communication. The premise for achieving D2D communication is that there are overlaps between users' session time, as shown in Figure 1.The communication time must be sufficient to ensure smoothly data transfer between user pairs. So it is necessary to take communication duration into consideration when investigating D2D communication.

The data set in this paper contains UDRs from the mobile cellular network in a prefecture-level city in China. The detail information of each record is shown in Table 1. We select UDRs of 6 base stations in different scenarios

Field	**Description**
UID	*Encrypted ID number of a user*
Session_start_time	*The timestamp of a session start*
Session_end_time	*The timestamp of a session stop*
AreaID, CellID	*The ID of a base station*

TABLE 1
Field description of the UDR data set

Scenario	**Number of users**	**Number of sessions**
Square	202	2024
Factor	326	5136
School	811	11084
Community	433	5603
Street	542	5368
Park	387	5699

TABLE 2
Statistics of sampled data

in one day. Table 2 summarizes the statistics of the sampled records. The maximum duration of a session is 15 minutes.

3.1 How possible can UEs achieve D2D communication in different scenarios?

In order to answer these questions, we investigate the three metrics above in different scenarios.

Figure 2 we mentioned in the former work [30], it shows the Cumulative Distribution Function (CDF) of CR_{D2D} in six scenarios. It clearly shows that in all the scenarios, 60% of users can establish D2D communication with other users with *CR* from 15% to 20%. Besides, CR_{D2D} in factories and parks are the highest, while those in squares and streets are the lowest. It is due to that the slow crowd flow in factories and parks are more likely to have session overlaps with each other. While in squares and streets people move more quickly, thus resulting in less session overlaps.

The CDF of CP_{D2D} are shown in Figure 3 also mentioned in the former work [30]. It is obvious that all distributions are basically the same. When

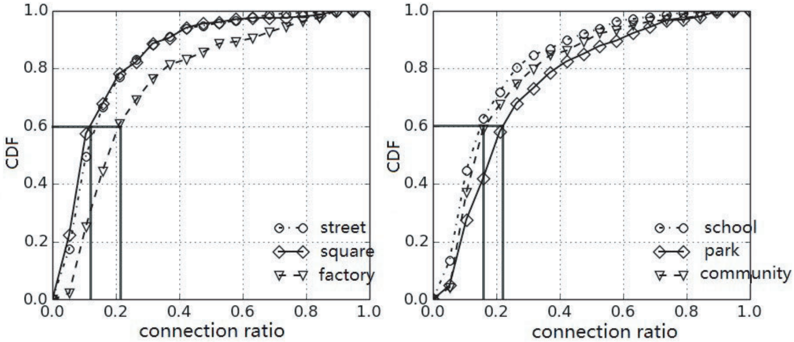

FIGURE 2
CDF of CR_{D2D} in different scenarios

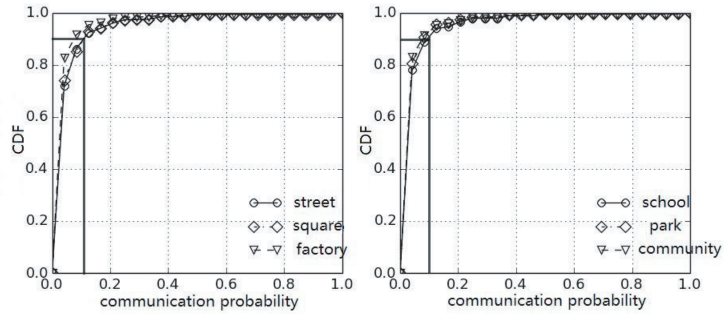

FIGURE 3
CDF of CP_{D2D} in different scenarios

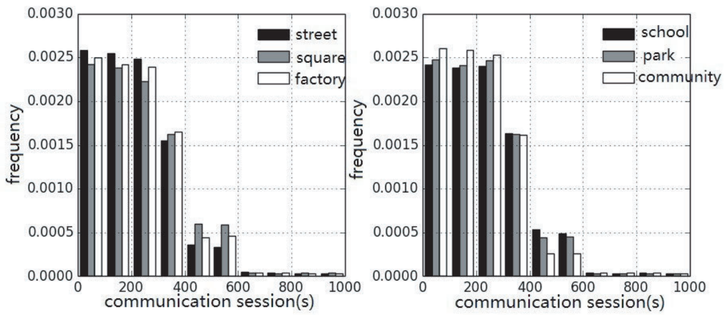

FIGURE 4
Frequency histograms of CD_{D2D}

the probability equals 0.9, the corresponding CP_{D2D} is about 0.1, indicating CP_{D2D} of nearly 10% users in all scenarios is higher than 0.1.

Figure 4 illustrates the frequency histograms of CD_{D2D}. It is clear that CD_{D2D} in all scenarios mainly concentrated in 0 600s, among which the duration 0 100s, 100s 200s, 200s 300s each accounts for 25%, and 300s 400s, 400s 500s, 500s 600s each accounts for 15%, 5% and 5%, respectively. Too short communication duration will result in failures of data transfer between users. The results show that 75% of CD_{D2D} exceeds 100s, indicating that the communication duration is quite adequate in most cases in D2D communication.

3.2 Does the number of online users also affect D2D communication?

The length of one session within 15 minutes indicates that the time span of session overlaps between user pairs will be less than 30 minutes. In this case, to ensure the minimum time interval and the session overlap existence

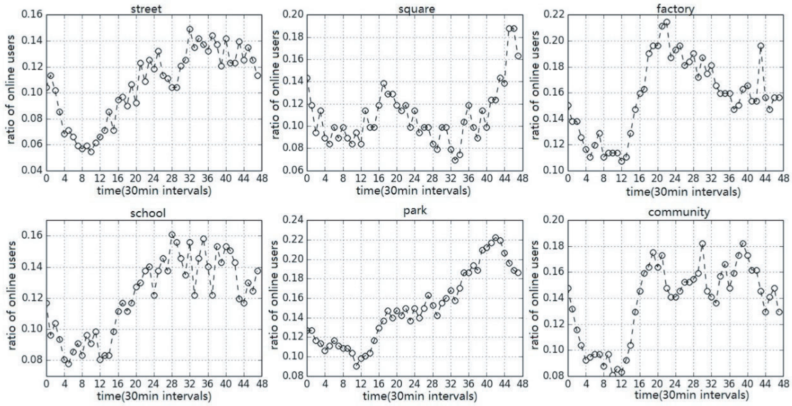

FIGURE 5
Ratio of online users with 30min intervals

between user pairs, we set a time interval of 30 minutes. Figure 5 reports the ratio of the number of online users in each 30 minutes account for the total number of users in one day. The highest ratio of online users 0.13 0.22 in the six scenarios is close to the connection ratio illustrated in section a. Ratios in parks and factories are the highest while those of streets and squares are the lowest. This is consistent with the communication probability displayed in Figure 3. The ratio variation in one day reveals users' spatial movements, which will affect the D2D communication performance to a large extent.

For user pairs who have time overlaps within 30 minutes intervals, the ratio of online users actually equals the communication probability of the user pairs. During one day, the average ratio of online users in all the 6 scenarios within 30 minutes is between 0.1 and 0.15, indicating the largest probability of D2D communication is between 0.1 and 0.15. As shown in Figure 3, the communication probability of 10% user is higher than 0.1, which is relatively close to the maximum communication probability in D2D communication. With all the analysis above, D2D communication is feasible in most cases.

4 AD-HOC-BASED D2D COMMUNICATION SCHEME

As discussed in Section 3, in D2D communication, the communication between user pairs should be based on the condition that they are online at the same time, which subjects the connection and communication probability between user pairs to certain constraints. In this section, we try to propose an ad-hoc-based D2D communication scheme to improve the connection and communication probability between user pairs.

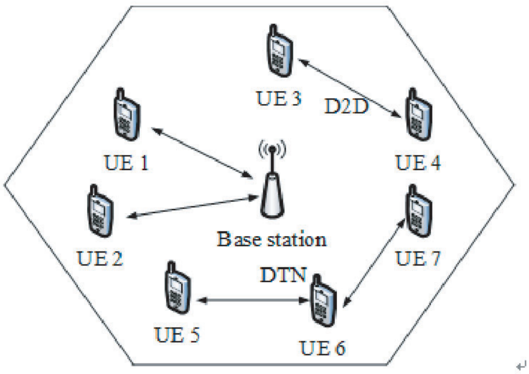

FIGURE 6
Various communication modes coexisting in cellular networks

A DTN (Delay-Tolerant Network) is a network designed to operate effectively over extreme distances which is constantly applied in ad-hoc networks. Based on the delay tolerant characteristics of DTN, the ad-hoc-based D2D communication scheme is proposed to improve the probability of D2D communication in cellular networks. In the scheme, intermediate UEs are added between a user pair which fail to establish D2D communication due to the lack of session overlap, forming DTN communications with one hop (only one intermediate UE) or multi-hops (with more than one intermediate UE). Since the intermediate UE has session overlaps with both of the user pair, it works as a carrier with the function of temporary data storage and forwarding. Figure 6 shows the base station with cellular communication, D2D communication and DTN communication. The ad-hoc-based D2D communication is a communication mode that when UEs fail to establish D2D communication, they will try to establish a DTN communication connection with intermediate UEs. In this paper, we focus on one-hop DTN communication with data forwarding via only one intermediate UE. The maximum tolerant delay is set to 2 hours.

Given three UEs: A, B and an intermediate UE C, the establishment of one-hop DTN communication link between A and B has two forms. One is shown in Figure 7(a), in which A and B establish a DTN communication link in the same session of C. The other form is shown in Figure 7(b), in which A and B establish DTN communication link in different sessions of C.

4.1 Simulation in different scenarios

The performance metrics of D2D communication is discussed in section 3 includes CR_{D2D}, CP_{D2D} and CD_{D2D}. In fact, DTN communication with one

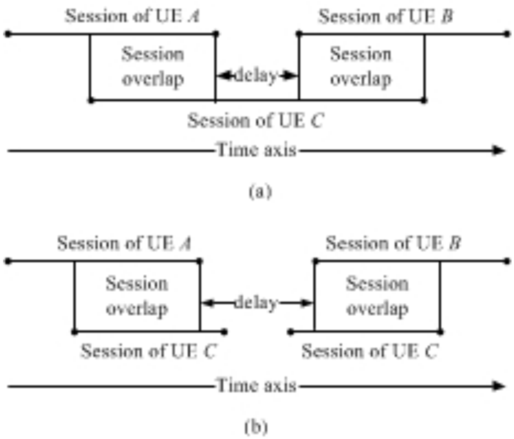

FIGURE 7
Session overlaps of UEs in DTN communication

hop can be seen as two D2D communication processes at different times. So we only consider CR and CP in DTN communication.

- CR_{DTN}:In DTN communication, CR can be also obtained according to Equation(1).
- CP_{DTN}:Since we regard the establishment of communication link as random sampling processes of user sessions. Different from D2D communication, DTN communication includes sampling processes of intermediate user sessions. As shown in Figure 7, the establishment of DTN communication link between A and B has two forms. Assuming that the number of sessions of A, B and C is a, b, c respectively. Then the form in Figure 7(a), we need to select a session from C besides that of A and B. Thus the number of choices is $C_a^1 \times C_b^1 \times C_c^1 = a \times b \times c$. And for the form in Figure 7(b), we need to select two sessions of C. The number of choices is $C_a^1 \times C_b^1 \times C_c^2 = a \times b \times c(c-1)/2$. So the probability of establishing one-hop DTN communication between A and B via C can be expressed as

$$P_{ACB} = \frac{C_{DTN1}}{a \times b \times c} + \frac{C_{DTN2}}{a \times b \times c(c-1)/2} \tag{3}$$

where C_{DTN1},C_{DTN2} is the link number of the two DTN communication forms, respectively.
In DTN communication, user pairs can select different forwarding UEs to establish DTN connection as shown in Figure 8. Then the CP between A

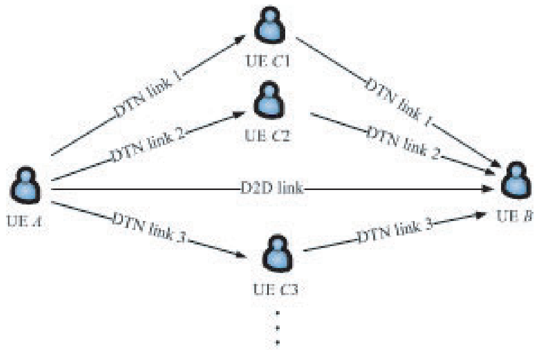

FIGURE 8
Communication links between user pairs in ad-hoc-based D2D communication

and B in DTN communication can be expressed as

$$CP_{DTN} = 1 - \prod_{i=1}^{n}(1 - P_i) \tag{4}$$

where P_i is the establishment probability of different DTN communication links, n is the number of DTN communication links between A and B.
As shown in Figure 8, in ad-hoc-based D2D communication, communication links between A and B are actually composed of a D2D link and multiple DTN links via different intermediate UEs, then CP between A and B can be expressed as

$$CP_{DTN-D2D} = 1 - (1 - CP_{D2D} \times (1 - CP_{DTN})) \tag{5}$$

- Communication probability
  The CDF of CR_{D2D}, CR_{DTN} and $CR_{DTN-D2D}$ under one base station in different scenarios are shown in Figure 9. When the cumulative probability value equals 0.6, CR_{DTN} is nearly double CR_{D2D}. While compared to CR_{DTN}, $CR_{DTN-D2D}$ does not increase significantly, indicating that UEs establishing D2D communication can also establish DTN communication. Additionally, the three metrics in parks and factories are the largest while those in squares and streets are the smallest. Overall, DTN communication and ad-hoc-based D2D communication significantly outperform D2D communication in connection ratio. It owes to the addition of intermediate UEs to help more user pairs without session overlap to establish communication connection.
- Communication probability

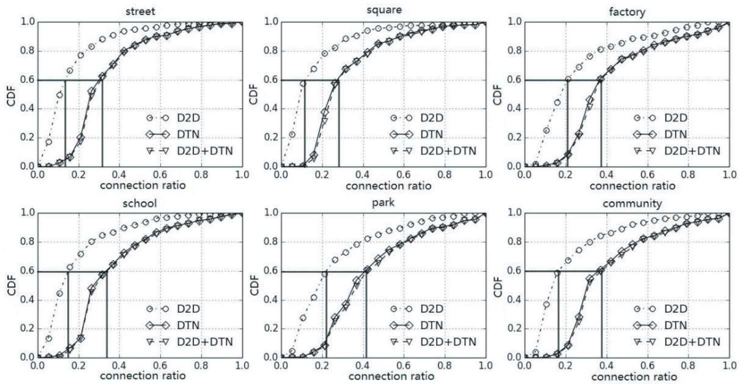

FIGURE 9
CDF of CR_{D2D}, CR_{DTN} and $CR_{DTN-D2D}$

The CDF of CP_{D2D}, CP_{DTN} and $CP_{DTN-D2D}$ under one base station in different scenarios are shown in Figure 10. Besides squares, $CP_{DTN-D2D}$ is higher than both CP_{D2D} and CP_{DTN} in the rest scenarios. At the point where the cumulative probability value equals 0.9, the communication probability increases from 0.1 to 0.15 0.2. In DTN communication, intermediate UEs increases the communication times and creates multiple DTN links for user pairs. However, the addition of intermediate UEs also increases the session selecting number, so there is no obvious improvement from CP_{D2D} to CP_{DTN}. But ad-hoc-based D2D communication can benefit from both DTN and D2D communication, resulting the highest CP.

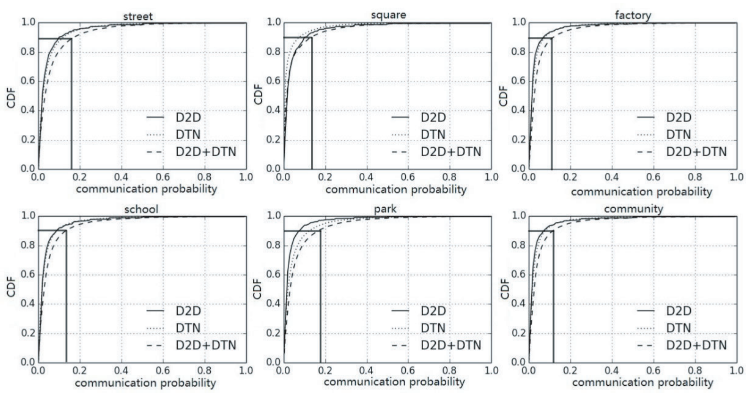

FIGURE 10
CDF of CP_{D2D}, CP_{DTN} and $CP_{DTN-D2D}$

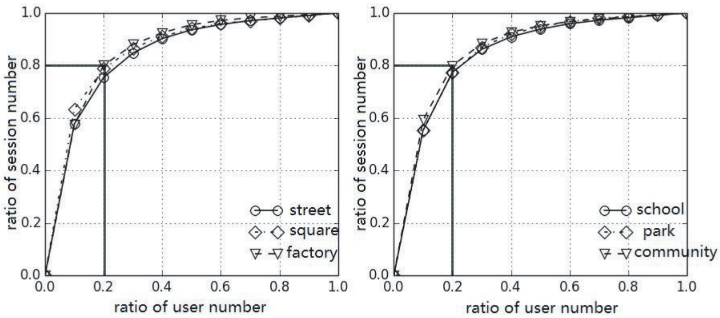

FIGURE 11
Proportion of users' session number

4.2 Analysis of simulation results

According to statistical results above, the performance of ad-hoc-based D2D communication is significantly improved in both CR and CP. This section focuses on the characteristics of user session data, aiming to find out the reasons of performance difference.

We calculate the number of sessions and the length of session time of each user and rank them in descending order, respectively. All the users are then divided into 100 parts and we calculate the proportion of session number and session length of each part over all. The distributions are shown in Figure 11 and Figure 12, respectively. Obviously, the proportion distributions of session number and session length in different scenarios are basically consistent. The top 20% of users account for 80% of both session number and session length, which is completely consistent with the Pareto rule [17]. As for the remaining 80% of users, the session number and session length are

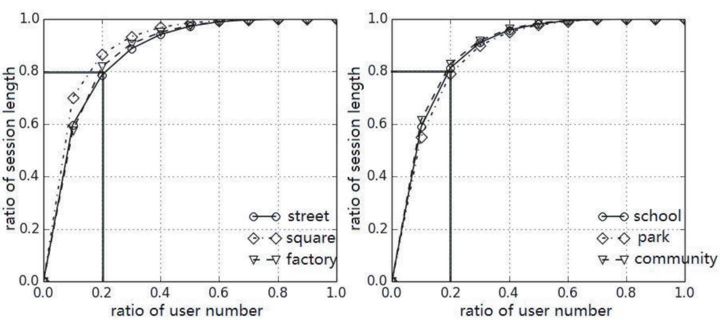

FIGURE 12
Proportion of users' session time

small and dispersedly distributed, resulting in rare session overlaps between them. It demonstrated that in D2D communication, due to the time and space constraints, connection ratios of user pairs are limited. While for base stations, the uneven distribution of sessions will result in “super users”, i.e., the top 20%. These “super users” generate sessions many times higher than ordinary users, and thus have session overlaps with many surrounding users. DTN communication makes use of these “super users” as bridges to connect user pairs who cannot establish communication directly due to the lack of session overlaps. Therefore, introducing DTN communication is very essential to improve the probability of D2D communication between user pairs.

5 CONCLUSIONS AND FUTURE WORKS

This paper study the probability of D2D communication based on a UDR data set. We first define three performance metrics of D2D communication: connection ratio, communication probability and communication duration. By analyzing these performance metrics and comparing them with the ratio of online users, we verified the high probability of D2D communication, there is still room for improvement. We then propose an ad-hoc-based D2D communication scheme by introducing the Delay Tolerant Networks (DTN) which are constantly applied in ad-hoc networks. It can achieve the delay tolerant communication by adding intermediate user equipments (UEs) as data forwarding nodes. Simulation results show that the ad-hoc-based D2D communication can significantly increase the connection ratio of user pairs, as well as improve the communication probability. Finally, according to the analysis of users’ session data, we find the existence of “super users”, which generate much more sessions than other users. They can be regarded as forwarding nodes via which UEs who cannot establish D2D communication due to the lack of session overlaps to establish DTN communication. In summary, the ad-hoc-based D2D communication can improve the probability of D2D communication significantly.

There is still room for improvement of our work: due to the computational complexity and time constraints, this paper only study the performance metrics of one-hop ad-hoc-based D2D communication. In future studies, multiple-hop transfer forms need to be analyzed. Moreover, energy efficiency issues [21, 22, 25, 26] will be considered in the proposed framework.

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