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User Satisfaction-Aware Resource Allocation for D2D Enhanced Communication

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ABSTRACT Fog radio access networks has emerged as a promising evolution path for 5G network architecture to satisfy the explosively increasing demands of high-speed data services and massive access requirements of various devices. As a key complement to this path, proximity-based device-to-device (D2D) communications with high transmission rate can better support the above services. For resource allocation in D2D communications, there are two fundamental challenges that should be addressed: 1) how to utilize the mobile characteristics and social relationships among users to enhance the user throughput and 2) how to efficiently allocate the limited resources to guarantee each user's service satisfaction. In this paper, a D2D dual-link enhanced communication model is developed to improve the throughput of D2D and cellular users (CUs) simultaneously. Then, based on the mobility characteristics and social relationships among users, an optimization problem about resource allocation is formulated and solved with the objective to maximize the user satisfaction. The simulation results verify that our proposed scheme can improve user satisfaction and throughput under limited spectrum resources simultaneously.

INDEX TERMS D2D communications, resource allocation, social relationships, user satisfaction, fog radio access networks.

I. INTRODUCTION

According to Cisco's Visual Networking Index (VNI) report, the global mobile data traffic will increase nearly 9-fold from 2015 to 2020 with 5.5 billion Global Mobile Users, 367 exabytes of total mobile traffic [1]. The explosive growth of mobile data services, especially high-speed data applications with massive access requirements has brought great challenges to the access infrastructure, e.g., base station (BS) [2]–[5]. To alleviate the heavy traffic burdens on BSs and improves the spectrum efficiency, D2D communications can be introduced into radio access networks due to the fact that D2D communications allow the direct communication between a pair of D2D users of physical proximity without going through BSs, which is also termed as fog radio access networks [6]–[9].

In particular, D2D communications mainly include two modes: overlay mode and underlay mode [10]–[13]. The latter one includes orthogonal multiplexing and nonorthogonal multiplexing. The overlay and orthogonal multiplexing modes allocate dedicated spectrum resources for D2D users to avoid co-channel interference [14]–[16]. However, when the number of users is large, the spectrum resources will become quite tense. Although the nonorthogonal multiplexing mode will cause co-channel interference, we can effectively avoid interference and improve the spectrum efficiency through resource allocation, interference management, access control and other methods [17]–[20]. So, we focus on nonorthogonal multiplexing in this paper.

Moreover, previous research works indicate that the Click-Through Rate (CTR) and popularity of a given video are closely correlated and follow the Zipf distribution [21]. For instance, 20% of the popular videos in top video streaming sites have 80% of the CTR [22]–[24]. Obviously, there is a large amount of repeated content requirements in the local business [25]. Traditional D2D communications allocate resources according to the distance between CUs and D2D users. However, if similar contents are transmitted simultaneously in some D2D and cellular links, traditional D2D communications need to allocate independent spectrum resources for each D2D and cellular link [26]. This method consumes amount of spectrum resources to transmit the same contents, significantly reducing spectrum efficiency. So, how to improve the resource allocation scheme to adapt to the above business characteristics is worth to be studied.

User equipments (UEs) carried by human beings generally have strong social attributes and mobility, which can be further utilized to enhance the performance of existing networks [27]–[29]. Although efforts have been devoted to find out effective resource allocation schemes combined with social attributes and mobility, there are several fundamental challenges should be addressed: 1) Due to the differentiated social attributes, users' content demands are heterogeneous. Conventional schemes treat all such demands the same, resulting in resource wasting to broadcast unpopular contents. 2) As users usually move frequently, channel quality of the D2D communication is hard to be guaranteed. 3) The service providers always allocate resources to users in terms of the network throughput, which may ignore the service experience of each user. 4) With explosively increasing demands of high-speed data services and massive access requirements, the traditional D2D communication model can't meet the above service requirements.

To solve the above problems, in this paper, we propose a D2D dual-link enhanced communication model. In this model, users can receive contents with high similarity from the dual-link simultaneously to obtain better transmission rate. Besides, by considering the mobile characteristics and social relationships among users, an optimization problem of resource allocation is formulated and solved with objective to maximize the user satisfaction. The main contributions of this paper are as follows:

- A D2D dual-link enhanced communication model is proposed. Allowing D2D and cellular users to share similar contents while multiplexing spectrum resources can further improve the spectrum efficiency and user throughput.
- By measuring the user mobility in terms of the partial historical trajectory information of each user, the encounter duration between any two users is analyzed to guarantee the channel quality of D2D communication. Moreover, the social relationship between users is measured from their own perspective, so that we can estimate how much different users are interested in similar contents.
- 1-1 Two-sided Satisfied Matching Algorithm Based on Preference Order (TSMA) is proposed to efficiently allocate resources, which can be solved with objective to maximize the user satisfaction.

The rest of this paper is organized as follows. The related works are introduced in Section II. The D2D dual-link enhancement model and the problems combining user characteristics are analyzed in Section III. Section IV measures the user throughput combined with mobility and social relationship. User satisfaction-aware resource allocation scheme is proposed in Section V. Section VI presents the simulation results. Finally, Section VII concludes this paper.

II. RELATED WORKS

In recent years, there have been some works studying resource allocation for D2D communications. Yu *et al.* [30] study the optimum resource allocation and power control between CUs and D2D links using different resource sharing modes such as cellular, orthogonal, and non-orthogonal mode. The aim of this study is to enable proper resource management that can result in improving the total throughput of D2D communications. Min *et al.* [31] derive a distance threshold beyond which the cellular and D2D users can reuse the same spectrum resources. To help the BS in managing spectrum resources, an optimization method is proposed for CUs to share spectrum resources with the D2D links, where the resource allocation problem is formulated as a linear assignment problem in [32]. A reverse iterative combinatorial auction mechanism is proposed to allocate resources between CUs and D2D links in [33]. All of the aforementioned works focus on the physical domain, and their common assumption is that CUs are willing to share their spectrum resources with any D2D links. However, since CUs suffer co-channel interference from D2D links, such assumption might be invalid.

Recently, it has been observed that UEs carried by humans exhibit strong social attributes including social bond, centrality, community, etc., which can be utilized to allocate resources more efficiently. A social attribute aware D2D communication architecture is proposed in [34]. This paper qualitatively analyzes how D2D communication improves performance from social attributes and further develops a new research direction for solving the D2D resource allocation problem. The work in [35] proposes a social-community-aware D2D resource allocation architecture, in which a two-step coalition game model is used to establish communities and allocates resources. Considering the social relationships and physical condition, a cluster formation scheme is proposed in [36]. The cluster head caches the file fragments requested by most of UEs in the cluster and then shares the fragments by D2D multicast. The three-phase approach for social-aware data dissemination is proposed in [37] which effectively improves the forwarding rate and the utilization of spectrum resources. Based on extensive research on the social propagation characteristics and user mobility patterns, the popularity degree of social content in different regions can be obtained and then propagation-and mobility-aware content replication strategy for edge-network regions is proposed in [38]. In this strategy, the content allocated to peculiar user is relatively popular in the next destination. However, these schemes mentioned above mainly allocate resources to users in terms of the network throughput, which may ignore the service satisfaction of each user. As a result, some users may not receive any services.

III. SYSTEM MODEL AND ANALYSIS

A. D2D DUAL-LINK ENHANCED COMMUNICATION MODEL

Ultra Reliable and Low Latency Communications (URLLC) is one of the three major application scenarios in 5G. In this

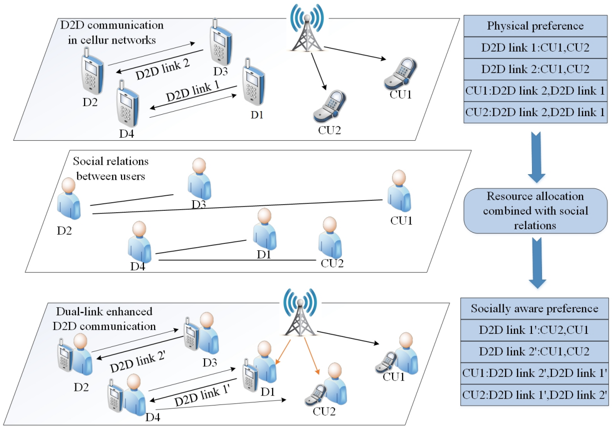


FIGURE 1. D2D dual-link enhanced communication model.

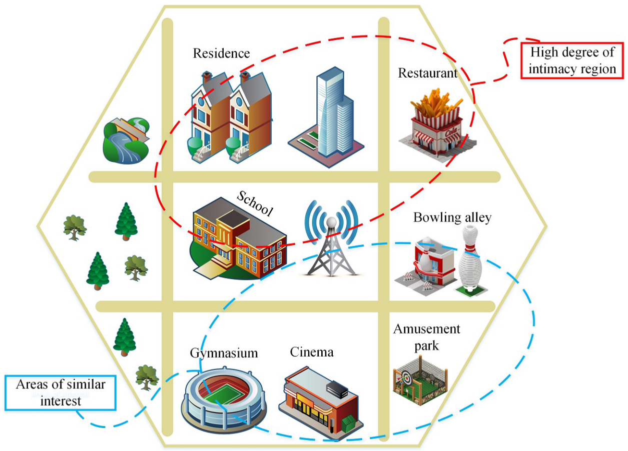


FIGURE 2. User's mobile scenario.

scenario, users have higher requirements on the communication delay and reliability. The traditional communication mode cannot meet these service requirements. Motivated by this, in this paper, a D2D dual-link enhanced communication mode is proposed, which can effectively improve the user throughput, transmission rate, and spectrum efficiency at the same time.

In traditional D2D communication, D2D links share spectrum with CUs according to the physical preference based on their relative physical locations. That is, each D2D link (e.g., D2D link 1 in Fig. 1) prefers to share the same spectrum with the CU (e.g., CU1 instead of CU2) that is located far from D2D users to avoid high cross-interference, as shown in the top of Fig. 1. However, it is possible that the contents diffused through D2D links may have higher similarity with the contents downloaded from the BS to CUs (e.g., the transmitter D4 of D2D link 1' and the BS send the same contents to their corresponding D2D receiver D1 and cellular users CU2, respectively). In this case, allowing each D2D link to share the same spectrum resource with the CU that shares the highly similar contents can further improve the spectrum efficiency, defined as D2D dual-link (e.g., by allowing D2D link 1' to share the same spectrum with the nearby cellular users CU2 with the highly similar contents, the D2D receiver D1 and cellular users CU2 can receive the contents from the base station and transmitter D4 of the D2D link 1' simultaneously), as shown in the bottom of Fig. 1.

B. PROBLEM ANALYSIS BASED ON USER CHARACTERISTICS

In D2D dual-link enhanced communication, when using the dual-link transmits irrelevant contents, the contents received by users are regarded as noise for each other. Additionally, as users usually move frequently, channel quality of the D2D communications is hard to guaranteed. Motivated by this, two types of user characteristics in D2D dual-link enhanced communication are considered as follows:

1) Users usually have strong social attributes, which greatly affects their behaviors. Specifically, users with strong social relationships are more likely to be interested in similar contents, providing contents sharing to each other. Therefore, by analyzing the social relationships, the D2D and cellular link whose D2D transmitter and CU own strong social relationships are selected as a dual-link preferentially. Then, the contents downloaded by the CU from BS is similar to the contents transmitted by the D2D transmitter, ensuring that the D2D and cellular links transmit highly similar contents.

2) Users usually move frequently, channel quality of the D2D communications is hard to guaranteed. Motivated by this, user mobility is characterized in terms of the partial historical trace information of each user. Based on this, the encounter duration between any two users is analyzed, which is used as the decision factors in the resource allocation process to provide better channel quality.

In D2D dual-link enhanced communication, different optimization goals need to design corresponding resource allocation schemes individually. In order to maximize the throughput of cellular or D2D users, when the D2D links and CUs are matched as dual-links, the matching in which cellular or D2D users can obtain more benefits is preferred to be chosen. Similarly, to maximize the overall network throughput, the matching in which total users can obtain more benefits is preferred to be chosen. Considering the mobility and social relationships among users simultaneously, the throughput obtained by each user in D2D dual-link enhanced communication can be calculated respectively.

IV. MEASUREMENT OF USER THROUGHPUT

A. MEASUREMENT OF USER MOBILITY

In general, user's mobility is not random, and their moving areas which are restricted by physical environment and social relationship present a certain regularity [39]. As shown in Fig. 2, the areas with longer average stay duration of users are divided into two types: one is the high intimacy area in which users have a high degree of intimacy with each other; and the other is an area with similar interests where users may not have a high degree of intimacy but have similar interests. In addition, the probability of users browsing information while driving or walking is small. Most of the data interaction occurs in the above two types of areas. Therefore, in these areas, users have more service requirements and better channel quality to implement D2D dual-link enhanced communication.

In order to measure user's mobility characteristics, through the statistical analysis on average stay duration of different users in the above areas, it is possible to predict the encounter duration between any two users in the range of D2D communication. D2D dual-link enhanced communication requires D2D and cellular users to stay within the D2D communication range. Therefore, using this encounter duration as a decision-making factor for resource allocation facilitates stable and continuous D2D communications.

Then, we can get the average stay duration of user u in a certain region according to part of historical trajectory information which is collected by BS, as shown in Eq. (1).

$$\overline{d_{u,l}} = \frac{\sum_{T=1}^{N_u^S} d_{u,l}^T}{N_u^S} \tag{1}$$

where S is a duration window, which represents the period for storing local information in the BS. N_u^S represents the total number of times that user u has come to area l within the time window S. T indicates user u visit this area for the Tth time. $d_{u,l}^T$ is u's stay duration for visiting area l in the Tth time. At last, the data in Eq. (1) is updated by BS in real time.

If only average stay duration is used to predict the encounter duration that two users u_a and u_b will stay in the D2D communication range after they meet in a certain area, due to inability to know the specific time when the user is in and out of the area, it is impossible to calculate the duration accurately. In order to solve this problem, the time that user u_a and u_b enter area l is denoted as $t_{u_a}^l$ and $t_{u_b}^l$ respectively. Then, we can calculate the specific time when two users enter and leave the area combined with Eq. (1), and further obtain the encounter duration of these two users, as shown in Eq. (2).

$$\begin{aligned} & AVG_{u_a,u_b}^l \\ &= \begin{cases} 0 & t_{u_a}^l > t_{u_b}^l + \overline{d_{u_b,l}} \\ t_{u_b}^l + \overline{d_{u_b,l}} - t_{u_a}^l & t_{u_a}^l + \overline{d_{u_a,l}} > t_{u_b}^l + \overline{d_{u_b,l}} \\ & \quad > t_{u_a}^l \text{ and } t_{u_a}^l > t_{u_b}^l \\ \overline{d_{u_b,l}} & t_{u_b}^l > t_{u_a}^l \text{ and } t_{u_a}^l + \overline{d_{u_a,l}} \\ & \quad > t_{u_b}^l + \overline{d_{u_b,l}} \\ \overline{d_{u_a,l}} & t_{u_a}^l > t_{u_b}^l \text{ and } t_{u_b}^l + \overline{d_{u_b,l}} \\ & \quad > t_{u_a}^l + \overline{d_{u_a,l}} \\ t_{u_a}^l + \overline{d_{u_a,l}} - t_{u_b}^l & t_{u_a}^l + \overline{d_{u_a,l}} > t_{u_b}^l + \overline{d_{u_b,l}} > t_{u_a}^l \\ & \quad \text{and } t_{u_b}^l + \overline{d_{u_b,l}} > t_{u_a}^l + \overline{d_{u_a,l}} \\ 0 & t_{u_b}^l > t_{u_a}^l + \overline{d_{u_a,l}} \end{cases} \end{aligned} \tag{2}$$

In addition, for a given time window S, when user's statistical samples of historical trajectory are too small, or there are a large number of statistical samples whose encounter duration is less than the average duration, simply considering the encounter duration between users can not truly reflect the channel quality possessed by users for continuous and stable D2D communication. For this reason, we also need to consider the number of user encounters within the time window S, and the probability that the encounter duration is longer than the average duration. Combined with the above factors, the connection strength between any two users is define as Eq. (3). It indicates the probability that two users continuously and stably complete the data transmission in this encounter. The larger the value, the more likely the data transmission task will be completed.

$$W_{u_a,u_b}^l = L_{u_a,u_b}^s \cdot M_{u_a,u_b}^s + AVG_{u_a,u_b}^l \tag{3}$$

where W_{u_a,u_b}^l is the quantified weight of the connection strength. L_{u_a,u_b}^s is the probability that the encounter duration is greater than the average duration AVG_{u_a,u_b}^l in time window S. M_{u_a,u_b}^s represents the number of times that two users encounter in time window S.

According to the above methods, the user's mobility characteristics can be fully utilized to predict the possibility of two users continuously and stably completing data transmission in the next encounter. Therefore, considering the connection strength in resource allocation, the channel quality required for D2D communication can be effectively ensured.

B. MEASUREMENT OF USER RELATIONSHIPS

As shown in Fig. 2, the areas where users stay for longer are divided into two types, which correspond to intimacy and interest-driven social relationships respectively. In most regions, two types of social relationships co-exist but some regions are dominated by one type. Therefore, the measurement of social relationships cannot be proceeded from only one type alone, but should be combined with two types of social relationships in corresponding scenarios comprehensively.

For intimacy-driven social relationships, the strength of social relationships depends on the intimacy degree between users. In D2D dual-link enhanced communication, users with high intimacy degree are more likely to assist and share contents. Because social belonging, utility and reputation are the basic human aspirations, the above factors can play a potential incentive role in intimately-driven social relationships. In addition, due to users' subjectivity, the social relationships among users show asymmetric characteristics. Therefore, the measurement of social relationships between users should be proceed from each users' perspective. Specifically, using intimacy-driven factor S_{u_a,u_b} denotes the strength of intimacy-driven social relationships from the perspective of user u_a. With the increase of the value of S_{u_a,u_b}, the user u_a have both higher degree of intimacy and greater probability of mutual assistance with u_b.

In interest-driven social relationships, the strength of social relationships depends on the similar interests between two users. The more similar interests are, the greater the probability that users will need similar contents. Unlike intimate-driven mode, users may not be familiar with each other. When a user helps the others, the user will receive higher priority to be assisted as the revenue. Similarly, due to users' subjectivity, the measurement of social relationships between users should be proceed from different users' perspective. Specifically, interest-driven factor is denoted as D_{u_a,u_b} from the perspective of user u_a. With the increase of D_{u_a,u_b}, user u_a and u_b are more interested in similar content.

To sum up, in D2D dual-link enhanced communication, the social relationships between two users need to be considered from two aspects with users' subjective differences. With the increase of social relationship strength among users, they are more likely to be interested in similar contents, providing contents sharing to each other. From u_a's perspective, the strength of social relationship between u_a and u_b is given as

$$ST_{u_a,u_b} = \lambda \cdot S_{u_a,u_b} + (1-\lambda) \cdot D_{u_a,u_b} \tag{4}$$

where λ is the weight factor, which indicates the importance of intimacy or interest-driven social relationships in different scenarios respectively. The intimacy-driven factor S_{u_a,u_b} consists of n influencing factors, such as relatives, friends, colleagues and so on. K_x is the weight of each influencing factor, indicating its importance. $J_x^{u_a}$ is the samples similarity between users corresponding to the factor x. combined with n influencing factors' weight K_x and samples similarity $J_x^{u_a}$, the weight of intimacy-driven factor S_{u_a,u_b} can be obtained, as shown in Eq. (5). Similarly, the weight of interest-driven factor is shown in Eq. (6).

$$S_{u_a,u_b} = \sum_{x=0}^{n} K_x J_x^{u_a} \tag{5}$$

$$D_{u_a,u_b} = \sum_{y=0}^{m} K_y J_y^{u_a} \tag{6}$$

where $J_x^{u_a}$ denotes the sample similarity of influence factor x from u_a's perspective. When the sample similarity is higher, the social relationships between users is stronger. Due to users' subjectivity, u_a and u_b have different measurement results for the same influencing factor x. That is, p_{xu_a} which the same part of these two user's samples of influencing factor x measured based on the perspective of u_a, is different from the measurement results p_{xu_b} based on the perspective of u_b. Therefore, the ratio of $|p_{xu_a}|$ to $|p_{xu_a} \cup p_{xu_b}|$ can be used to represent the sample similarity of influence factor x from the perspective of u_a, as shown in Eq. (7). Similarly, the sample similarity J_y of the interest-driven influencing factor y is given by Eq. (8). Compared with Eq. (7), only the influencing factors considered are different. The former one belongs to the intimacy-driven factors, and the latter one belongs to the interest-driven factors.

$$J_x^{u_a} = \frac{|p_{xu_a}|}{|p_{xu_a} \cup p_{xu_b}|} \tag{7}$$

$$J_y^{u_a} = \frac{|p_{yu_a}|}{|p_{yu_a} \cup p_{yu_b}|} \tag{8}$$

According to Eq. (5) and Eq. (6), it can be seen that in different scenarios, the social relationship strength is determined by multiple intimacy and interest-driven factors. According to the weight proportion of these two types influencing factors, the weight factor λ is expressed as

$$\lambda = \frac{\sum_{x=0}^{n} K_x}{\sum_{y=0}^{m} K_y + \sum_{x=0}^{n} K_x} \tag{9}$$

C. MEASUREMENT OF USER THROUGHPUT

As mentioned above, we measure user's throughput in D2D dual-link enhanced communication as the prerequisite for resource allocation. Combined with user mobility and relationships, the throughput obtained by D2D and cellular users can be measured respectively.

First of all, the content similarity in D2D links and cellular downlinks needs to be considered. The strength of social relationship is positively related to the content similarity transmitted by the two links, which is composed of the intimacy and interest-driven factors. The interest-driven factor is greater, the more similar contents are cached in the D2D transmitters and CUs, and the probably that both users are interested in the similar contents is higher. The greater the intimacy-driven factor indicates the users more tend to assist in sharing similar contents. However, the dimensions are different between the social relationship strength and content similarity, so they need to be normalized. When the sample similarity between users is 1 under all influencing factors, the upper limit of the corresponding social relationship strength is taken as a baseline. The baseline is mapped to a situation where the contents similarity transmitted by these two links is 1. By calculating the ratio of social relationship strength to baseline, the content similarity is obtained as

$$CS_{u_a,u_b} = \frac{ST_{u_a,u_b}}{\lambda \sum_{x=0}^{n} K_x + (1-\lambda) \sum_{y=0}^{m} K_y} \tag{10}$$

The similar and difference contents transmitted in dual-link are regarded as received signals and noise respectively. The SNR of receiver is calculated by combining the content similarity and transmission power. Further, motivated by the previous research on dual-link communications [40], [41], the maximum transmission rate of the D2D receiver and CU can be calculated by Eq. (11) and Eq. (12).

$$\begin{aligned}&\Re^{i}_{D_{rcv}}(CS_{D_{trans},CU_j})\\&\quad = W \log\Big(1 + \frac{h_{D_{rcv},D_{trans}} p_{trans} + CS_{D_{trans},CU_j} g_{B,D_{rcv}} p_B}{\delta_{D_{rcv}} + (1 - CS_{D_{trans},CU_j}) g_{B,D_{rcv}} p_B}\Big)\end{aligned} \tag{11}$$

where Eq. (11) denotes the maximum transmission rate of receiver D_{rcv} in D2D link i. D_{trans} is the transmitter in D2D link i. CS_{D_{trans},CU_j} is the content similarity transmitted between the D2D link i and cellular link j from the perspective of D2D link i. p_{trans} and p_B are the transmit power of transmitter D_{trans} and BS respectively. $h_{D_{rcv},D_{trans}}$, $g_{B,D_{rcv}}$ are the channel gains from the D_{trans} and BS to D_{rcv} respectively. δ_{rcv} is the additive noise received by D_{rcv}, and W is the transmission bandwidth.

$$\Re^{i}_{CU_j}(CS_{CU_j,D_{trans}}) = W\log\left(1+\frac{h_{D_{trans},CU_j}p_{trans}CS_{CU_j,D_{trans}}+g_{B,CU_j}p_B}{\delta_{CU_j}+(1-CS_{CU_j,D_{trans}})p_{trans}h_{D_{trans},CU_j}}\right) \tag{12}$$

where Eq. (12) is the maximum transmission rate of CU_j whose downlink resources is reused by D2D link i. $CS_{CU_j,D_{trans}}$ represents the similarity of contents transmitted between the D2D link i and cellular link j from the perspective of CU_j. h_{D_{trans},CU_j}, g_{B,CU_j} are the channel gains from D_{trans} and BS to CU_j. δ_{CU_j} is the additive noise received by CU_j.

Secondly, as users usually move frequently, channel quality of the D2D communications is hard to guaranteed. Therefore, simply considering the maximum transmission rate cannot truly reflect the transmission benefits obtained by each user. Moreover, in D2D dual-link enhanced communication, CUs also need to obtain similar contents through D2D communication from the D2D transmitter. Therefore, in this paper, the stable communication duration is defined as the length of time during which the D2D receiver and CU maintain the D2D communication range relative to the D2D transmitter. In this case, the D2D transmitter, receiver and CU are in the same area, and the connection strength of these users is calculated by Eq. (3) respectively. Then the minimum weight is selected as the stable communication duration, as shown in Eq. (13).

$$W^{l}_{i,CU_j} = \min\{W^{l}_{D_{trans},D_{rcv}}, W^{l}_{CU_j,D_{rcv}}, W^{l}_{CU_j,D_{trans}}\} \tag{13}$$

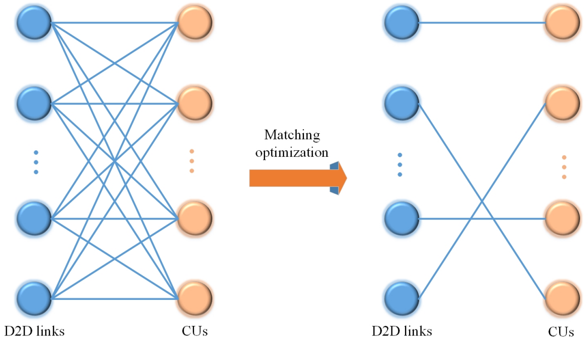
Combined with stable communication duration and maximum transmission rate, the throughput obtained by D2D and cellular users can be measured. When D2D link i multiplexing the spectrum resources of CU cu_j, the throughput obtained by the receiver in D2D link i can be calculated as Eq. (14). When the transmitter continues to send contents, the user with better throughput can get more needed contents and the probability of completing the transmission service is higher.

$$\varphi_{i,CU_j} = W^{l}_{i,CU_j} \cdot \Re^{i}_{D_{rcv}}(CS_{D_{trans},CU_j}) \tag{14}$$

Similarly, according to Eq. (12) and Eq. (13), the throughput obtained by CU_j is given as

$$\varphi_{CU_j,i} = W^{l}_{i,CU_j} \cdot \Re^{i}_{CU_j}(CS_{CU_j,D_{trans}}) \tag{15}$$

Moreover, most traditional D2D resource allocation solutions are aim at maximizing the network throughput while ignoring the service satisfaction of each user. In the process of resource allocation, some of the users' service experience has been sacrificed. Motivated by this, in this paper, an optimization problem about resource allocation is formulated and solved with objective to maximizing the user satisfaction which achieves a good tradeoff between the network throughput and user satisfaction.



a.Establish preferences sequence

b.The maximum weight match

FIGURE 3. 1-1 Two-sided satisfied matching based on preference order.

V. USER SATISFACTION-AWARE RESOURCE ALLOCATION

In D2D dual-link enhanced communication, the spectrum resource allocation is the frequency band selection and reuse process for CUs. In fact, this process can be seen as a one-to-one matching optimization problem between D2D links and CUs. The successful matching between one D2D link and one CU indicates that this CU's spectrum resource is multiplexed to form a dual-link enhanced communication. As shown in Fig. 3.a, different D2D links have a variety of CUs' resources to reuse. According to Eq. (14) and Eq. (15), the throughput obtained by D2D and cellular users varies with different matching options. Based on the throughput obtained by each user in different matching options, its preference order of the other side is given. After selecting the other side with higher preference order to match, users can obtain better throughput and satisfaction. In summary, the user satisfaction is closely related to matching preference order between D2D links and CUs.

For a match between D2D links and CUs, the user satisfaction obtained by these two sides is different. The purpose of this paper is to ensure that both D2D and cellular users get better satisfaction. Therefore, in the matching process, the user satisfaction of both D2D and cellular users is taken into consideration simultaneously. Further, the resource allocation problem is equivalent to 1-1 two-sided satisfied matching optimization problem based on preference order, as shown in Fig. 3.b. The goal is to maximize the total matching weight, that is, to maximize the sum of user satisfaction.

In order to solve the matching optimization problem, we proposes a 1-1 Two-sided Satisfied Matching Algorithm Based on Preference Order, in which two phases are required. The first one is initialization phase. Firstly, the two-sided users to be matched are determined according to specific service scenario, that is, the D2D links set and CUs set in this paper. Secondly, according to the throughput obtained, each user's preference order of the other side is given from their own perspective; the second one is the decision-making analysis phase. Firstly, we introduce a user satisfaction function to establish the functional relationship between satisfaction and preference order. Based on this, a two-sided satisfied matching optimization model is constructed. Then, according to the number of D2D links and CUs and the relationship between exact and perfect match, the optimization model is simplified to standard assignment model, which can be solved by Hungarian algorithm.

A. USER SATISFACTION CALCULATION

As mentioned above, the matching preference order between D2D links and CUs is closely related to user satisfaction. This paper introduces user satisfaction function to establish the functional relationship between satisfaction and preference order. Then the user satisfaction is obtained through matching preference order based on the throughput. For concise expression, we denote $A = \{A_1, A_2, \cdots A_{m'}\}$ and $B = \{B_1, B_2, \cdots B_{n'}\}$ as the D2D links set and CUs set, including m' D2D links and n' CUs respectively. Their subscript sets are represented as $I = \{1, 2, 3 \cdots m'\}$, $C = \{1, 2, 3 \cdots n'\}$.

Moreover, for convenience of analysis, a preference order matrix between two-sided users is constructed. r_{ij}, $i \in I$, $j \in C$ represents the matching preference order of CU j from the perspective of D2D link i. The preference order can be formulated according to the value of Eq. (14), from big to small, sequentially ranked from 1 to n'. That is, with the increase of the throughput obtained by the D2D user in the match, the CU's preference order for it is higher. Similarly, v_{ij}, $i \in I, j \in C$ is the matching preference order of D2D link i from the perspective of CU j, the order ranked by the value of Eq. (15) descending from 1 to m'.

Based on the above works, the preference order matrix of D2D links to CUs is constructed, as shown in Eq. (16). The rows and columns of the matrix represent the subscripts of D2D links and the CUs, respectively.

$$R = [r_{ij}]_{m' \times n'} \tag{16}$$

Similarly, the preference order matrix of CUs to D2D links is constructed, as shown in Eq. (17). The rows and columns of the matrix have the same meaning as in Eq. (16).

$$V = [v_{ij}]_{m' \times n'} \tag{17}$$

In the two-sided satisfied matching optimization problem, the preference information given by both two-sided users is preference order. If D2D link A_i ranks CU B_j before B_k, it indicates that user satisfaction obtained by D2D link A_i after matching with B_j is higher than B_k. In order to meet human's thinking habits, satisfaction is defined in the range 0 to 1. It can be seen that user satisfaction and matching preference orders among users are positively correlated. Motivated by this, we introduce user satisfaction function to establish the functional relationship between satisfaction and preference order.

We define τ_{ij}, τ'_{ij} as D2D receiver and CU's satisfaction respectively, after D2D link i matches with CU j. User satisfaction is a function of preference order, expressed as

$$\tau_{ij} = \phi(r_{ij}) \quad i \in I;\ j \in C \tag{18}$$

$$\tau'_{ij} = \phi(v_{ij}) \quad i \in I;\ j \in C \tag{19}$$

When a D2D link has matched a CU with relatively high preference order, the throughput occupied by it is already saturated. Continuing to assign a CU with better preference order will only consume a large amount of resources with minimal gain. In contrast, when a D2D link matches a CU with fairly low preference order, the throughput occupied by it is quite scarce. Assigning a CU with higher preference order to it will greatly enhance its user satisfaction. Motivated by this, the relationship between user satisfaction and preference order is nonlinear. As the preference order increases, user satisfaction gradually increases and the growth rate gradually slows down and stabilizes. Then, the satisfaction function $\phi(\cdot)$ can be defined as

$$\phi(z) = -(\frac{z-1}{\theta})^2 + 1, \quad z \in N \tag{20}$$

where z is the preference order. $\theta = \max\{m', n'\}$ denotes a pre-configured parameter which is used to pulled up the curve of satisfaction function laterally. To ensure that the satisfaction function is positive in defined domain, the value of θ is higher when there are more users in the scenario. Specifically, $\phi(\cdot)$ is a strictly monotonically decreasing function with $\phi(1) = 1$. That is, when the preference order is higher, the satisfaction is higher. The first derivative of $\phi(\cdot)$ is ${}^{-2z+2}\!/_{\theta^2}$. Therefore, with the increase of independent variables, $\phi(\cdot)$ declines faster and faster, the change of initial function value is not obvious. In summary, the satisfaction function $\phi(\cdot)$ meets the requirements mentioned above.

The objective function of this paper is to maximize the sum of user satisfaction, so the matching weight is the sum of user satisfaction, as shown in Eq. (21).

$$\sigma_{ij} = (\tau_{ij} + \tau'_{ij}) + \upsilon(\left|\tau_{ij} - \tau'_{ij}\right|) \quad i \in I,\ j \in C \tag{21}$$

where $\upsilon(\left|\tau_{ij} - \tau'_{ij}\right|)$ is a preference adjustment function. If the difference in user satisfaction between two-sided users in a match is not considered, then $\upsilon(\cdot) = 0$. If the difference need to be limited, then setting $\upsilon(\cdot)$ as a decreasing function.

Further, in order to facilitate the calculation, the matching weight σ_{ij} is normalized as

$$\omega_{ij} = \sigma_{ij} \Big/ \max_{i,j} \sigma_{ij}, \quad i \in I,\ j \in C \tag{22}$$

B. ESTABLISHMENT AND SOLUTION OF MATCHING MODEL

The method to determine the matching weights between D2D links and CUs is given above. Based on this, we can solve the two-sided satisfied matching optimization problem by using max-weight matching model on complete bipartite graph. In order to establish the max-weight matching model, the relationship between exact match and perfect match must be analyzed. Based on the definition of exact match, perfect match and relative concept of weighted matching in bipartite graph, Theorem 1 is derived as

Theorem 1: In two-sided matching based on preference orders, if both users are $A = \{A_1, A_2, \cdots A_{m'}\}$ and

$B = \{B_1, B_2, \cdots B_{n'}\}$, when $m' < n'$ the corresponding max-weight match is an exact match of A to B, and a perfect match when $m' = n'$.

Proof: When $m' < n'$, assuming M is the max-weight match of A to B, the number of sides for M is q. Assuming M is not an exact match of A to B, then it can be obtained that $q < m' < n'$. That is, there are several users that are not matched in A and B simultaneously. Assuming $A_l \in A$ and $B_k \in B$ are not matched, we add a matching edge e_{lk} to the original match M to form a new match M'. Since the corresponding value of edge e_{lk} is greater than 0, we can get $\Psi(M') > \Psi(M)$. so that, M is not the max-weight match. Therefore, the assumption does not hold, at least one of A_l and B_k has been matched. Due to $m' < n'$, users in set A are all matched and M is the exact match of A to B. Similarly, when $m' = n'$, M is the perfect match.

For concise description, D2D links and CUs in two-sided matching are recorded as nodes next. According to Theorem 1, when $m' < n'$, that is, the number of D2D links is smaller than CUs, the max-weight matching must be an exact match of A to B. In the optimal solution, the nodes in set A are all saturated, while the nodes in B will not be all matched. This max-weight matching problem can be represented by the following maximum integer programming model:

$$\max f_1 = \sum_{i=1}^{m'} \sum_{j=1}^{n'} \omega_{ij} x_{ij} \tag{23}$$

$$\sum_{j=1}^{n'} x_{ij} = 1, \quad i \in I \tag{24}$$

$$\sum_{i=1}^{m'} x_{ij} \leq 1, \quad j \in C \tag{25}$$

$$x_{ij} = 0 \quad or\ 1, \quad i \in I,\ j \in C \tag{26}$$

where Eq. (23) is the objective function to maximize the sum of user satisfaction. Constraints Eq. (24) and Eq. (25) ensure that each link in D2D links set A has one and only one edge to CUs. what's more, the nodes in CUs set B are not saturated. In Eq. (26), $x_{ij} = 0$ indicates that D2D link i is not matched with CU j and matched when the value is 1.

To solve this integer programming model, we add $n' - m'$ virtual nodes in A. The added virtual nodes $A_{m'+1}, \ldots, A_{n'}$ update the original D2D links set to $A' = \{A_1, A_2, \cdots A_{m'}, A_{m'+1}, \ldots, A_{n'}\}$. Then, the edges between virtual nodes and all CUs are added with a weight of 0, so as to get the new matching weight $\overline{\omega_{ij}}$, as shown in Eq. (27).

$$\overline{\omega_{ij}} = \begin{cases} \omega_{ij}, & i = 1, 2, \ldots, m';\ j = 1, 2, \ldots, n' \\ 0, & i = m' + 1, \ldots, n';\ j = 1, 2, \ldots, n' \end{cases} \tag{27}$$

After adding virtual nodes, a new weighted bipartite graph G' is formed between A' and B. Since the number of nodes in two sets is the same, the max-weight match between the two sets is a perfect match based on theorem 1. After remove edges with weight of 0 in the perfect match, the max-weight matching of original bipartite graph can be obtained. Then we can transform the integer programming model represented by Eq. (23) into:

$$\max f_2 = \sum_{i=1}^{n'} \sum_{j=1}^{n'} \overline{\omega_{ij}} x_{ij} \tag{28}$$

$$\sum_{j=1}^{n'} x_{ij} = 1, \quad i \in C \tag{29}$$

$$\sum_{i=1}^{n'} x_{ij} = 1, \quad j \in C \tag{30}$$

$$x_{ij} = 0 \quad or\ 1, \quad i \in C,\ j \in C \tag{31}$$

Compared with Eq. (23), Eq. (28) adds virtual nodes to convert the problem into a perfect match. If m'=n' in the initial phase, there is no need to go through the virtual node adding process. For the convenience of solving the above matching model, it is further transformed into:

$$\min f_3 = \sum_{i=1}^{n'} \sum_{j=1}^{n'} (\overline{\omega_{ij}}^{*} - \overline{\omega_{ij}}) x_{ij} \tag{32}$$

$$\sum_{j=1}^{n'} x_{ij} = 1, \quad i \in C \tag{33}$$

$$\sum_{i=1}^{n'} x_{ij} = 1, \quad j \in C \tag{34}$$

$$x_{ij} = 0 \quad or\ 1, \quad i \in C,\ j \in C \tag{35}$$

where in Eq. (32) $\underset{i,j\in(1,2,\ldots,n)}{\overline{\omega_{ij}}^{*}} = \max\{\omega_{ij}\}$, the model is a common standard assignment model. As a typical algorithm of standard assignment model, it can be solved by Hungarian algorithm to get the maximum bipartite graph matching [42]. In order to save space, the solution process will not be described again.

In summary, the resource allocation scheme proposed in this paper is summarized as following Algorithm 1.

VI. PERFORMANCE EVALUATION

In this section, we evaluate the performance of proposed TSMA algorithm based on D2D dual-link enhanced communication model in MATLAB. The simulation is carried out in a single cell scenario, in which there are multiple hot spot areas. We choose a hot spot area to allocate resources, in which 5 pairs of D2D links and 5 to 68 CUs are randomly distributed. Both path-loss model and shadow fading are considered for cellular and D2D links. The wireless propagation is modeled according to WINNER II channel models [43]. D2D channel is based on office/indoor scenario while cellular channel is based on the urban microcell scenario. The path-loss exponent for free space propagation path-loss model is set to be 4. The main parameters used in our simulation are listed in Table 1.

Algorithm 1 1-1 Two-sided Satisfied Matching Algorithm Based on Preference Order

```
**Initialization phase**
A set of D2D links $A = \{A_1, A_2, \cdots A_{m'}\}$;
A set of CSs $B = \{B_1, B_2, \cdots B_{n'}\}$;
**Input**: $A$, $B$;
**Output**: $r_{ij}$, $v_{ij}$, $R$, $V$;
**for** $A_i \in A$ **do**
    **for** $B_j \in B$ **do**
        Calculate the performance gain $\varphi_{i,CU_j}$, $\varphi_{CU_j,i}$, separately of D2D links and CUs by using Eq. (14), Eq. (15).
        Establish the preference list $r_{ij}$ and $v_{ij}$ by sorting the throughput in descending order.
    **end for**
**end for**
**Decision-making analysis phase**
Convert the preference order to satisfaction by using Eq. (18), Eq. (19), Eq. (20).
Get the comprehensive satisfaction matching weight $\omega_{ij}$;

**if** $m' < n'$ **then**
    Formulate the integer programming model by using Eq. (23) to Eq. (26) and then convert it to perfect matching problem by adding virtual nodes;
**else**
    **if** $m' = n'$ **then**
        Formulate the integer programming mode directly by using Eq. (28) to Eq. (31);
    **end if**
**end if**
Convert the perfect matching problem to standard assignment model and solve it by Hungarian algorithm;
**END**
```

TABLE 1. Simulation parameters.

Parameter	Value
The radius of the cell	500 m
Noise spectral density	174dbm/Hz
Transmission bandwidth	15MHz
Transmit power of UEs	23dbm
Transmit power of eNB	46dbm
MAX D2D transmission distance	30m
The radius of the hot spot area	50m
Number of D2D links	5
Number of CUs	68

Without loss of generality, we use human mobility trace datasets Infocom 06 in performance evaluation, which is real mobility trace and encounter of users [44]. The datasets records 78 participants' trajectories during the conference IEEE Infocom 2006. Among them, there are 20 static nods deployed in different areas to record the movement trajectories of other users. The coverage area of each static node is a hot spot area. In addition, this dataset contains participants' social characteristics information including citizenship, school, language and job title, which is used to construct social relationships among them.

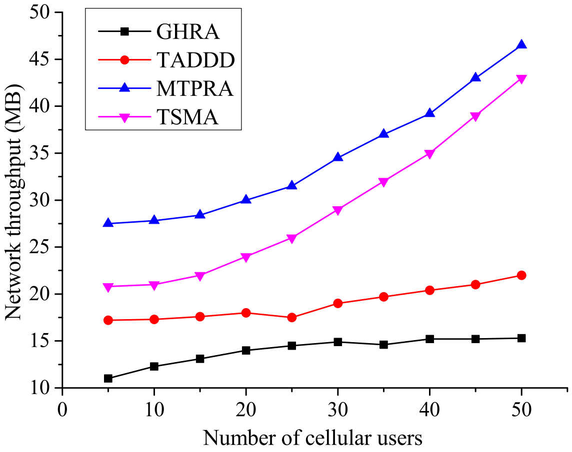


FIGURE 4. Network throughput.

The algorithm proposed in this paper is compared with three typical resource allocation schemes. The first is Greedy Heuristic Radio Resource Allocation Algorithm (GHRA) [45], which allocate CU's spectrum resources with remote physical locations and better channel quality for D2D users. The second is Three-phase Approach for D2D Data Dissemination (TADDD) [37], which selects the seed node to allocate spectrum resources, and then forward data among socially connected and cooperative users through two phases respectively. The third one is Maximize Transmission Performance Resource Allocation (MTPRA), which adopts the D2D dual-link enhanced communication model proposed in this paper to maximize the network throughput. The main performance indicators include the network throughput, transmission rate, transmission success rate, user satisfaction and spectrum efficiency which indicates contents transmit by 5 pairs of D2D users and corresponding multiplexed CUs in unit spectrum resource.

Network throughput under various number of CUs in the hot spot area is shown in Fig. 4. With the growth of the number of CUs, the network throughput of proposed algorithm TSMA and comparison scheme MTPRA both increase faster and faster, the gap between the two schemes is gradually narrowed; the network throughput of comparison schemes GHRA increases rapidly at the beginning and then remains unchanged. The main reason is that, as the number of CUs increases, the benefit of allocating resources by location preference to avoid interference has reached the limit; Due to the adoption of multi-phase transmission mode, the network throughput of comparison schemes TDAAA is increasing slowly. Numerical results show that the network throughput of TSMA compared with TADDD and GHRA is improved by 20.9% and 89.1% on average.

Fig. 5 demonstrates the change in number of D2D and CUs whose maximum transmission rate is below a certain threshold, with the increasing number of CUs in the hot spot area. GHRA adopts the traditional resource allocation scheme,

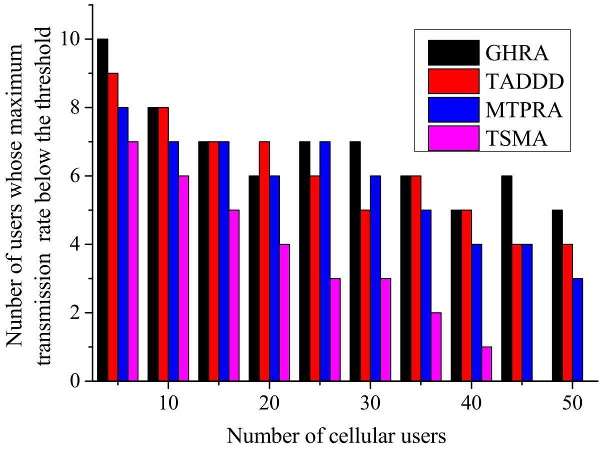


FIGURE 5. Users' maximum transmission rate.

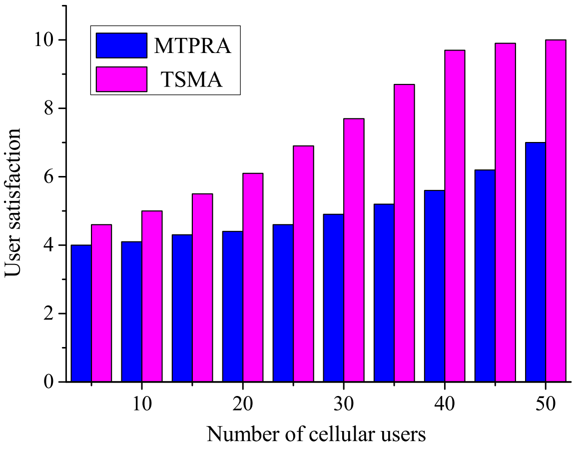


FIGURE 6. User satisfaction.

which can avoid the co-channel interference and improve the transmission rate of users to a certain extent; the user's transmission rate benefits from social relations in TADDD, but it is not obvious without considering transmission rate; As the social relationships between users becomes stronger, the advantages of TSMA and MTPRA adopting dual-link communication are more obvious. So the number of users whose transmission rate is below the threshold decreases rapidly. Compared with the other three resource allocation schemes, our proposed TSMA fully considers the transmission rate of each user. Therefore, the number of users below the threshold is the least, and decreases rapidly until to 0.

Fig. 6 demonstrates the change of user satisfaction in MTPRA and TSMA with the increasing number of CUs in the hot spot area. Our proposed TSMA can guarantee the service experience of each user better than MTPRA. When alternative CUs reach a certain number, the user satisfaction is close to the upper limit. Numerical results show that the user satisfaction of TSMA is improved by 32.2% compared with MTPRA on average.

Fig. 7 illustrates the transmission success rate under various numbers of CUs. The transmission success rates of TSMA, MTPRA, TADDD and GHRA boht increase with

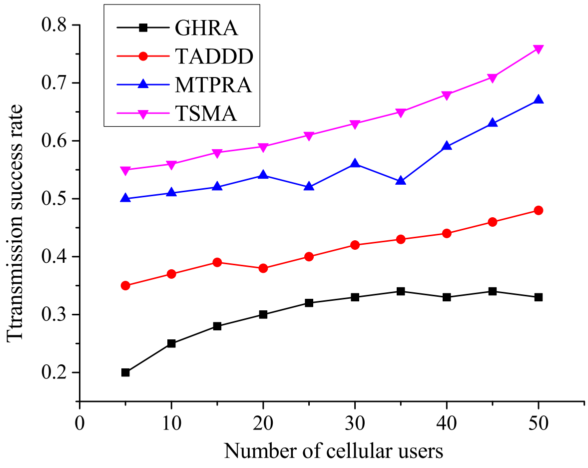


FIGURE 7. Transmission success rate.

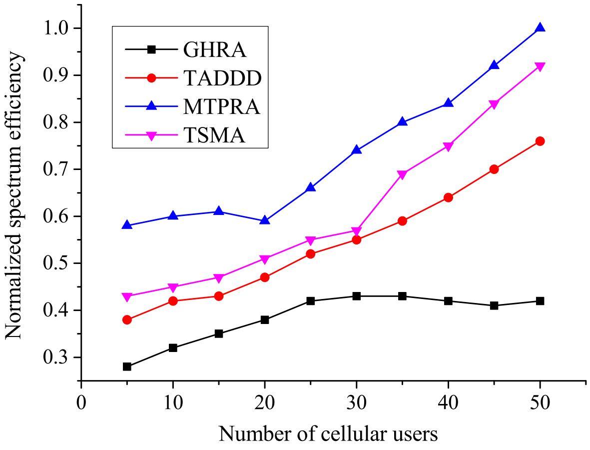


FIGURE 8. Normalized spectrum efficiency.

the growth of the number of CUs. Considering each user's throught, our proposed TSMA allocates spectrum resources more evenly than MTPRA, so the overall transmission success rate is higher. Numerical results show that the transmission success rate of TSMA compared with MTPRA, TADDD and GHRA is improved by 13.5%, 53.4% and 109.31% respectively.

Fig. 8 demonstrates the change in normalized spectrum efficiency of different schemes with the increasing number of CUs. Numerical results show that the normalized spectrum efficiency of TSMA compared with TDAAA and GHRA is improved by 13.2% and 53.6% respectively. As the number of CUs increases, the advantages of TSMA are more obvious. In addition, the gap between TSMA and MTPRA narrows with the strengthen of social relationships among users.

VII. CONCLUSION

In order to improve D2D and cellular users' satisfaction with limited spectrum resources simultaneously, in this paper, we propose a D2D dual-link enhanced communication model that combines two links to reuse the same spectrum resource and transmit similar contents to users at the same time.

In addition, based on the mobility and social relationships among users, the BS dynamically obtains each user's benefits and corresponding preference orders under different resource allocation choices. Furthermore, a Two-sided Satisfied Matching Algorithm Based on Preference Order is proposed to allocate spectrum resources in order to deliver the best user satisfaction. Comprehensive simulation results demonstrate that the proposed scheme can significantly improve each user's satisfaction and throughput under limited spectrum resources.

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