A Novel Social Aware Reverse Relay Selection Scheme for Underlaying Multi-Hop D2D Communications

Liang Li[1], Xinjie Yang[1,2,3*], Yuanjie Zheng[4], and Jiazhi Yang[1]
[1] Faculty of Electrical Engineering and Computer Science, Ningbo University
Ningbo, ZJ 315211 China
[e-mail: 2011082114@nbu.edu.cn, yangxinjie@nbu.edu.cn, 2211100163@nbu.edu.cn]
[2] State key Laboratory of Networking and Switching Technology,
Beijing University of Posts and Telecommunications, Beijing, 100876 China
[3] Ningbo ArrowDeep Internet Technology Co., Ltd.
Ningbo, ZJ 315021 China
[e-mail: yangxinjie@arrowdeep.com]
[4] Ningbo Edge IoT Technology Co., Ltd.
Ningbo, ZJ 315211 China
[e-mail: zhengyj@25soft.com]
[*]Corresponding author: Xinjie Yang

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Abstract

Device-to-Device (D2D) communication has received increasing attention and been studied extensively thanks to its advantages in improving spectral efficiency and energy efficiency of cellular networks. This paper proposes a novel relay selection algorithm for multi-hop full-duplex D2D communications underlaying cellular networks. By selecting the relay of each hop in a reverse manner, the proposed algorithm reduces the heavy signaling overhead that traditional relay selection algorithms introduce. In addition, the social domain information of mobile terminals is taken into consideration and its influence on the performance of D2D communications studied, which is found significant enough not to be overlooked. Moreover, simulations show that the proposed algorithm, in absence of social relationship information, improves data throughput by around 70% and 7% and energy efficiency by 64% and 6%, compared with two benchmark algorithms, when D2D distance is 260 meters. In a more practical implementation considering social relationship information, although the proposed algorithm naturally achieves less throughput, it substantially increases the energy efficiency than the benchmarks.

Keywords: Device-to-device, full-duplex, multi-hop, relay selection, social aware.

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1. Introduction

Recent years have seen an upsurge of smart wireless terminals and the explosive increase of mobile subscribers thanks to the rapid development of Internet industry and the adoption of advanced mobile communication technologies [1]. Providing services to so many users increases the network load and worsens many known network issues such as scarce yet under-utilized spectrum resources. Researchers have therefore proposed Device-to-Device (D2D) communications that allows two nearby devices to directly communicate without the intervention from the base station (BS) [2]. Direct data exchange between two adjacent mobile devices underlaying conventional cellular network can improve spectrum usage and transmission latency [3]. Moreover, the D2D technology provides high-speed data transmission that operates with or without the existence of a BS [4].

D2D communications can be classified into inband and outband operation modes, based on the spectrum band exploitation [5]. The former, where D2D links are allowed to reuse the licensed cellular spectrum, can significantly improve spectrum utilization, helping mitigate the spectrum shortage problem. Moreover, it demonstrates potentials to improve data throughput, energy efficiency, delay, and user fairness [6]. Thanks to the various advantages, inband D2D has been chosen by the global standardization body 3GPP (the 3rd Generation Partnership Project) as one of the key technologies for 5G systems and beyond. It thereafter has rapidly attracted increasing research interests globally in further developing D2D technologies in various aspects.

However, it is also discovered that direct D2D communication can suffer from problems such as short communication distance, high device power consumption, and sometimes severe interference to/from cellular networks. To tackle these problems, relay devices can be used to enable longer D2D distance to form multi-hop D2D communications. Different devices acting as relays can lead to considerably varying performances of D2D links because of different relay distance, channel quality, etc. Therefore, the selection of relays is one of the key challenges in D2D relay communications [7].

The relays were assumed half-duplex in the early studies of D2D relay selection to avoid self and other user interference. It intrinsically limits D2D link performances. Full-duplex improves the spectral efficiency of overall system [8], however, introduces so-called self-interference [9]. Various advanced interference mitigation/cancellation techniques [10] [11] are available to significantly mitigate such interference. Using frequency division duplex (FDD) mode for relays can also alleviate this problem.

When modelling practical mobile communications, researchers are made aware that the device selected as a relay may not be entirely willing to help the D2D device forward data. This means that the device with good channel quality may refuse to use its full or partial transmit power for the relay link. The willingness of the device/user can be modeled by social interaction information between users and therefore is referred to as social factor. Its role and impacts on the multi-hop D2D communications have not been thoroughly studied in literature.

The rest of this paper is organized as follows. In Section 2, some related works are surveyed and summarized. The system model is constructed in Section 3, which covers both physical and social domains. Section 4 introduces a social-aware relay selection algorithm. Section 5 verifies the performance of the proposed algorithm, and the conclusions are drawn in Section 6.

2. Related Work

Different from previous researchers who choose single relay selection criterion, Xia et al. [12] studied two-hop D2D communications and proposes a relay selection strategy that can be based on either the relay's CSI (Channel State Information) or distance, depending on the radio link quality. Moreover, Ma et al. [13] propose a relay selection algorithm for full-duplex relay based D2D networks. It demonstrates better power efficiency of mobile devices compared to half-duplex devices.

The above-mentioned works assume the algorithms be executed in the BS, wherein excessive signaling is generated. Therefore, researchers have studied relay selection algorithms that do not require the participation of the BS. For instance, a timer-based relay selection method proposed in [14] can determine the best relay in a distributed manner. Its performance is close to that of the centralized optimal method. A device-centric relay selection scheme is proposed in [15], which obtains the common neighboring devices of D2D devices and selects relays based on various parameters, such as SINR, link capacity, residual energy, buffer space, and reliability. However, these distributed schemes only work in the ideal situations because the information assumed accessible to D2D devices may not be practically available to the terminals in real-life systems.

D2D performance could be enhanced by extending from two-hop to multi-hop relay to achieve larger D2D communication range. In [16], a D2D multi-hop routing algorithm based on the Dijkstra's algorithm is proposed and compared with the exhaustive search algorithm. In [17], an adaptive interference-aware multi-hop path selection algorithm is proposed, where the D2D path consists of "escape", "migrate" and "return" parts. This algorithm considerably enhances the overall network capacity with only a fractional capacity loss of overlaying cellular network. Unlike previous works that focus on relay selection algorithms, Wen et al. [18] analyze the upper bound of achievable D2D link throughput of a multi-hop D2D system assuming half-duplex relays in time-division duplex mode.

The above-mentioned works demonstrate that relay-assisted transmission can effectively improve the performance of D2D networks. However, they all imply that the relay device is willing to help forward data, which may not be the case in real-life. Researchers therefore introduce the social domain of the devices into the D2D studies. It is reported that this can more accurately and sometimes more effectively address technical issues and improve system performances [19].

Hu et al. [20] propose a social-aware relay selection algorithm where the selfish and trusty relationship between users is considered. The strength (strong or weak) of the social relationship between users is modelled by analyzing their historical information of location check-in and access to interest communities. The strength of the social relationship is used as an important input to determine the most suitable relay. Considering that most relevant works only consider social information of the transmitter and the relay, Wang et al. [21] propose a relay selection scheme that is based on the social relationship between the transmitter and relays and between the receiver and relays. Furthermore, D2D relay selection with social information is studied in IoT (Internet of Things) networks. For instance, Chen et al. [22] propose a relay selection algorithm incorporating trust probability of D2D connections derived from a ranking-based trust model. This algorithm works in a distributed manner and its performance is close to that of the exhaustive relay search.

In summary, most studies on relay selection in multi-hop D2D communications so far are based on half-duplex relay and lack considerations of the algorithm complexity and its impacts on execution and implementation. To solve the issue, distributed D2D schemes are proposed but assume that all the required information is available to the terminals. Furthermore, the impacts of social domain information on the system performance are not sufficiently studied particularly in multi-hop full-duplex based D2D communications. Therefore, in this paper, a novel relay selection algorithm is proposed for multi-hop full-duplex D2D communications underlaying cellular networks. The aim is to improve system performance and to guarantee link stability. The algorithm considers the willingness of relay devices and purposely select the relays in a reverse order.

The main contributions of this paper are summarized as follows:

(1) A reverse relay selection algorithm is proposed for multi-hop full-duplex D2D communications underlaying cellular networks, where the relays are selected from last relay link backwards to the first link. Such design allows the algorithm to be executed in a semi-distributed mode and significantly reduces the role of BS hence resulting in less signalling overload.

(2) The social relationship between users is taken into account. The social relationship is based on a model derived from real-life data between the candidate relays and the D2D source and destination.

(3) When designing the cellular user channel reuse scheme, two special considerations are taken to assure the quality of service (QoS) of cellular users not degraded. Firstly, a protection area is introduced wherein a cellular user will not share its channel with D2D devices. Secondly, the channel-sharing cellular users are distant enough from D2D devices to minimize interference between them.

(4) The proposed algorithm is thoroughly analyzed and its performances are simulated and compared against two benchmark algorithms. It shows that the system throughput and power efficiency considerably outperform the benchmark algorithms.

3. System Model

The system model considered in this paper is shown in **Fig. 1**. The system consists of a BS located at the center of the cell, a number of active cellular equipment (CE) communicating with BS, some idle equipment (IE), source (S) and destination (D) of the D2D communication, and a number of relays (R) that are selected from IEs to form a multi-hop link to forward data from S to D. It is assumed that all devices are equipped with two antennas. We consider only the uplink communication of the cellular, where the uplink channels of all CEs are orthogonal to each other. The red lines indicate the uplink channels from CEs to BS. The solid black lines indicate channels from S to D via relays. The dotted black line indicates that there might be more relays over S to D path which are not shown in the figure.

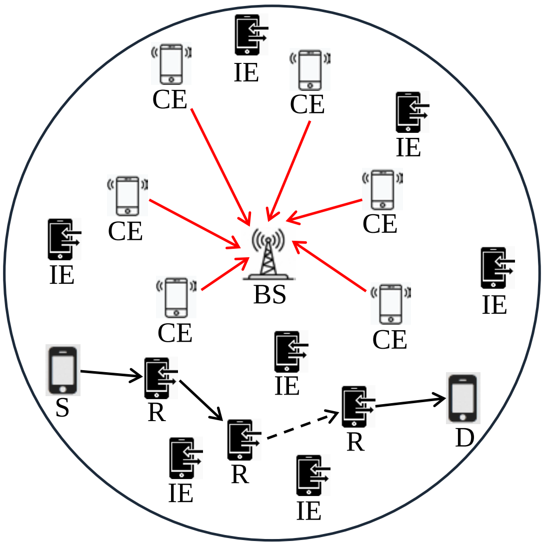

Fig. 1. System model for multi-hop D2D communications coexisted with cellular network

To improve spectral efficiency, multi-hop D2D inband operation mode is assumed where D2D devices reuse CEs' uplink channels. This means that the D2D links will interfere the CEs' uplinks at the BS. It is designed so due to the fact that in cellular networks, uplink channel is generally underutilized due to less data to transmit and the BS is a central node and can eliminate the other user interference more effectively than the CEs.

3.1 Channel Model

It is assumed that all wireless channels between two nodes are line-of-sight, therefore, the slow fading is not considered. The channel model consists of a distance-based path loss model and independent and identically distributed Rayleigh fading channels. Therefore, the received signal power of node y from transmitter node x is:

$$P_x^y = P_x h_x^y (d_x^y)^{-\alpha} \tag{1}$$

$$h_x^y = |h_0|^2 \tag{2}$$

where P_x denotes the transmit power of node x, h_x^y denotes the channel coefficient from x to y, d_x^y denotes the distance between x and y, α denotes the path loss exponent, and h_0 follows the complex Gaussian distribution with zero mean and unit variance.

3.2 Social Relationship Model

In practical D2D communications, the users of selected relays may not be willing to act as a relay for others or contribute part of its battery power to forward others' data because the power resource of the devices is limited. On the other hand, two people are more likely to help each other if they are close in real life. Taking into account these two factors, we introduce social relationships into the relay selection algorithm.

In real life, two people who are more closely related contact each other more frequently with longer communication time (such as phone calls and social media interactions), and vice versa. Please note that this is based on statistical data and there exists cases where strong social links do not represent good relationship. In this paper, the frequency and duration of online contacts between users are used to measure the strength of their social relationships, as shown below:

$$u_{i,j}=\left(\frac{T_{i,j}}{\sum T_{i,k}}+\frac{D_{i,j}}{\sum D_{i,k}}\right)/2 \tag{3}$$

where $u_{i,j}$ denotes the strength of social relationship between user j and user i and it is in the range of [0,1]. $T_{i,j}$ and $D_{i,j}$ denote the contact frequency and the total contact duration between them, respectively, $\sum T_{i,k}$ and $\sum D_{i,k}$ denote the sum of contact frequency and the sum of contact duration between user i and all other users, respectively.

According to the study of real-life social media data in [23], most users have strong social relationships with only a few other users, which can be rather accurately modeled by the pareto distribution. In this study, the pareto distribution is employed to model the strength of social relationships of (relay, S) and (relay, D) that are consequently applied to cap the relay's transmit power.

Using $u_{\mathrm{S},j}$ and $u_{\mathrm{D},j}$ to denote the strength of the social relationship between device j and S, D, respectively. When device j is selected as a relay, its transmit power's upper bound is then adjusted to:

$$P_j^{'}=\max\{u_{\mathrm{S},j},u_{\mathrm{D},j}\}\cdot P_{max} \tag{4}$$

where P_{max} indicates the maximum transmit power of the IE.

4. Relay Selection Algorithm

We consider the scenario where S initiates a data transfer to D by D2D communication. However, they are too distant that the communication can only be successfully established with the help of multiple relays selected from IEs. Hence, how to select relays from IEs is the key issue to solve. In this work, we propose a three-phased reverse relay selection algorithm as described below. Please note that in the D2D communications with or without relays, there exists an important step which is device discovery. This process enables a device to sense neighboring devices as D2D destination or relays. It is assumed that device discovery is performed and is not within the scope of the proposed algorithm.

4.1 Phase-1: Determine the Candidate Relays

The ideal relays can be selected by exhaustively examining all IEs in the cell. However, this leads to excessive complexity of the algorithm and is unsuitable for practical implementation. Inspired by the research works of relay selection and routing strategies in multi-hop cognitive wireless networks [24] and cognitive relay networks [25], and to keep the algorithm complexity low, we propose a cluster-based relay determination scheme, in which only IEs in certain regions (clusters) are considered as candidate relays.

Assuming that the distance between S and D is $d_{\mathrm{S}}^{\mathrm{D}}$ and M-1 relays are needed (i.e. M hops, $M\geq3$). Each relay will be selected from IEs located in its cluster. The locations of the clusters are determined by the direct line between S and D. Please note that the sizes of the clusters are dependent on the device discovery process and can be pre-defined by the BS as parameters. Without losing generality, in this paper, the distance between clusters is set as pre-defined fixed value L. Each cluster is assumed to be a r-radiused circular area centered on the S to D direct line. The distance between the first cluster center and S is set to r. The distance between the centers of the following two clusters is set to L ($L\geq2r$), and the distance between D and the center of the last cluster is denoted by l. When $L/2<l\leq L$, the last cluster radius is set to r, as shown in **Fig. 2**. When $0<l\leq L/2$, as the distance between last relay and D become quite small, the link between them may well deviate from the S, D direction and degrade the performance

of the D2D link, we adjust the last cluster's radius to $r/2$, and the distance between its center and the penultimate cluster therefore becomes L-$r/2$, as shown in **Fig. 3**.

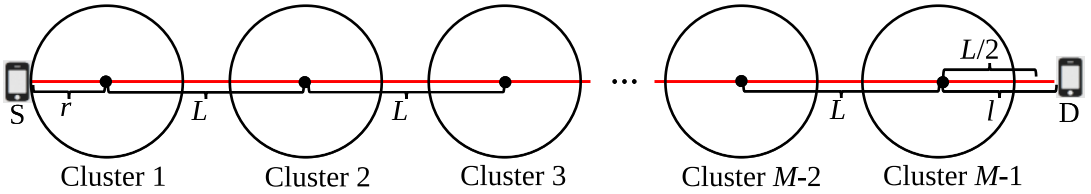

Fig. 2. Design of clusters in normal case

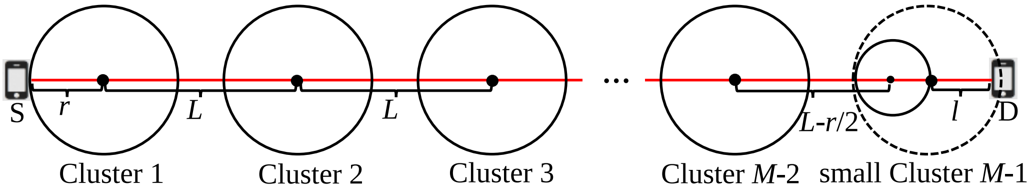

Fig. 3. Design of clusters in special case

4.2 Phase-2: Determine the CEs for Channel Reuse

To improve the throughput of D2D communication, all relays are assumed to be full-duplex equipment. To avoid inter-hop interference, each hop reuses the uplink channel of different CEs. This means that the relays operate in FDD mode with full-duplex relays.

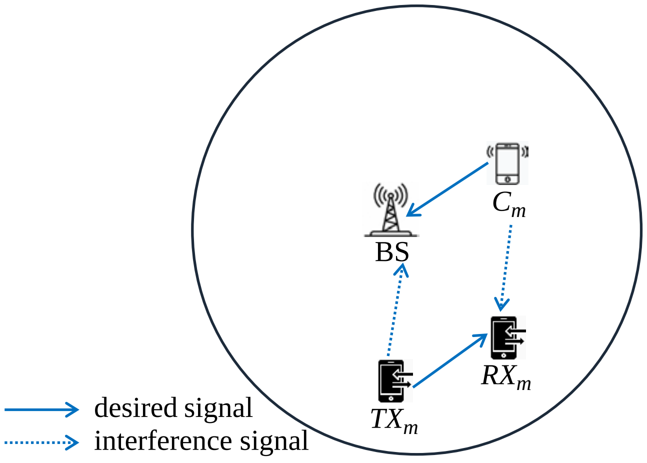

Fig. 4. Interference in the m-th hop D2D communication

As shown in **Fig. 4**, we refer TX_m and RX_m as the transmitter and receiver of the m-th hop of the D2D communication, respectively, and C_m as the CE whose uplink channel is reused at this hop. To ensure CE's link quality, the SINR (Signal to Interference plus Noise Ratio) of C_m's signal received by the BS needs to be greater than the threshold, i.e.:

$$SINR_{C_m}^{\mathrm{BS}}=\frac{P_{C_m}(d_{C_m}^{\mathrm{BS}})^{-\alpha}h_{C_m}^{\mathrm{BS}}}{P_{TX_m}(d_{TX_m}^{\mathrm{BS}})^{-\alpha}h_{TX_m}^{\mathrm{BS}}+N_0}\geq r_{th} \tag{5}$$

where P_{C_m} denotes the transmit power of C_m (for all CEs, P_{C_m} is set to its maximum value P_C), P_{TX_m} denotes the transmit power of TX_m, $d_{C_m}^{\mathrm{BS}}$, $h_{C_m}^{\mathrm{BS}}$ denote the distance and channel coefficient between C_m and BS, respectively, $d_{TX_m}^{\mathrm{BS}}$, $h_{TX_m}^{\mathrm{BS}}$ denote the distance and channel coefficient between TX_m and BS, respectively, r_{th} denotes the SINR threshold for CEs in the uplink, and N_0 denotes the power of background noise following Gaussian distribution $N(0, N_0)$. Therefore,

$$P_{TX_m} \leq \frac{\frac{P_{C_m}\left(d_{C_m}^{\mathrm{BS}}\right)^{-\alpha} \mathrm{h}_{\mathrm{Cm}}^{\mathrm{BS}}}{r_{th}} - N_0}{\left(d_{TX_m}^{\mathrm{BS}}\right)^{-\alpha} h_{TX_m}^{\mathrm{BS}}} \tag{6}$$

Taking

$$P_{TX_m} = \frac{\frac{P_{C_m}\left(d_{C_m}^{\mathrm{BS}}\right)^{-\alpha} h_{C_m}^{\mathrm{BS}}}{r_{th}} - N_0}{\left(d_{TX_m}^{\mathrm{BS}}\right)^{-\alpha} h_{TX_m}^{\mathrm{BS}}} \tag{7}$$

where one can observe that P_{TX_m} increases with the decrease of $d_{C_m}^{\mathrm{BS}}$. The SINR of the signal received by RX_m from TX_m is:

$$SINR_{TX_m}^{RX_m} = \frac{P_{TX_m}\left(d_{TX_m}^{RX_m}\right)^{-\alpha} h_{TX_m}^{RX_m}}{P_{C_m}\left(d_{C_m}^{RX_m}\right)^{-\alpha} h_{C_m}^{RX_m} + N_0} \tag{8}$$

where $d_{TX_m}^{RX_m}$, $h_{TX_m}^{RX_m}$ denote the distance and channel coefficient between TX_m and RX_m, respectively, and $d_{C_m}^{RX_m}$, $h_{C_m}^{RX_m}$ denote the distance and channel coefficient between C_m and RX_m, respectively. It is observed that $SINR_{TX_m}^{RX_m}$ increases with increased P_{TX_m} and $d_{C_m}^{RX_m}$. Since the allowable throughput of this hop is based on $SINR_{TX_m}^{RX_m}$, one can increase P_{TX_m}, i.e., decreasing $d_{C_m}^{\mathrm{BS}}$, or increase $d_{C_m}^{RX_m}$ to increase this hop's throughput. At the same time, a short distance between TX_m and BS ($d_{TX_m}^{\mathrm{BS}}$) will lead to excessive interference to C_m's uplink. Therefore, it is suggested to set a circular protection area with radius A_r around the BS wherein D2D communications are not allowed.

Thereafter, the C_m can be selected as shown in **Fig. 5**. We first draw a straight line from the center of m-th cluster (where RX_m is located) to BS, extend it further and draw a circle inner tangent to the protection area with its center on the extension line and radius being $r/2$. Within this circle, the CE with maximum received signal power at BS is selected as C_m. This design can achieve a good trade-off between CE uplink quality and D2D hop's throughput. Please note that, in the last hop, RX_m is D and its location is interpreted as the relay cluster center.

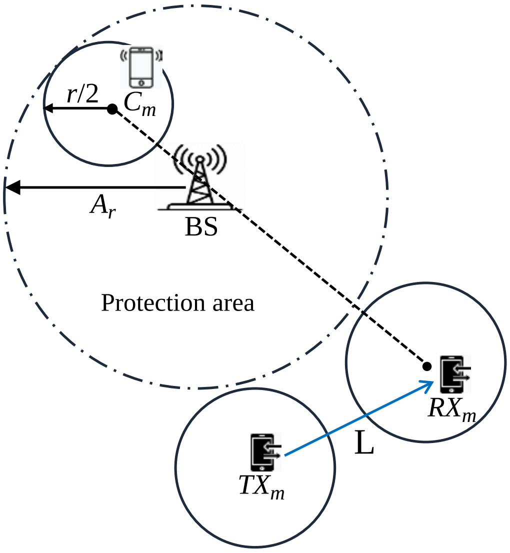

Fig. 5. D2D only allowed outside the protection area

4.3 Phase-3: Determine the Multi-hop Relays

The multi-hop D2D communication involves, in each hop, selecting a CE for channel sharing and a relay from IEs located in the cluster. Relay selection process centrally placed in and managed by BS will generate excessive computation load and large signaling overhead. Therefore, in this paper, a semi-centralized relay selection algorithm is proposed where BS only needs to collect relevant information such as essential channel coefficients and node locations and the relay selection is managed by the D2D devices involved.

It is assumed that the channel coefficient h_y^x is known to node x by node y transmitting a pre-defined and fixed powered sequence. When node x uses the same frequency channel to transmit, due to the channel reciprocity, h_x^y will be known to node y. And we also assume all channel state information is known at the BS.

Assuming that the D2D communication between S and D is M hops, uplink frequency channels of M CEs are shared, denoted as $\boldsymbol{F} = \{f_1, f_2, \ldots, f_M\}$, and the corresponding CEs are $\boldsymbol{C} = \{C_1, C_2, \ldots, C_M\}$. In addition, M-1 relays are to be selected from M-1 relay clusters. Assuming N IEs in each normal cluster and N/4 IEs in small cluster, the set of IEs in the m-th cluster is referred to as $\boldsymbol{IE_m}=\{IE_{1,m}, \ldots, IE_{n,m}, \ldots, IE_{K,m}\}$, m=1, …, M-1, $K = N$ for normal sized clusters and $K = N/4$ for last small cluster. Define $P'_{n,m}$ as the transmit power of $IE_{n,m}$ calculated by (4) considering social relations and a set $\boldsymbol{P}'=\{P'_{1,1}, \ldots, P'_{n,m}, \ldots, P'_{K,M-1}\}$ can be formed. Similarly, define $P''_{n,m}$ as the maximum transmit power of $IE_{n,m}$ calculated by (7) considering interference and a set $\boldsymbol{P}''=\{P''_{1,1}, \ldots, P''_{n,m}, \ldots, P''_{K,M-1}\}$ is formed.

The proposed relay selection algorithm thereafter is named as SAA (Social Aware Algorithm) and its details are presented in Algorithm 1.

Algorithm 1 SAA

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Input: system setup including the locations of BS, CEs, IEs, S and D, frequency channel used by all the CEs in the uplink.
Output: All the relay IEs are selected, and all the reused frequency channels are decided. The S starts D2D communication via all the relays to D.

Step 1: S and D send D2D communication requests to the BS;
Step 2: BS determines the locations of S and D, the location of each relay cluster, as well as the location of IEs therein, according to Phase-1;
Step 3: BS determines $\boldsymbol{C}$ according to Phase-2 and records $\boldsymbol{F}$; calculates $\boldsymbol{P}'$ and $\boldsymbol{P}''$ and takes $\boldsymbol{P} = \min\{\boldsymbol{P}', \boldsymbol{P}''\}$; and collects channel coefficients from $C_1$ to IEs in $\boldsymbol{IE_1}$ and from $C_2$ to IEs in $\boldsymbol{IE_2}$ that will be used in Step 8;
Step 4: BS sends to D all location information, channel coefficients, $\boldsymbol{P}$, and $\boldsymbol{F}$.
Step 5: D sends received data to IEs in $\boldsymbol{IE_{M-1}}$ on channel $f_M$ (in this process IEs in $\boldsymbol{IE_{M-1}}$ obtain the channel coefficients to/from D) and sets its receiver frequency to $f_M$;
Step 6: Assuming sending a fix power signal on $f_M$, each IE in $\boldsymbol{IE_{M-1}}$ calculate D's received signal power. A timer is set inversely proportional to the received signal power for each IE and all timers set off at the same time. The IE whose timer times out first is selected as the relay $R_{M-1}$ and other IEs are notified of this message by $R_{M-1}$ .The $R_{M-1}$ sends the received data to IEs in $\boldsymbol{IE_{M-2}}$ on $f_{M-1}$ and sets its transmit and receive channels to $f_M$ and $f_{M-1}$, respectively;
$m=M-2$;
Repeat
    Step 7: The IEs in $\boldsymbol{IE_m}$ calculate the received signal power, assuming sending a fix power signal to $R_{m+1}$ on $f_{m+1}$. A timer is set inversely proportional to the received signal power for each IE and all timers set off at the same time. The IE whose timer times out first is selected as the relay $R_m$ and other IEs are notified of this message by $R_m$. The $R_m$ sends the received data to $IE_{m-1}$ on channel $f_{m+1}$ and sets its transmit and receive channels to $f_{m+1}$ and $f_m$, respectively, afterwards;
    $m=m-1$;
until $m=1$
Step 8: From the channel coefficients collected in Step 3, the IEs in $\boldsymbol{IE_1}$ calculate the SINRs to $R_2$ and send them together with received data to S. S calculates the SINR to the IEs in $\boldsymbol{IE_1}$. For each IE in $\boldsymbol{IE_1}$, the smaller value of received SINRs of the first hop and second hop is chosen and compared with other IEs and the IE with highest value is selected as $R_1$. $R_1$ adjusts the transmit and receive channels accordingly.
Step 9: S calculates its transmission power according to (7), sets the transmit channel to $f_1$ and starts D2D communication.
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It is noted that the proposed algorithm selects the relay of each hop from D to S, in a reverse fashion. That means the SAA algorithm decides the last relay first and other relays are selected one by one in a reverse order till to the first relay.

The reason of taking this approach is that the IEs can use received signal to obtain the channel coefficients to/from next relay or D. Therefore, by taking advantage of the channel reciprocity, the proposed algorithm relies on the IEs to make relay selection decision without

BS involvement. Hence, it is a semi-centralized algorithm and significantly reduces the computation and signalling load at BS.

The computational complexity analysis of SAA: Giving the distance between S and D is $d_{\mathrm{S}}^{\mathrm{D}}$ and the radius of each cluster is r, and the number of IEs in each cluster is n. the time complexity of Phase-1 is $O(\lfloor d_{\mathrm{S}}^{\mathrm{D}} \rfloor n + \lfloor d_{\mathrm{S}}^{\mathrm{D}} \rfloor + n)$, and the time complexity of Phase-2 is $O(\lfloor d_{\mathrm{S}}^{\mathrm{D}} \rfloor)$, the time complexity of Phase-3 is $O(\lfloor d_{\mathrm{S}}^{\mathrm{D}} \rfloor n + \lfloor d_{\mathrm{S}}^{\mathrm{D}} \rfloor + n)$. Eventually, the time complexity of SAA algorithm can be obtained as $O(\lfloor d_{\mathrm{S}}^{\mathrm{D}} \rfloor n + \lfloor d_{\mathrm{S}}^{\mathrm{D}} \rfloor + n)$. This time complexity is linear to the viables and therefore reasonable.

After determining the multi-hop links based on the above algorithm, the throughput of each hop can be calculated. Assuming that the spectrum bandwidth of the CE is B, the throughput of the first hop is:

$$\Omega_1 = B \cdot \log_2\left(1 + \frac{P_{\mathrm{S}}\left(d_{\mathrm{S}}^{R_1}\right)^{-\alpha} h_{\mathrm{S}}^{R_1}}{P_{C_1}\left(d_{C_1}^{R_1}\right)^{-\alpha} h_{C_1}^{R_1} + N_0}\right) \tag{9}$$

The throughput of the m-th hop is:

$$\Omega_m = B \cdot \log_2\left(1 + \frac{P_{R_{m-1}}\left(d_{R_{m-1}}^{R_m}\right)^{-\alpha} h_{R_{m-1}}^{R_m}}{P_{C_m}\left(d_{C_m}^{R_m}\right)^{-\alpha} h_{C_m}^{R_m} + N_0}\right),\ m=2, \ldots, M\text{-}1 \tag{10}$$

And the throughput of the last hop is:

$$\Omega_M = B \cdot \log_2\left(1 + \frac{P_{R_{M-1}}\left(d_{R_{M-1}}^{\mathrm{D}}\right)^{-\alpha} h_{R_{M-1}}^{\mathrm{D}}}{P_{C_M}\left(d_{C_M}^{\mathrm{D}}\right)^{-\alpha} h_{C_M}^{\mathrm{D}} + N_0}\right) \tag{11}$$

The throughput of the multi-hop D2D link (DT) is limited by the hop with minimum throughput as below:

$$\mathrm{DT} = \min\{\Omega_1, \ \ldots, \Omega_m, \ \ldots, \Omega_M\} \tag{12}$$

Since relays must consume additional power for receiving and relaying data, it is also very important to study the energy efficiency of D2D link (DEE), which is defined as below:

$$\mathrm{DEE} = \frac{\mathrm{DT}}{P_{\mathrm{S}} + \sum_{m=1}^{M-1} P_{R_m}} \tag{13}$$

Regarding the spectrum efficiency, the SAA algorithm enables D2D links to reuse the cellular users' uplink frequency channels, while guaranteeing cellular users SIR, hence their data throughput. Therefore, over the total spectrum bandwidth, additional data throughput of DT resulted from D2D can be supported. The overall system spectrum efficiency hence is enhanced by D2D communications.

5. Numerical Results and Performance Analysis

In this section, due to the complex nature of the problem and the algorithm designed to solve the problem, the system level simulation is used to achieve the solutions. The performance of proposed algorithm is evaluated through extensive Monte Carlo system level simulations. To investigate the impacts of social domain information on the D2D performance, we investigate the algorithm with and without social information, respectively:

SAA (Social Aware Algorithm): the proposed algorithm with social information considered;

SUAA (Social Un-Aware Algorithm): the proposed algorithm without social information (taking $\boldsymbol{P} = \boldsymbol{P}''$ in **Step 3**).

Two most recently developed and most referenced algorithms are selected as benchmarks for performance comparison, which, are the most suitable given the similar use cases and assumptions made by authors.

MLS (Max Link Selection): SNR-based relay selection from the first to the last hop [26].

HTPRS (Highest Transmit Power Relay Selection): relay selection based on transmit power from the first to the last hop [27].

After analysis, it is noted that the above two benchmark algorithms, when applied to the system mode, have the same computational complexity as SAA.

The simulations consider an omni-directional single-cell with radius of 500 meters, wherein D2D pairs and CEs are randomly and uniformly located. The D2D link distance normally in practical systems shall be much smaller than the cell radius and it is reflected in the simulations, where the S-D distance is set to 140-380 meters. Key parameters and their settings of simulations are summarized in **Table 1**.

Table 1. Simulation parameters and settings

Parameters	**Value**
Uplink channel bandwidth B	1 Mhz
Path loss exponent α	3
Noise power	-174 dBm/Hz
Transmit power of CE P_C	23 dBm
Maximum transmit power of IE P_{max}	23 dBm
SINR threshold value of CE r_{th}	10 dB
Distance between adjacent clusters L	60 m
Radius of cluster r	20 m
Radius of protection area A_r	100 m
Pareto distribution k	1/1500
Pareto distribution *sigma*	0.1
Pareto distribution *theta*	0.1

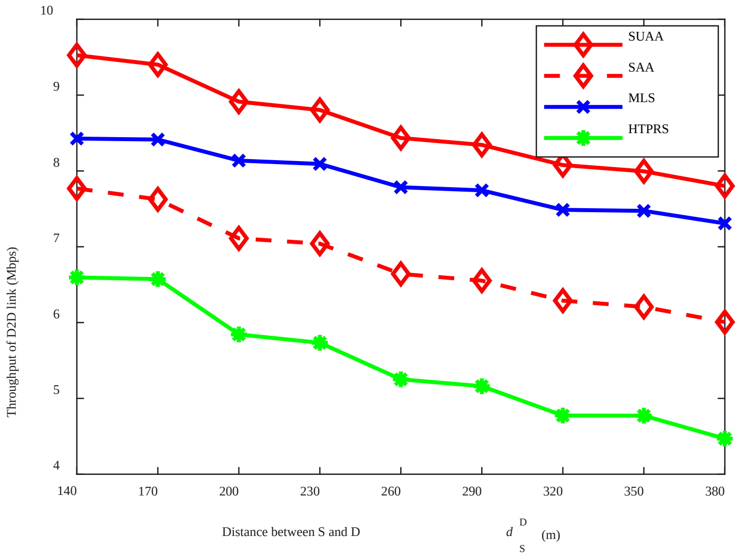

Fig. 6. Throughput of D2D link versus S-D distance

Fig. 6 presents D2D link throughput versus S-D distance $d_{\mathrm{D}}^{\mathrm{S}}$. The throughput of all algorithms decreases as the distance increases. This is because increased S-D distance leads to more hops hence a higher chance for more limited throughput. It is observed that the throughput reduction of some data points is relatively insignificant. These data points represent the cases where the last cluster is a small one, which has relatively less impact on the D2D throughput. Proposed SUAA algorithm outperforms two benchmarks because its relay selection is based on SINR which is directly related to the link throughput. The SAA achieves less throughput than SUAA because of the extra constraint imposed on the relays' allowable transmit power by social relationship.

Fig. 7 shows that the energy efficiency decreases as S-D distance increases. This is because a larger S-D distance decreases link throughput and increases total transmit power of D2D devices. At some data points, the reduction in energy efficiency is insignificant due to the same reason explained above. It is depicted that SUAA outperforms two benchmarks because the throughput of SUAA is larger while the total transmit powers of D2D devices of all three algorithms are not significantly different. Moreover, SAA considerably outperforms SUAA because the social relationship throttles relay's transmit power leading to considerable reduction in total transmit power.

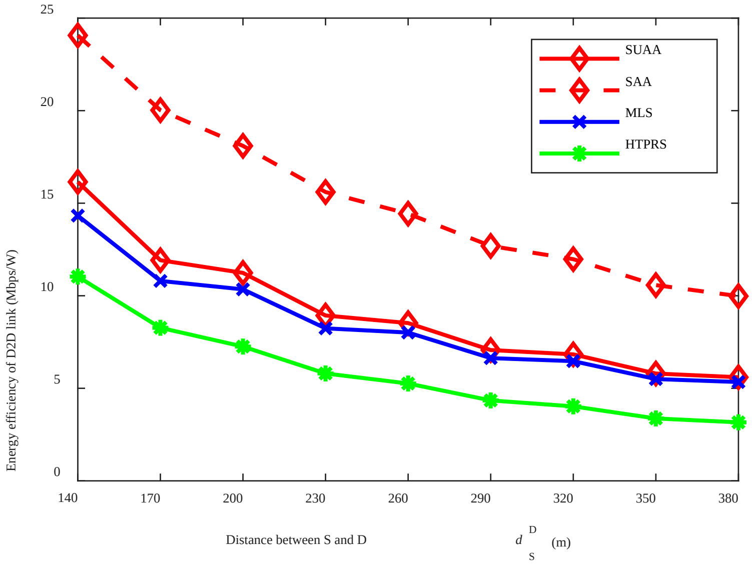

Fig. 7. Energy efficiency of D2D link versus S-D distance

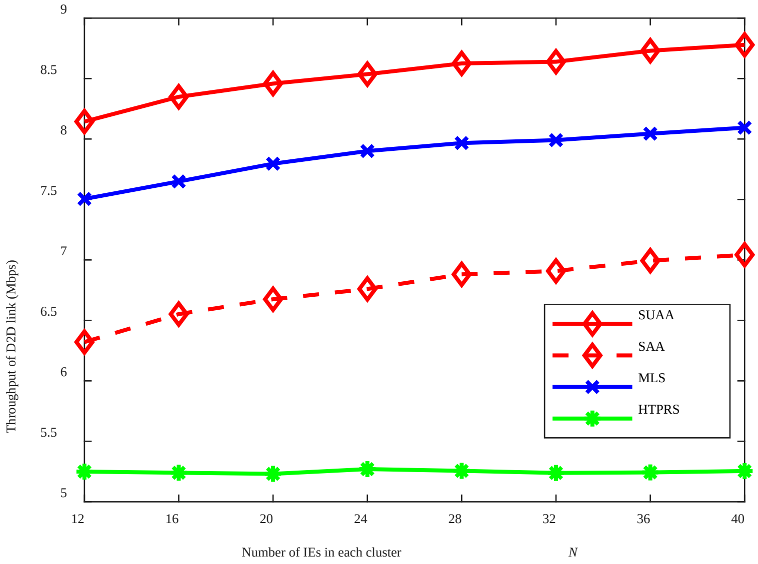

Fig. 8. Throughput of D2D link versus number of IEs

D2D link throughput versus the number of IEs in a relay cluster is shown in **Fig. 8**. It is observed that as the number of IEs increases, the throughput of SUAA, MLS, and SAA increases, while that of HTPRS remains almost unchanged. The reason is that HTPRS algorithm selects relays in a more random fashion and cannot take advantage of having more candidate IEs.

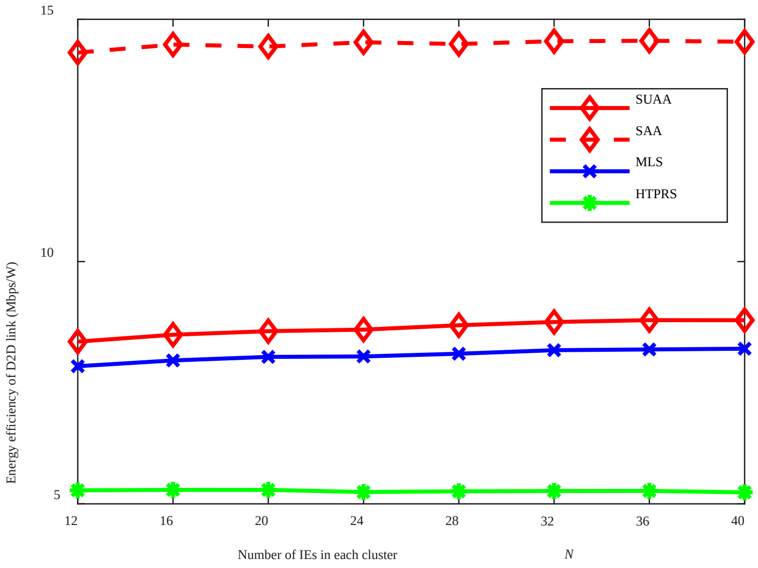

Fig. 9. Energy efficiency of D2D link versus number of IEs

Fig. 9 shows that the increased number of IEs does not change DEE of all algorithms considerably. This is because although the throughput of the first three algorithms increases with increased number of IEs, the total transmit power of the D2D devices also increases. HTPRS, unlike others, selects the relays more randomly, leading to unchanged throughput and transmit power of relays regardless of number of IEs.

Fig. 10 studies the impact of protection area radii A_r on the D2D link throughput for SAA algorithm. It demonstrates that a lager A_r leads to increased throughput. This is because on one hand, a larger A_r will increase the distance between the relay and the BS, so the BS can tolerate the relay to transmit more power. On the other hand, the distance between the CU and the relay also increases, leading to reduced interference to the relay. Consequently, a higher SINR for the relay can be achieved hence a higher throughput of the D2D link.

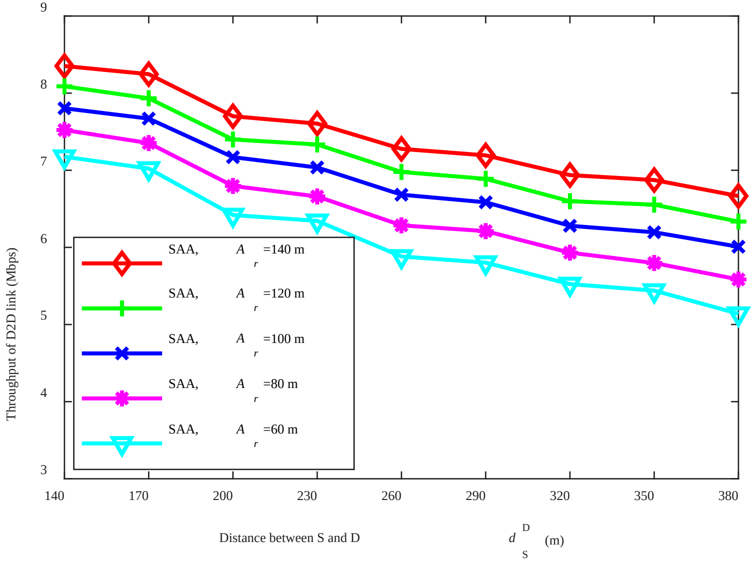

Fig. 10. Throughput of D2D link for different protection area radii

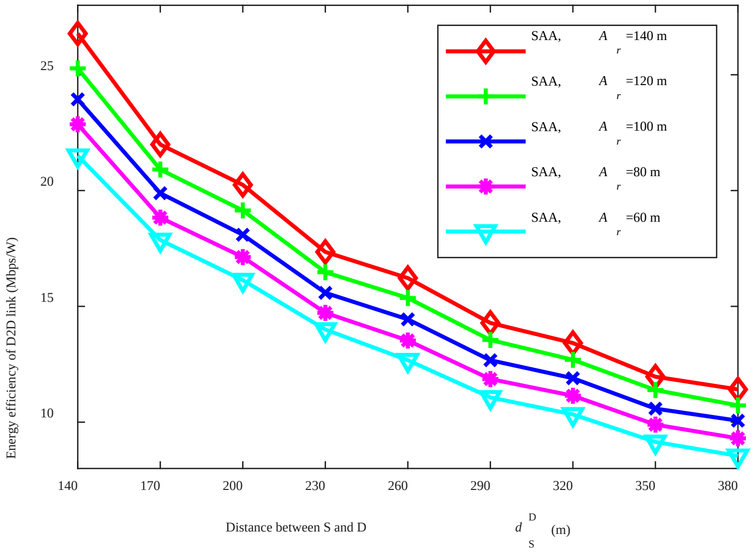

Fig. 11. Energy efficiency of D2D link for different protection area radii

In **Fig. 11**, it is shown that when A_r increases, the energy efficiency increases. This is because the throughput of the D2D link increases as A_r increases while the total transmit power is not affected, so the energy efficiency increases.

To demonstrate the impact of social domain on the relay performances, a comparison of SAA and SUAA′s performances at different S-D distance d_D^S is summarized in **Table 2**. It can be seen that SAA and SUAA differ considerably in both throughput and energy efficiency. It therefore can conclude that the role of social domain information is significant enough not to be overlooked in the study of practical D2D communications.

Table 2. Performance comparison of SAA and SUAA

d_D^S (m)	140	170	200	230	260	290	320	350	380
SUAA/SAA (DT)	1.226	1.233	1.254	1.250	1.270	1.273	1.284	1.288	1.299
SAA/SUAA (DEE)	1.490	1.680	1.611	1.747	1.693	1.796	1.753	1.824	1.783

6. Conclusion

This paper proposed a novel relay selection algorithm for multi-hop full-duplex D2D communications underlaying cellular networks. The algorithm works in a reverse and semi-distributed manner to significantly reduce base station signalling overload. The social relationship between users is taken into account in the algorithm design, which is proved to be critical in practical systems. The proposed algorithm is thoroughly analyzed and compared against two benchmark algorithms. It is observed that the overall system throughput and power efficiency of proposed algorithm considerably outperform those of benchmarks.

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Liang Li is currently a master student in the Faculty of Electrical Engineering and Computer Science, Ningbo University, Ningbo, China. His research interest is D2D communication.

Xinjie Yang is a professor at the Faculty of Electrical Engineering and Computer Science, Ningbo University. His research interests focus on mobile network resource management, cellular IoT network and mobile computing.

Yuanjie Zheng received Master degree from Zhejiang University, China in 2011 and currently is the managing director of Ningbo Edge IoT Technology Co.,Ltd.. His research interests include AI based IoT networks and mobile edge computing.

Jiazhi Yang is currently a master student in the Faculty of Electrical Engineering and Computer Science, Ningbo University, Ningbo, China. His research interest is performance analysis of cellular Internet of Things systems.