Joint Relay Selection and Frequency Allocation for D2D Communications

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Abstract. High demand for bandwidth has been the primary motivation for device to device (D2D) communication. In cases where direct communication is not possible, two D2D devices are allowed to communicate via relay nodes. The relay selection problem is concerned with the selection of suitable relay device for each such D2D pairs while frequency assignment problem aims to optimally share the available spectrum resources among the active devices satisfying their quality of service requirements. In this work, we present a joint approach to solve the relay selection and frequency allocation problem in context of D2D communications. We incorporated a network coding strategy into our problem formulation which halves the required time slots for a two-way D2D communication. Considering the underlying problem is NP-Complete, we formulated a linear programming based greedy method which shows near-optimal performance with polynomial time complexity. We also compare our proposed algorithm with two existing works and show throughput improvement.

Keywords: D2D communications · Channel assignment · Relay selection

1 Introduction

The increase of various smart handheld devices, together with their bandwidth hungry applications like video calls, high definition television, video streaming services, mobile gaming etc., demand high data rate which is beyond the limits of conventional cellular network. To cope up with ever increasing data rate demands, several schemes for cooperative communication have already been proposed , chief among them being fixed terminal relaying through small base stations (BSs) to assist the communications [6]. Although these strategies show significant improvements in spectral and energy efficiency as well as in user quality-of-service (QoS), the current capacity is no where close to being enough to meet the required demand. To this end, communication using the millimeter-wave (mmWave) frequency has aroused considerable interest for providing device-to-device (D2D) communication in next generation cellular networks to provide such high data rate [13,16].

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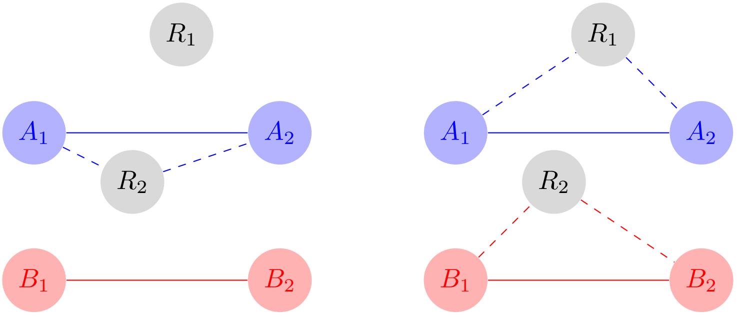
In D2D communications, two nearby devices are allowed to directly communicate with each other with limited or no involvement of BS. D2D communication enables dramatic improvements in spectral reuse. The close proximity of devices comes with the promises of higher data rates, lowers delays, and reduced power consumption. In fact, communicating with giga-Hertz frequencies having small wavelength, typically measured in millimeters, can offer very high speed data in the range of gigabits per second [13]. However, these signals suffer from higher transmission and penetration losses than their low frequency counterparts making them apt for close proximity communications [12].

In D2D communications, if the source and destination devices are not in the vicinity of one another or suffering from inferior direct link quality, it is possible to establish a D2D connection with one or more relay devices in between. More often than not, a relay based communication having a few shorter links offer more throughput than a traditional communication via the base station, thus such relay based D2D communications has gained popularity over the past few years. The full potential of cooperative communication can be utilized by device relaying [16]. A D2D device pai may have multiple candidate relay devices in its vicinity. Whereas, a relay device might be candidate for many D2D pairs, but it cannot serve more than one D2D pairs simultaneously. Figure 1a shows a sub-optimal scenario where relay R_2 is assigned to D2D pair A_1–A_2 whereas D2D pair B_1–B_2 has no relay allocated to it while relay R_1 is not utilized. In Fig. 1b relay R_1 has been assigned to D2D pair A_1–A_2 and relay R_2 is assigned to D2D pair B_1–B_2. Figure 1b thus depicts an ideal relay assignment for this example. By Fig. 1 it is evident that, optimal relay selection is a 2-dimensional matching problem where a D2D pair is matched with a suitable relay device, assuming a valid frequency allocation is always feasible.



(a) Non optimal assignment (b) Optimal relay assignment

Fig. 1. Optimal relay selection as matching problem

With limited number of available frequency channels in a licensed band and plenty of requesting D2D users in a service area, the spectrum sharing is a must and thus induces interference. The objective of the frequency channel allocation problem is to assign frequency channels to the requesting D2D users in such a way that their data rate requirements are satisfied. Consider the scenario given in Fig. 1b once again, assuming relay R_2 is in close proximity of the A_1–A_2 D2D pair, the QoS offered by the relay R_2 to the D2D pair B_1–B_2 is dependant of their frequency assignment. Therefore, the relay selection and frequency channel assignment are dependent on each other making them computationally hard to deal with. More precisely, the combined problem of relay selection and frequency allocation has been shown to be NP-complete [8].

Thus, the relay selection and frequency allocation must be dealt jointly, otherwise like in any multistage strategies, result of a former stage will heavily influence the quality of the solution obtained at the end of the subsequent stages. Even if one solves the former stage optimally there is no guaranty of it being part of the overall optimal solution of the joint problem. One can easily come up with instances where doing relay selection independent of frequency allocation in two stages produces non-optimal results and vice-versa.

Furthermore, a two-way communication via a relay, takes four time slots using store and forward method where the first two time slots are used to send data from one device of a D2D pair to the other via the intermediate relay device, and the subsequent two time slots are required to send data in the other direction. Application of efficient network coding can bring this down to two time slots [7], where the relay device receives data simultaneously from the two devices in a D2D pair in the first time slot and transmits back the combined data in the next time slot. Both the receivers receive the data simultaneously and decode its required data from it with negligible overhead.

In this work, we aim to maximize the number of activated links which in turn improves the overall system throughput for relay aided two-way D2D overlay communications. For this, we propose an algorithm to jointly solve the relay selection and frequency allocation problem for two-way communication with reduced time slots using network coding. We allow reusing a channel among many D2D pairs as long as the required signal to interference plus noise ratio (SINR) is satisfied. Our proposed algorithm is a greedy approach based on linear programming (LP) relaxation of the underlying hard problem. Simulation results show near optimal performance of our proposed algorithm in terms of number of links activated. We also show that our proposed algorithm outperforms a state-of-the-art classical algorithm as well as one recent algorithm in terms of overall system throughput.

The rest of the paper is organized as follows. The literature review is given in Sect. 2. Section 3 presents the system model. The joint problem formulation is given in Sect. 4. Our proposed solution is given in Sect. 5 followed by its simulation results in Sect. 6. We conclude this work with Sect. 7.

2 Related Works

In D2D communications, one of the challenging tasks is to optimally allocate resources to the devices [17]. The main objective of the frequency allocation and power control is to maximize the SINR or minimize the interference value to improve link quality. Channel assignment for orthogonal frequency division multiple access (OFDMA) based D2D systems has been studied in [5,8,16,17]. The resource allocation problem for D2D communications has been investigated in [3]. Here the problem has been solved in successive stages. It first selects admissible D2D pairs satisfying the QoS requirements and then allocates powers to the devices. Next, a maximum weight bipartite matching is employed to allocate frequency to each admissible D2D pair in order to maximize the overall system throughput.

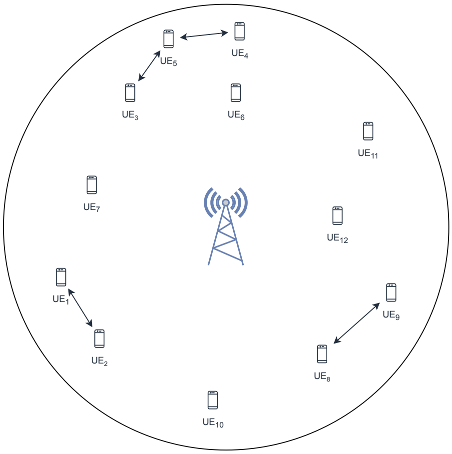
In [5] authors have formulated a mode selection and resource allocation problem to maximize the system throughput of D2D and cellular links satisfying minimum rate requirements of the links. To solve this problem, optimal power requirements of the D2D links operating in the direct or relay mode have been calculated. Then, using these power allocations, the joint mode selection and relay assignment has been formulated as a job assignment problem whose optimal solution can be obtained in polynomial time. Various challenges for relay selection have been mentioned in [16]. Authors of [19] proposed a joint relay selection and resource allocation algorithm, which first allocates resources to relay links based on maximum received SINR values and then determines the optimal relay device fulfilling the QoS requirement of D2D users. In [9], authors formulated a mixed integer non-linear programming problem for the joint power and channel allocation in relay-assisted D2D communications and proposed two heuristic algorithms. One algorithm first allocates optimal powers to the links under given channel assignment followed by channel allocation, while the other one does the same in reverse order. In [4] authors proposed a two stage process for relay selection and resource allocation in which first the relay candidates are shortlisted by their position in the sectored cell and then relays and frequencies are selected. In [2], relaying based on D2D communication in an integrated mmWave 5G network has been considered. In [18], a coding technique has been used to improve reliability of the communication. Here first an integer non-linear programming problem has been formulated for the joint resource allocation, later it is converted into binary integer linear programming problem using a concept of D2D cluster and solved using branch-and-cut algorithm.

Both in [8] and [15], the joint relay selection along with related sub-channel and power allocation problem has been investigated. The proposed scheme in [8] first allocates power to the devices then formulates the relay selection and channel allocation problem as a 3-dimensional matching problem which is known to be NP-complete. They proposed an iterative technique to near-optimally solve the matching problem which decomposes the 3-dimensional matching problem into a sequence of 2-dimensional matching problems by fixing one dimension in each stage of an iteration. While in [15], authors aim to maximize the system throughput by considering the relay-aided communications. For this they have considered four subproblems, namely power control, relay selection with area division, mode selection, and finally link selection for activation.

Most of the studies above does not allow reusing the same channel among multiple D2D pairs. We also found that most of the works considers one-way communication scenarios, while many modern applications like video calling requires two-way communication in which high data rate is needed in both directions. In this work, we jointly deal with the problems of relay selection and frequency allocation for two-way communications, where we allow reusing the same channel among many D2D pairs as long as the required SINR is satisfied. Moreover, we make use of network coding to provide two-way communication with reduced time slots which in turn increases the number of activated links and hence the overall system throughput.

3 System Model

We assume a single cell BS controlled D2D overlay scenario where we have M pairs of D2D user equipments (UEs) and N number of idle UEs. Some of these D2D pairs can directly communicate with each other whereas others need an intermediate relay device for their communication. We are only considering one hop relay assisted D2D communications in such cases. We further assume that an idle UE can serve as a relay between only one D2D pair. Figure 2 depicts such a scenario. All these devices need to be allocated spectrum resources where we have F number of dedicated orthogonal sub-channels available for the D2D communications. We assume time is discretized into time slots $\{t_0, t_1, t_2, \ldots\}$ with small Δt time span for each time slot. We denote a pair of successive time-slots as a *superslot*. We denote $\mathscr{D}$ as the set of D2D pairs requiring a relay and $\mathscr{D}'$ as the set of D2D pairs communicating directly.



requesting D2D pairs:	UE$_1$-UE$_2$, UE$_3$-UE$_4$, UE$_8$-UE$_9$
idle D2D UEs:	UE$_5$, UE$_6$, UE$_7$, UE$_{10}$, UE$_{11}$, UE$_{12}$
direct links:	UE$_1$-UE$_2$, UE$_8$-UE$_9$
relay aided links:	UE$_3$-UE$_5$-UE$_4$

Fig. 2. System model

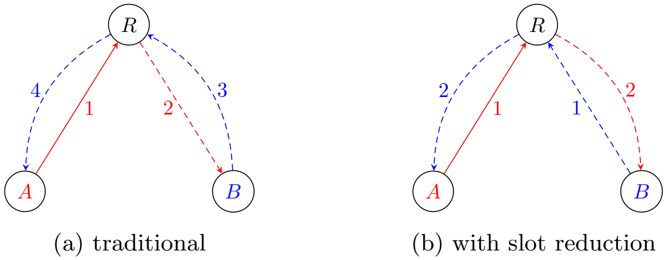
Mobility Consideration. We consider the nodes to be pseudo-stationary, that is they do not change their position for the duration of a superslot. As we solve the problem for a superslot, therefore their movement in between superslots do not affect our proposed solution. For a particular superslot, position of an UE can be determined with great accuracy [11] and is available to the BS.

Candidate Relays. Similar to [4] and [14], we assume all idle D2D UEs are capable and willing to participate in device relaying. Furthermore, we assume that a D2D pair can communicate among each other via a single relay making a one-hop relay assisted communication in cases where direct communication link is poor or does not exist. For a D2D pair, all idle devices within its vicinity, thus possibly having good SINR values, are eligible for being a candidate relay for that pair. An idle device can be in more than one such candidate list, but can only be assigned to a single D2D pair for relaying. We denote $\mathscr{R}$ to be the set of all candidate relay nodes in the service area.

Frequency Allocation. We need to allocate frequency channels to each of the D2D links and also to their relay link (if any). With limited number of frequency channels we need to employ frequency reuse keeping the SINR values above the required QoS threshold. We denote $\mathscr{F}$ to be the set of available orthogonal frequency channels.

Power Allocation and Channel Gain. We assume all transmitter devices are transmitting at a fixed power P. As in [3], for pathloss model we consider both the fast fading due to multi-path propagation and slow fading due to shadowing. Thus, the channel gain between device a and device b can be expressed as $h_{a,b} = K\beta_{a,b}\zeta_{a,b}L_{a,b}^{-\alpha}$, where K is a constant determined by system parameters, $\beta_{a,b}$ is fast fading gain with exponential distribution, $\zeta_{a,b}$ is the slow fading gain with log-normal distribution, α is the pathloss exponent, and $L_{a,b}$ is the distance between devices a and b.

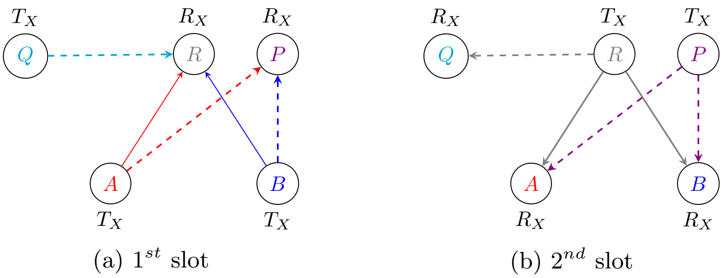
Slot Reduction. In [7], it is shown that for a two-way communication it is possible to reduce number of required time slots by use of network coding technique. System requirements to support such channel coding is given in [1,7]. As shown in Fig. 3a it would take two time slots to send A's data to B via relay R and another two time slots for sending B's data to A via R. The data transmissions are denoted by directed arrows, marked with slot numbers, in the figure. But with proper network coding R can receive from both A and B simultaneously in one time slot and sends back the combined received data in the next time slot as depicted in Fig. 3b. Here both A and B receive the combined data simultaneously from R and decodes the required data from it. This shows a clear benefit in reduction of number of time slots from four to two which supersedes the small overheads incurred for use of this network coding [7]. We assume relay nodes have limited memory thus the data in a time slot must be sent out in next time slot. Our task thus reduces to solving the problem just for a single superslot.



(a) traditional (b) with slot reduction

Fig. 3. Slot reduction using network coding for two-way communication

Interference Consideration. Consider a D2D pair A-B communicating via a relay R. As shown in Fig. 4a, in the first time slot, both A and B will act as transmitter and R will act as receiver. Both A and B will contribute to interference of all other devices, such as P, receiving using the same frequency in which both A and B transmit. Similarly, all other devices, such as Q, transmitting in the same frequency will cause interference at R. Whereas in second time slot, receiving/transmitting role of the devices reverses. As shown in Fig. 4b, R now becomes transmitter and relays back the data to B and A, both of which are now in receiving mode. Thus A and B get interference from all other devices, such as P, transmitting using the same frequency. Similarly, R causes interference to all other devices, such as Q, receiving in the same frequency.



(a) 1^{st} slot (b) 2^{nd} slot

Fig. 4. Interference from other transmitters for the two time slots

4 Problem Formulation

Assuming all devices transmit using fixed power P, we define received power from device a to device b as $R(a,b) = P \times h_{a,b}$. We define binary allocation matrices $X \in \{0,1\}^{|\mathscr{D}|\times|\mathscr{R}|\times|\mathscr{F}|}$ and $Y \in \{0,1\}^{|\mathscr{D}'|\times|\mathscr{F}|}$ of which entries $X_{i,r,f}$ and $Y_{k,f}$ are defined as follows.

$$X_{i,r,f} = \begin{cases} 1 & \text{if i-th D2D pair communicate via} \\ & \text{relay } r \text{ using frequency } f \\ 0 & \text{otherwise} \end{cases}$$

$$Y_{k,f} = \begin{cases} 1 & \text{if k-th D2D pair communicate directly} \\ & \text{using frequency } f \\ 0 & \text{otherwise} \end{cases}$$

We denote $i = (i_1, i_2)$ for a D2D pair i consisting of devices i_1 and i_2. In the first time slot, for a D2D pair $i = (i_1, i_2)$ communicating via relay r, both i_1 and i_2 act as the transmitters and r acts as the receiver. Even with all transmitters transmitting with same fixed power P, the received signal strength will vary due to different gain obtained at different positions. Thus to ensure *no buffering* is needed at the receiver r, the effective received power at r is set as the minimum of the received powers from the two transmitters i_1 and i_2, that is, $min(R(i_1, r), R(i_2, r))$. The total interference for D2D pair i from all other D2D pairs $j = (j_1, j_2) \in \mathscr{D}$ and $k = (k_1, k_2) \in \mathscr{D}'$ operating on the same frequency f is given in equation (1) where sum of received power from a D2D pair j to a device a is defined as $R_s(j, a) = R(j_1, a) + R(j_2, a)$.

$$Int_{i,r,f} = \sum_{\substack{j \in \mathscr{D} \\ j \neq i}} \sum_{\substack{r' \in \mathscr{R} \\ r' \neq r}} R_s(j, r) X_{j,r',f} + \sum_{k \in \mathscr{D}'} R(k_1, r) Y_{k,f} \tag{1}$$

Therefore, SINR for the D2D pair i communicating via relay r using frequency channel f can be given as

$$SINR_{i,r,f} = \frac{min(R(i_1, r), R(i_2, r))}{\eta_0 + Int_{i,r,f}}$$

where η_0 is the thermal noise. Furthermore, for D2D pair i the SINR value must be larger than or equal to the required SINR threshold th_i whenever $X_{i,r,f} = 1$. We can write this as linear inequalities (2) and (3), where M is a suitably large constant value, representing positive infinity.

$$(1 - X_{i,r,f})M + R(i_1, r) \geq (\eta_0 + Int_{i,r,f}) th_i \tag{2}$$

$$(1 - X_{i,r,f})M + R(i_2, r) \geq (\eta_0 + Int_{i,r,f}) th_i \tag{3}$$

In the second slot, the role of transmitters and receivers reverses. That is, both i_1 and i_2 act as the receivers and r acts as a transmitter. We calculate the interference at i_1 and i_2 in equations (4) and (5) respectively.

$$Int'_{i_1,r,f} = \sum_{\substack{j \in \mathscr{D} \\ j \neq i}} \sum_{\substack{r' \in \mathscr{R} \\ r' \neq r}} R(r', i_1) X_{j,r',f} + \sum_{k \in \mathscr{D}'} R(k_2, i_1) Y_{k,f} \tag{4}$$

$$Int''_{i_2,r,f} = \sum_{\substack{j \in \mathscr{D} \\ j \neq i}} \sum_{\substack{r' \in \mathscr{R} \\ r' \neq r}} R(r', i_2) X_{j,r',f} + \sum_{k \in \mathscr{D}'} R(k_2, i_2) Y_{k,f} \tag{5}$$

Thus effective SINR in second time slot is given as

$$SINR'_{i,r,f} = min\left(\frac{R(r,i_1)}{\eta_0 + Int'_{i_1,r,f}}, \frac{R(r,i_2)}{\eta_0 + Int''_{i_2,r,f}}\right).$$

This SINR value must also be larger than th_i whenever $X_{i,r,f} = 1$. We can similarly write this as linear inequalities (6) and (7).

$$(1 - X_{i,r,f})M + R(r, i_1) \geq (\eta_0 + Int'_{i_1,r,f})th_i \tag{6}$$

$$(1 - X_{i,r,f})M + R(r, i_2) \geq (\eta_0 + Int''_{i_2,r,f})th_i \tag{7}$$

For a D2D pair $k = (k_1, k_2)$ communicating directly using frequency f, interference at k_2 in slot 1 and at k_1 in slot 2 are given in equations (8) and (9) respectively.

$$Int'''_{k_2,f} = \sum_{i\in\mathscr{D}} \sum_{r\in\mathscr{R}} R_s(i, k_2)X_{i,r,f} + \sum_{\substack{k'\in\mathscr{D}'\\ k'\neq k}} R(k'_1, k_2)Y_{k',f} \tag{8}$$

$$Int''''_{k_1,f} = \sum_{i\in\mathscr{D}} \sum_{r\in\mathscr{R}} R(r, k_1)X_{i,r,f} + \sum_{\substack{k'\in\mathscr{D}'\\ k'\neq k}} R(k'_2, k_1)Y_{k',f} \tag{9}$$

Similarly, linear inequalities in (10) and (11) ensure SINR value for the D2D pair k communicating using frequency f is larger or equal to threshold th_k whenever $Y_{k,f} = 1$.

$$(1 - Y_{k,f})M + R(k_1, k_2) \geq (\eta_0 + Int'''_{k_2,f})th_k \tag{10}$$

$$(1 - Y_{k,f})M + R(k_2, k_1) \geq (\eta_0 + Int''''_{k_1,f})th_k \tag{11}$$

Inequality (12) ensures that a relay device can be used for at most one D2D pair and can transmit using a single frequency.

$$\sum_{i\in\mathscr{D}} \sum_{f\in\mathscr{F}} X_{i,r,f} \leq 1 \ \forall r \in \mathscr{R} \tag{12}$$

A D2D pair can have at most one relay and can transmit using a single frequency. This gives us the inequality (13). A D2D pair communicating directly also can transmit using a single frequency and gives inequality (14).

$$\sum_{r\in\mathscr{R}} \sum_{f\in\mathscr{F}} X_{i,r,f} \leq 1 \ \forall i \in \mathscr{D} \tag{13}$$

$$\sum_{f\in\mathscr{F}} Y_{k,f} \leq 1 \ \forall k \in \mathscr{D}' \tag{14}$$

We also have the integrality constraints (15) and (16).

$$X_{i,r,f} \in \{0, 1\} \ \forall \ i \in \mathscr{D}, r \in \mathscr{R}, f \in \mathscr{F} \tag{15}$$

$$Y_{k,f} \in \{0, 1\} \ \forall \ k \in \mathscr{D}', f \in \mathscr{F} \tag{16}$$

In order to maximize the number of links that can be activated together the following integer linear program (ILP) can be formulated.

$$\max \sum_{i \in \mathscr{D}} \sum_{r \in \mathscr{R}} \sum_{f \in \mathscr{F}} X_{i,r,f} + \sum_{k \in \mathscr{D}'} \sum_{f \in \mathscr{F}} Y_{k,f} \tag{17}$$

subject to constraints (2), (3), (6), (7) and (10) through (16).

5 Joint Relay Selection and Frequency Assignment

We begin with elimination of the allocation matrix Y by introducing a dummy virtual relay node r_k for each D2D pair $k = (k_1, k_2)$ in $\mathscr{D}'$ in order to simplify the equations. We set this virtual node r_k as the only relay candidate of this D2D pair k. While calculating SINR values, we consider position of r_k is same as transmitter k_1 for the first slot and the position is same as transmitter k_2 for the second slot. We set $\mathscr{D} = \mathscr{D} \cup \mathscr{D}'$ and $\mathscr{R} = \mathscr{R} \cup \{r_k \mid k \in \mathscr{D}'\}$. Now the purpose of Y matrix can be served with X matrix itself with updated dimensions. We also update the definition of received power for a transmit power P as follows.

$$R(a,b) = \begin{cases} \infty & \text{if } a \in \mathscr{D}' \text{ and } b = r_a \\ P \times h_{a,b} & \text{otherwise} \end{cases}$$

Interference calculations in (1), (4) and (5) thus reduces to (18), (19) and (20)

$$Int_{i,r,f} = \sum_{\substack{j \in \mathscr{D} \\ j \neq i}} \sum_{\substack{r' \in \mathscr{R} \\ r' \neq r}} [R(j_1, r) + R(j_2, r)] X_{j,r',f} \tag{18}$$

$$Int'_{i_1,r,f} = \sum_{\substack{j \in \mathscr{D} \\ j \neq i}} \sum_{\substack{r' \in \mathscr{R} \\ r' \neq r}} R(r', i_1) X_{j,r',f} \tag{19}$$

$$Int''_{i_2,r,f} = \sum_{\substack{j \in \mathscr{D} \\ j \neq i}} \sum_{\substack{r' \in \mathscr{R} \\ r' \neq r}} R(r', i_2) X_{j,r',f} \tag{20}$$

respectively and the objective function simplifies to

$$\max \sum_{i \in \mathscr{D}} \sum_{r \in \mathscr{R}} \sum_{f \in \mathscr{F}} X_{i,r,f} \tag{21}$$

We devise a linear programming relaxation based greedy algorithm to near optimally solve the problem. We start by relaxing the integrality constraints in (15) in order to allow the indicator variables to have fractional values between 0 and 1, as shown in Eq. (22).

$$X_{i,r,f} \in [0,1] \ \forall\ i \in \mathscr{D}, r \in \mathscr{R}, f \in \mathscr{F} \tag{22}$$

We thus have an linear program (LP) with objective given in (21) subject to constraints (2), (3), (6), (7), (12), (13) and (22). Solving this relaxed LP we obtain

Algorithm 1: Relay Selection-Frequency Allocation

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solve the relaxed LP to obtain solution vector $\tilde{X}$
apply rounding-off scheme on $\tilde{X}$ such that constraints (12), (13) and (22) are satisfied
create the frequency classes $\mathscr{C} = \{C_1, C_2, \ldots, C_{|\mathscr{F}|}\}$
set $\mathscr{L} = \phi$
foreach class $C_f \in \mathscr{C}$ do
    while $C_f$ not satisfying QoS constraints (2), (3), (6) and (7) do
        foreach link $(i, r) \in C_f$ do
            set $I_{i,r} = Int_{i,r,f} + Int'_{i_1,r,f} + Int''_{i_2,r,f}$
        set $(\hat{i}, \hat{r}) = \arg\max_{(i,r) \in C_f} \{I_{i,r}\}$
        set $C_f = C_f \setminus \{(\hat{i}, \hat{r})\}$ and $\mathscr{L} = \mathscr{L} \cup \{(\hat{i}, \hat{r})\}$
while $\mathscr{L} \neq \phi$ do
    foreach link $(i, r) \in \mathscr{L}$ do
        foreach $f \in \mathscr{F}$ do
            if $C_f \cup \{(i, r)\}$ satisfies QoS constraint then
                set $I_{i,r,f} = Int_{i,r,f} + Int'_{i_1,r,f} + Int''_{i_2,r,f}$
            else
                $I_{i,r,f} = \infty$
    set $(\hat{i}, \hat{r}, \hat{f}) = \arg\min_{(i,r) \in \mathscr{L}, f \in \mathscr{F}} \{I_{i,r,f}\}$
    if $I_{\hat{i},\hat{r},\hat{f}} \neq \infty$ then
        update $C_{\hat{k}} = C_{\hat{k}} \cup \{(\hat{i}, \hat{r})\}$
    update $\mathscr{L} = \mathscr{L} \setminus \{(\hat{i}, \hat{r})\}$
return $\mathscr{C}$
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an allocation matrix X with fractional entries. We apply a simple rounding-off mechanism to change these fractional values to 0–1 integral values satisfying constraints (12) and (13). The resultant solution might not be a valid one with respect to the QoS constraints (2), (3), (6) and (7). Nevertheless, this gives us $|\mathscr{F}|$ frequency classes, $\mathscr{C} = \{C_1, C_2, \ldots, C_{|\mathscr{F}|}\}$, where C_f represents set of links are to be activated with frequency f. More precisely, we store (i, r) pairs in a C_f, denoting that i-th D2D pair is assigned relay r and transmits using frequency f. Admissibility of each such frequency class can be tested independently of other frequency classes using the QoS constraints (2), (3), (6) and (7). For each such C_f, disabling a few links might just satisfy the QoS constraints of the remaining links and thus can be activated with the same frequency f. We mark a link in C_f as *victim link* if it causes maximum interference to all other links in C_f. We remove this victim link into a common *discarded pool* of links $\mathscr{L}$ for later consideration. This removal of links is done iteratively until all links of C_f can be activated with same frequency f without violating QoS constraints. Repeating the same process for all the frequency classes, we can activate all of the remaining links in $\bigcup_{C_f \in \mathscr{C}} C_f$ together.

Now a link $l \in \mathscr{L}$ can be accommodated back into some frequency class C_f such that $C_f \cup \{l\}$ satisfies the QoS constraints. We should note that the order in which the links are reinserted has a significant impact on the number of links that can be activated together. Here again we employ a simple greedy scheme by iteratively finding the most *economical link* in $\mathscr{L}$ and inserting it into its most *economical frequency class* satisfying the QoS constraints. We call (l, f) the most economical link-class pair if link l incurs minimum interference into frequency class C_f for all such (l, f) pairs, where $l \in \mathscr{L}, C_f \in \mathscr{C}$. If for some link l no such accommodating frequency class satisfying the QoS constraints can be found, we permanently discard this link and move onto the next economical link. We continue this process until no new link can be admitted. The formal description of this proposed scheme is given in Algorithm 1.

Lemma 1. *Algorithm 1 terminates with a solution as good as any single frequency reuse algorithm.*

Proof. After the rounding-off we check for admissibility of each of the frequency classes and make necessary changes. This ensures that each frequency class must contain at least one link if not more. Thus, at this point, in terms of the number of D2D links activated, the solution obtained by our proposed method must be as large as any solution produced by any algorithm which consider only single use of a frequency channel. Furthermore, next we try to pack more links in the frequency classes which can only improve the solution and bring it closer to the optimal one. This iterative improvement process must terminate as we consider each of the remaining link only once. □

6 Simulation Results

In this section we present the simulation results to demonstrate the performance of our proposed scheme. We have considered a single cell scenario similar to [15]. We take 5–20 D2D pairs and 200 idle D2D devices eligible for device relaying within a cell of 500 m. The maximum distance between a D2D pair is 50 m. Other channel parameters are also adapted from [15]. The maximum transmission power is 25 dBm, SINR threshold is 5 dB, thermal noise is −174 dBm/Hz and the pathloss exponent is 4.

For the comparison we choose two other algorithms namely iterative Hungarian method (IHM) [8] and uplink resource allocation (ULRA) [15] described in Sect. 2. Since both IHM and ULRA do not deal with network coding, for a fair comparison, we have considered a version of our algorithm which does not uses the network coding for slot reduction. We slightly modify our approach similar to [15] by halving the available bandwidth for a time slot in case of a relay aided communication. Since both IHM and ULRA reuse a channel allocated to a cellular user (CU) we consider the presence of 10 active CUs each using a unique orthogonal frequency channel similar to [15]. We assume the base station is placed at the center of the cells and CUs are distributed uniformly at random in the cell. For accurate measurements we ran these algorithm on 1000 random instances and took the average of them. Furthermore, to enable two-way communication we run these algorithm twice, once for the forward direction and on this result we run the algorithm a second time for the other direction. We only activate those links which are still feasible after the second round of execution. We compare the performance of our approach with these two algorithms in terms of number of links activated and total system throughput achieved with varying system load. By system load we imply the number of requesting D2D pairs. For throughput calculations we only select the links outputted by an algorithm for activation and apply the Shannon capacity formula. As depicted in Fig. 5 our proposed scheme outperforms both of these algorithms. This improvement can be attributed to the fact that we have considered the two problems jointly and allowed multiple frequency reuse.

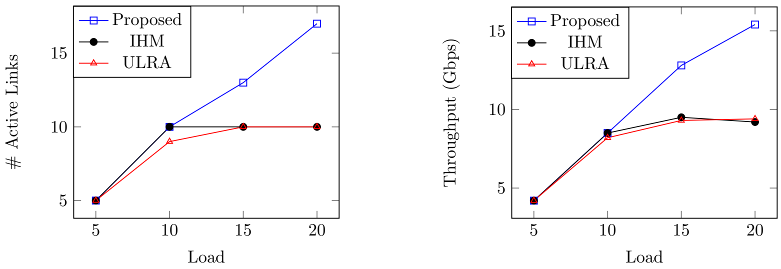

Fig. 5. Proposed vs IHM and ULRA without network coding

The true potential of our algorithm is observed when the network coding is enabled. For reference we also consider the *optimal* scheme where we directly solve the formulated ILP. Modern optimization solvers like Gurobi [10] can solve an ILP efficiently within reasonable amount of time for smaller instances. Figure 6 shows how well our proposed algorithm perform to achieve a near optimal solution in comparison to the optimal scheme.

The IHM algorithm has a running time of $O(jB^3)$, where $B = max(|\mathscr{D}|, |\mathscr{R}|, |\mathscr{F}|)$ and j is the number of iterations in IHM and the time complexity for ULRA is $O(|\mathscr{D}||\mathscr{R}||\mathscr{F}|)$. While our algorithm has a running time of $O(L)$ where L is the time complexity for solving the LP with $|\mathscr{D}||\mathscr{R}||\mathscr{F}|$ variables. Our algorithm has higher time complexity due to the fact that it allows multiple frequency reuse, while both IHM and ULRA allow only single reuse. Thus by jointly dealing the relay selection and frequency allocation problem with multiple frequency reuse our proposed algorithm results into improved system throughput. The use of network coding for slot reduction also plays a significant role in the throughput improvement.

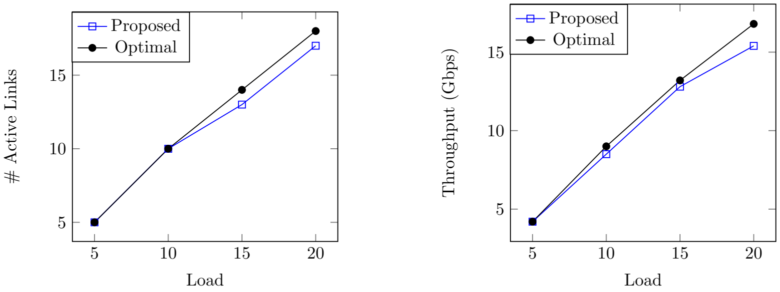

Fig. 6. Proposed vs *optimal* with network coding

7 Conclusion

We have addressed the joint relay selection and frequency allocation problem in a relay aided D2D communication and devised a LP relaxation based greedy strategy. The simulation results shows that our proposed scheme solves the problem near-optimally. Moreover, our algorithm outperforms the IHM and ULRA algorithms in terms of system throughput. This improvement can be attributed to the fact that we have jointly dealt the two problems unlike solving it in multiple stages like in IHM or ULRA algorithm. Moreover using the network coding scheme for slot reduction also contribute in throughput improvements. Lastly, instead of single reuse of frequencies, our proposed scheme allows multiple reuse to further improve the system throughput.

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