ON OPTIMAL ROUTING AND POWER ALLOCATION FOR D2D COMMUNICATIONS

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ABSTRACT

In this paper, we propose algorithms for finding the optimum multi-hop routes and corresponding transmit powers that maximize the throughput between a pair of device-to-device (D2D) nodes, under a constraint on the maximum interference caused to the cellular network. Our solution involves two steps. In the first step, we determine the set of *feasible* D2D links, based on the interference constraint. In the second step, we use the celebrated Dijkstra's algorithm to find throughput-optimal routes between a given pair of D2D nodes under two scenarios: *a) The Fixed Rate Scheme* and *b) The Fixed Power Scheme*. The dependency of the net D2D throughput on the system parameters such as target SINR is analyzed for both the schemes, and a procedure to find the optimum parameter setting is proposed. The performance of the algorithms is illustrated using computer simulations. The results show that, depending on the network topology, a significantly higher throughput can be achieved by using multi-hop paths compared to using single-hop, direct D2D communication.

Index Terms— Optimal routing, D2D communications, Interference avoidance, Dijkstra's algorithm.

1. INTRODUCTION

Device-to-Device (D2D) Communication has recently received much research attention, as it promises to improve the spectral efficiency [1–4], power efficiency [5, 6], and coverage [7] of the network. It has also found its way into the LTE-A standard [8–10]. An excellent survey on D2D communication can be found in [11]. It is defined as the direct communication that takes place between devices without traversing the core cellular network. Major challenges in D2D communication include *a)* interference management, *b)* time-frequency-power resource allocation, *c)* mode selection, and *d)* device discovery. In many practical scenarios, when two devices may wish to communicate with each other in the D2D mode, the direct path may not be optimal or even feasible due to the interference constraint to the cellular network. One could possibly achieve higher throughput by considering routing the data over multiple short-range, high-rate links. In this paper, we propose algorithms for finding the optimal route and power allocation for D2D communication between a source and a destination, subject to a constraint on the maximum interference caused to the core cellular network.

Most of the past work on D2D focuses on *inband D2D*, where the D2D users use the spectrum licensed by cellular users. It has been shown that, by employing interference-aware resource allocation [1–3, 12] and mode selection [4, 5] techniques, it is possible to significantly improve on the spectral efficiency of the network as a whole. In [1], the authors propose a scheme where D2D users listen to a control channel and adjust their operating parameters such that the interference from the D2D communication to the uplink cellular link is below a maximum allowed level. In [2, 12], the authors consider an interference avoidance scheme wherein the base station (BS) identifies the so-called at-risk users and broadcasts their locations as well as the resources allocated to them. With this information in hand, the D2D users perform radio resource management to avoid causing interference to those users. In [3], the authors propose an algorithm in which interference-limited areas are formed around the D2D transmitter and receiver. Resources are allocated such that there is no cellular user employing the same resource in the interference-limited regions. The approach adopted here for D2D routing and resource allocation uses a similar model to limit the interference caused to the cellular network.

Consider a scenario where users are densely located in a region with partial cellular coverage in each frequency band. The question we wish to answer is, what is the optimal route for D2D communication? The direct path between the source and destination may have a low rate due to the constraint on the interference to the cellular users; while using several short-range, high-rate links may also be suboptimal because of the multiple hops involved. To the best of our knowledge, such a problem of optimal multi-hop routing in D2D communications has not been considered in literature. We make a modest, initial attempt at this problem, under two D2D communication models: *a) A fixed rate scheme*, in which all the D2D links have the same rate, and *b) A fixed power scheme*, in which all the D2D users transmit at the same power level. The fundamental difference between routing problems in D2D communication compared to conventional routing problems lies in the constraint on the maximum interference that the D2D links are allowed to cause to the cellular network. Moreover, the optimum route and the throughput achieved by it are a function of the D2D operational parameters. We also develop algorithms to find the optimal parameter settings that maximize the throughput. Our main contributions are:

- We propose an algorithm to find the set of feasible D2D links under a constraint on the maximum allowable interference to the cellular users.
- We consider a scheme in which all the D2D links operate at the same rate. We use the well-known Dijkstra's algorithm to find the optimal route between a given source and destination pair, using the set of feasible links. We analyze the dependence of the throughput between a given source and destination pair on the value of the fixed rate. We propose an algorithm to find the optimum value of the fixed rate that maximizes the throughput.
- We consider another scheme where all the D2D users transmit at the same power level. Similar to the previous case, we find the optimal route among the feasible links using Dijkstra's algorithm, and propose an algorithm to find the optimum level for the fixed power to maximize the D2D throughput.

We illustrate the performance of the algorithms, and demonstrate their optimality in terms of the throughput, using computer simulations. The results underline the importance of a systematic approach

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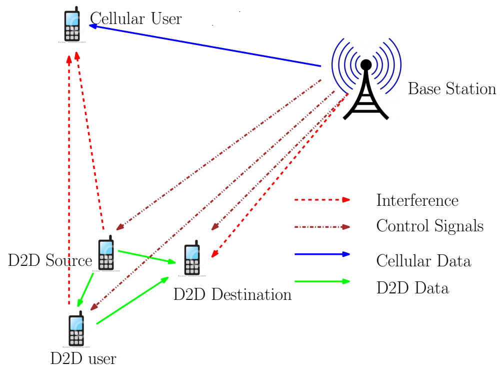

Fig. 1. The system model considered in this work.

to routing and power allocation in D2D networks. We start with describing the system model.

2. SYSTEM MODEL

We consider a network in which N BSs and M D2D users are deployed in a given area of interest. The locations of BSs as well as D2D users are assumed to be known, but those of the cellular (mobile) users are unknown. For simplicity, all BSs are assumed to be transmitting independent signals at the same power, P, in a downlink frequency band of interest. We quantify the interference caused by the BSs to the D2D receivers using the path loss model, with a known path loss exponent. Note that, although not trivial, it is possible to incorporate fading into this model, by making the interference constraints probabilistic rather than deterministic. We consider an *underlay, inband* D2D communication scheme, due to which, there are two types of interferences that need to be reckoned with: *a)* Interference from the BS to the D2D receiver and *b)* Interference from the D2D transmitter to the cellular receiver. Figure 1 illustrates the system model with $(M = 3)$ D2D users and $(N = 1)$ BS.

We consider three types of constraints on the D2D users. First, each D2D link must be sufficiently reliable: we denote the minimum/target SINR at the receiver of any D2D link by γ, in dB. Next, since the locations of cellular users are unknown, we consider two separate constraints – a minimum SNR constraint and a maximum interference constraint. The minimum SNR constraint, denoted by γ_b, determines the *exclusion zone* around the BS within which a D2D user is simply not allowed to transmit. The maximum interference constraint, denoted by γ_d, represents the highest interference that the cellular user can tolerate from any D2D transmitter. Our first task is to determine which of the $M(M-1)$ directional D2D links are feasible, we address this next.

3. FEASIBLE D2D LINKS

As mentioned earlier, a link is said to be *feasible* if reliable communication can take place on the link while also satisfying a constraint on the interference to any cellular user regardless of its location. This represents a conservative approach, which is necessary because the mobile/cellular users' locations are assumed to be unknown to the D2D users or BS. Thus, we mandate that only D2D links for which *a)* the SINR at the D2D receiver exceeds γ *and b)* the D2D transmitter is outside the exclusion zone of all BSs *and c)* the interference due to the D2D transmitter is below γ_d at all locations where the SNR from the BS exceeds γ_b, are feasible for D2D communication. We describe algorithm to determine the feasible D2D links for the fixed rate scheme as follows. In the fixed rate scheme, each D2D link has a target rate, and, correspondingly, a minimum SINR for that rate to be achievable. We denote this minimum SINR by γ, in dB, as mentioned earlier.

Step 1 Find the aggregate interference (caused by the BSs) plus noise power $P_{\text{int}}^{d_R}$, in dB, at a D2D user, d_R.

Step 2 Find the minimum transmit power required, $P_{d_T}^{d_R}$, in dB, for a given D2D transmitter, d_T, to transmit reliably to d_R. This depends upon the SINR threshold γ and the interference from the cellular system as follows:

$$P_{d_T}^{d_R} = P_{\text{int}}^{d_R} + \gamma + 10\alpha \log(D_{d_T}^{d_R})$$

where $D_{d_T}^{d_R}$ is the distance between d_T and d_R. Do this for every pair of d_T and d_R.

Step 3 The region around the BS i, A_{BS_i}, in which the SNR for the corresponding cellular users is at least γ_b dB is a circular region with radius $D\text{max} = 10^{\left(\frac{P-\gamma_b}{10\alpha}\right)}$ centered at the location of BS_i. Shut down all the D2D links whose transmitters are within distance $D\text{max}$ of any BS, and declare all links originating from those D2D transmitters as infeasible.

Step 4 For a particular D2D transmitter d_T outside the area $A_{BS_i}, i = 1, 2, \ldots N$, calculate the power level for d_T that ensures that the maximum interference at any point in A_{BS_i} is below γ_d for each i. This is found based on $D\text{max}$ and the distance D_{d_T,BS_i} between d_T and BS_i, using

$$P_{d_T,BS_i}^{\text{max}} = \gamma_d + 10\alpha \log(D_{d_T,BS_i} - D\text{max}).$$

The above ensures that the interference at a hypothetical cellular receiver at distance $D\text{max}$ from BS_i along the direction of d_T is also below γ_d. Thus, to satisfy the interference constraint for all the BSs, the maximum power d_T can use is simply the minimum of $P_{d_T,BS_i}^{\text{max}}$. Set $P_{d_T}^{\text{max}} = \min_{1 \le i \le N} P_{d_T,BS_i}^{\text{max}}$.

Step 5 Declare the link $d_T \longrightarrow d_R$ *infeasible* if $P_{d_T}^{d_R} > P_{d_T}^{\text{max}}$.

Remark: For the fixed power scheme, all D2D transmissions occur at a power P_D, the procedure for determining the feasible links is simpler than the above. Steps 1 and 2 are not necessary, and in step 5, we declare the link infeasible if $P_D > P_{d_T}^{\text{max}}$.

Using the above procedure, we can now form a directed graph $G_\gamma(V, E)$ (in the fixed-power case, $G_{P_D}(V, E)$), with the nodes V being the D2D users and the directed edges E being the indicators of feasibility of the links. Our next task is to determine the optimal route between a D2D source-destination pair, which we discuss below.

4. THROUGHPUT-OPTIMAL D2D ROUTING SCHEMES

In this section, we consider a D2D user d_S that wishes to send data to another D2D user d_D over the network of feasible links determined above. We consider the fixed rate scheme and the fixed power scheme in the following two subsections.

4.1. Fixed Rate Scheme

Here, D2D links that can achieve a fixed target rate are deemed to be feasible. Since there is a one-to-one correspondence between the

SINR at the D2D receiver and the rate achieved on the link (for example, through the Shannon capacity formula), the procedure presented in the previous section for a given SINR threshold γ can be used to find the D2D network graph $G_\gamma(V,E)$. The end-to-end throughput is simply the rate achieved by any individual link divided by the number of hops in the path. Hence, given the SINR threshold, the optimal route is simply the shortest path in terms of the number of hops, which can be determined efficiently by the well-known Dijkstra's algorithm. Note that, here, in order to limit the interference to the cellular users and to each other, we allow only one D2D link to be active at a time in the given frequency band and area of interest. The net rate R_{eff} achieved between d_S and d_D is thus given by:

$$R_{\text{eff}}(\gamma) = \frac{\log(1+\gamma)}{\text{Number of hops}} \text{ bps per Hz.}$$

Now, as γ is increased, the numerator in $R_{\text{eff}}(\gamma)$ increases, but the denominator could also increase as the longer-range links become infeasible, thereby increasing the number of hops to reach the destination. While γ_b and γ_d are generally specified by the cellular system, the D2D SINR threshold γ can be varied to maximize the effective rate, by solving the optimization problem

$$\gamma_{\text{opt}} = \arg\max_{\gamma} R_{\text{eff}}(\gamma).$$

We present a procedure for solving the above problem in Sec. 5.

4.2. Fixed Power Scheme

In the fixed power scheme, all D2D transmissions occur at a fixed power level P_D. Again, the procedure described in the previous section can be used to obtain the directed graph $G_{P_D}(V,E)$ of feasible D2D links. In this scheme, each feasible link achieves a different rate, depending on the SINR at the corresponding receiver. Hence, the shortest path is not necessarily the throughput maximizing path in this case. However, with a little work, it can be shown that the maximum rate that can be achieved on any path is simply the harmonic mean of the rates that are achieved in each of the links divided by the number of hops in the path. The division by the number of hops is because only one D2D link is enabled at a given time-slot, as discussed in the previous subsection. Thus, we seek to find the path for which the scaled harmonic mean of the rates of the links in the path is maximum. This can be done by setting the inverse of the rate achieved on each link as the link weight, and using the weighted Dijkstra's algorithm to find the shortest weighted distance path. We omit the details due to lack of space.

In the fixed power scheme, as P_D increases, the rate achieved by the individual links improves, but more of the D2D transmitters might be shut down due to the interference constraint. In turn, this could lead to a higher number of hops in the optimal path obtained, resulting in a lower end-to-end rate. Hence, the D2D transmit power P_D can be optimized to maximize the throughput $R_{\text{eff}}(P_D)$ in a manner similar to the previous subsection, where $R_{\text{eff}}(P_D)$ is the throughput achieved by the optimal path returned by Dijkstra's algorithm using the weighted cost minimization procedure, when the power constraint is P_D. We propose a solution to this problem of finding the optimal operating point P_D in the next section.

5. OPTIMUM OPERATING POINTS

5.1. Fixed Rate Scheme

At $\gamma = -\infty$ dB, all the D2D links are feasible, but the rate that can be achieved on all the links is zero. As γ increases, the rate of each link increases and hence the throughput R_{eff} between d_S and d_D also increases. However, as γ is increased beyond the point where one of the links *in the current best path* becomes infeasible, the throughput drops, since the number of hops now has to increase, without any appreciable increase in the rate achieved on each individual link. Further increase of γ increases the throughput till one more link in the current best path becomes infeasible. Thus, the problem of finding γ_{opt} that maximizes the throughput is equivalent to identifying the peaks in a plot of the throughput versus γ and determining the best among them. This can be solved as follows:

Step 1 Find the maximum power ($P_{d_S}^{\text{max}}$) at which the source d_S is allowed to transmit. Find the SINR ($\gamma_{d_S}^{d_D}$) at d_D corresponding to that power. This is the best SINR that can be achieved using the direct link. The first peak occurs precisely at this SINR. Call this SINR γ_1.

Step 2 Consider a d_i and the path $d_S \longrightarrow d_i \longrightarrow d_D$. Suppose the maximum feasible transmit powers of d_S and d_i are $P_{d_S}^{\text{max}}$ and $P_{d_i}^{\text{max}}$, respectively. Find the SINR achieved on the two links (say, $\gamma_{d_S}^{d_i}$ and $\gamma_{d_i}^{d_D}$). The maximum SINR at which this path remains feasible is the minimum of the two SINRs. The maximum SINR at which some two-hop path is feasible is given by

$$\gamma_2 = \max_{i \neq D,S} \left(\min(\gamma_{d_S}^{d_i}, \gamma_{d_i}^{d_D}) \right)$$

A peak occurs here only if γ_2 is greater than γ_1. Due to this, we can ignore all the links (and the paths involving those links) that achieve an SINR less than γ_1, thereby simplifying the computational complexity of the above step. If there is no node i such that $\min(\gamma_{d_S}^{d_i}, \gamma_{d_i}^{d_D}) > \gamma_1$, we say that γ_2 does not exist.

Step 3 Repeat Step 2 for all possible three hop paths, and determine

$$\gamma_3 = \max_{i \neq D,S, j \neq D,S,i} \left(\min(\gamma_{d_S}^{d_i}, \gamma_{d_i}^{d_j}, \gamma_{d_j}^{d_D}) \right)$$

A peak exists here if γ_3 is greater than the previous γ (i.e., γ_2, or γ_1 if γ_2 does not exist). Again, all the paths involving a link that achieves a lower SINR than the previous γ can be ignored, to reduce the computational complexity.

Step 4 Repeat the above step with increasing number of hops; a point γ_f is found such that when $\gamma > \gamma_f$, d_S and d_D are no longer connected in the graph $G_\gamma(V,E)$. The existence of γ_f is guaranteed by the fact that the number of edges in $G_\gamma(V,E)$ is a monotonically non-increasing function of γ and goes to 0 as γ goes to ∞.

Step 5 Set $\gamma_{\text{opt}} = \arg\max_{1 \leq i \leq M, \gamma_i \text{ exists}} R_{\text{eff}}(\gamma_i)$

5.2. Fixed Power Scheme

As before, at $P_D = -\infty$ dB, all links are feasible, and each link achieves zero rate. Following the same arguments in the previous subsection, the plot of the throughput $R_{\text{eff}}(P_D)$ versus P_D also exhibits multiple peaks; and the task at hand is to determine the best among them. The relationship between the rates on various links and R_{eff} (the scaled harmonic mean) is not as simple as in the previous case, but the following procedure identifies all the points where the peaks occur.

At sufficiently low transmit power, all the D2D links are feasible. As P_D is increased, $R_{\text{eff}}(P_D)$ increases until one of the D2D transmitters becomes infeasible. This happens when $P_D > P_{d_T}^{\text{max}}$ (as defined in Section 3) for one of the D2D nodes d_T. If the best path

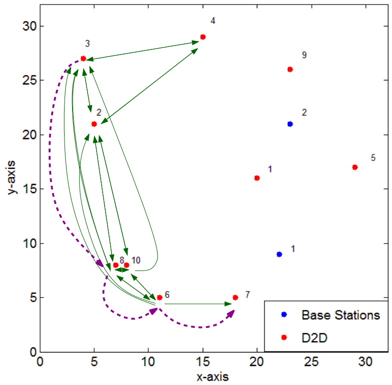

Fig. 2. Locations of the BSs and D2D users in the area of interest. The solid green lines show the feasible links for fixed rate communication at an SINR threshold of $\gamma = -1$ dB; the dashed magenta line shows the optimal route from Node 3 to Node 7.

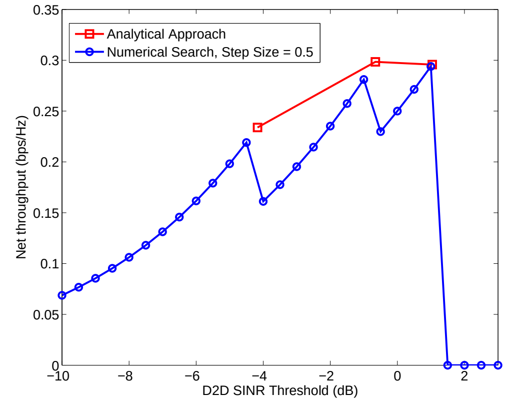

Fig. 3. Fixed rate scheme: Illustration of the numerical search approach and the analytical approach for finding the maximum achievable throughput.

connecting d_S and d_D at that value of P_D involves that D2D user, R_{eff} drops, as an alternate path with lower R_{eff} has to be used. The throughput continues to increase as P_D is further increased till one more D2D transmitter becomes infeasible. Eventually, at large enough P_D, the source and the destination become disconnected, and the search ends. Thus, P_D^{opt} is given by

$$P_D^{\text{opt}} = \arg \max_{P_{d_T}^{\text{max}}} R_{\text{eff}}(P_{d_T}^{\text{max}})$$

Note that there are at most M values of P_D for which the throughput needs to be evaluated, to find the optimum solution.

6. SIMULATION RESULTS

We consider a square area of side 32 units containing $N = 2$ BSs and $M = 10$ D2D users. Figure 2 shows one such random topology of nodes and BSs. We consider D2D users 3 and 7 as the source and destination node, respectively. We assume a path loss exponent of 4 and a reference distance of 1 unit for computing the path loss. We set the minimum SNR constraint as $\gamma_b = 3$ dB and the interference threshold as $\gamma_d = 1$ dB.

We vary the SINR threshold γ and the D2D transmit power P_D in the fixed-rate and fixed-power cases, respectively, with the goal of determining the optimum end-to-end throughput. Given γ (or P_D), we first determine the set of feasible links and the connectivity graph $G_\gamma(V, E)$ (or $G_{P_D}(V, E)$) using the algorithm presented in Sec. 3. Next, we determine the values of γ_{opt} and P_D^{opt} in two ways: by a discrete numerical search with a step size of 0.5 dB, and by using the procedure described in Sec. 5 to evaluate the throughput for at most $M = 10$ values of γ (or P_D).

For the fixed rate scheme, the results of the numerical search and the algorithm presented in Section 5.1 are compared in Figure 3. We note that the algorithm correctly finds the points where the peaks occur. The best throughput is achieved at $\gamma_{\text{opt}} \approx -1$ dB; the corresponding three-hop path is also shown in Figure 2. More importantly, the discrete search misses the optimal throughput point (which is around $\gamma = -1$ dB), and incorrectly suggests that $\gamma =$

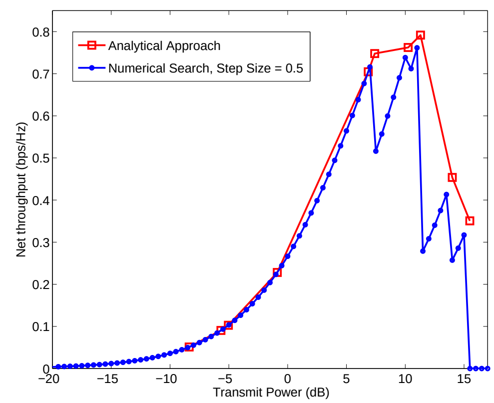

Fig. 4. Fixed power scheme: Illustration of the numerical search and analytical approaches.

1 dB is optimal. This illustrates the utility of the procedure developed in this paper for finding the optimal throughput. Further, the optimum throughput is many orders of magnitude superior to the maximum throughput achievable with single-hop communication.

A similar plot for the fixed power scheme, with P_D on the x-axis, is shown in Figure 4. Again, we see that by employing the analytical approach presented in Section 5.2, we are able to correctly identify the optimal operating point.

To conclude, in this paper, we investigated the problem of finding the optimum multi-hop route that maximizes the throughput between a given pair of D2D users. We considered two schemes for D2D communication, a fixed rate scheme, and a fixed power scheme, and developed algorithms to find the optimum operating points for both the schemes. The performance of the algorithms was illustrated through computer simulations, by comparing it with that obtained by exhaustive search. Future work could involve accounting for fading to provide probabilistic guarantees for protection of the cellular users, while maximizing the throughput of the D2D users.

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