UAV-Direct: Facilitating D2D Communications for Dynamic and Infrastructure-less Networking

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ABSTRACT

In this paper, a new and novel approach called (Unmanned Areal Vehicle) UAV-Direct is proposed, where the UAV helps in optimizing the bandwidth and power allocations of Device-to-Device (D2D) communication. In addition to that, the UAV can play the role of a relay if needed to maintain the communication links between the devices that are out of communication ranges of each other. We design a UAV-Direct protocol to manage the resource allocations to improve the system throughput. We formulate an optimization problem that maximizes the minimum device throughput while satisfying resource allocation constraints. Since the formulated optimization problem is non-convex, we propose to solve this problem in two steps. In the first step, a Taylor series successive convex approximation solution is proposed to optimize the resource allocations. Then, we propose an efficient algorithm based on a recursive shrink-and-realign process to optimize the UAV trajectory.

ACM Reference Format:
Ahmad Alsharoa and Murat Yuksel. 2018. UAV-Direct: Facilitating D2D Communications for Dynamic and Infrastructure-less Networking. In *DroNet'18: 4th ACM Workshop on Micro Aerial Vehicle Networks, Systems, and Applications, June 10–15, 2018, Munich, Germany*. ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3213526.3213537

1 INTRODUCTION

Energy and bandwidth efficiency solutions based on resource allocations, careful scheduling, and interference mitigation in Device-to-Device (D2D) communications became one of the goals of the next generation wireless networks. D2D communication has been proposed to allow close proximity wireless devices to communicate with each other using a direct link, and thus, enhance the data transfer rate and latency due to a shorter traversal than with the legacy cellular infrastructure. Various short-range wireless technologies in the literature have been proposed to enable D2D communication such as Bluetooth, WiFi-Direct and LTE-Direct [8]. The differences between these technologies lie in ranges, applications, and discovery mechanisms.

DroNet'18, June 10–15, 2018, Munich, Germany

ACM ISBN 978-1-4503-5839-2/18/06.
https://doi.org/10.1145/3213526.3213537

In terms of co-existence with legacy cellular communications, D2D spectrum usage is primarily classified into two types: underlay and overlay [8]. In the first one, the D2D communication and the other cellular communications use the same spectrum. In the latter type, the spectrum is to be divided into orthogonal portions between D2D and cellular communications. In fact, overlay type helps in eliminating the interference between D2D and cellular communications although interference may still be present from other D2D pairs.

Recently, there have been notable interests in LTE-Direct, also known as Proximity-based Services (ProSe), to enable D2D communication where it is defined by the 3GPP standard in Rel. 12 [1]. ProSe allows physically nearby devices to discover and communicate with each other via direct links. There are two types of discovery that can initiate the D2D link. The first one is device discovery, where the discovery is instigated by the devices using radio frequency sensing. The second one is network discovery, where the discovery is done by the base station on behalf of the devices [10]. The device discovery has a shorter range because the devices' transmission power are constrained compared to the network discovery, while, the network discovery covers a broader area and thus saves devices' resources. In high-traffic D2D communication, a base station is needed to control the bandwidth and transmit power allocations in order to reduce the interference, and hence, increase the aggregate data rate. However, the LTE-Direct has not facilitated to investigate the delay and devices' mobility in addition to the case where the ground infrastructure maybe unavailable or damaged by disasters.

D2D communication becomes more challenging if a dynamic environment is considered. When infrastructure support does not exist (e.g., during or after a disaster), LTE-Direct will not be available [2]. UAVs can practically serve as base stations to organize and optimize communications among a swarm of devices while also acting as a relay to extend the devices' communication range. In [13], a dynamic protocol was proposed to enable inter-cell D2D communication using a relay device. The performance of the dynamic environment can be significantly improved by using UAVs to organize the D2D resources in the network and help in maintaining the communication links between out of range devices by working as a mobile relay.

As another dimension, optimizing the UAV trajectories to support D2D can significantly enhance the network performance by determining the best coverage areas for D2D communication, and thus, optimize the resources. Few works in the literature discuss the trajectory optimization of the UAVs. For instance, in [14], Selim *et. al* propose a novel trajectory optimization approach under a self-healing management framework, where multiple UAVs need to optimize their trajectories to heal the devices associated to a failed base station. The UAV trajectory optimization using sequential convex optimization technique has been studied in [16] for a point-to-point system model using only one UAV. In [17], the authors solve a one-dimensional placement problem and consider one UAV serving multiple ground users in a time sharing manner. This work simplifies the analysis but limits applicability in practice. In [12], the authors studied the coexistence between one UAV and underlaid D2D communication in the downlink scenario. This UAV can serve only one device at a time, thus it needs to travel from one stop point to another to serve other devices. Note that, the D2D link is not managed or organized by the UAV, and it is just considered as interference to the UAV device. However, this approach limits the practicality of using a UAV as a base station and may also consume a large amount of energy by forcing the UAV to travel from one point to another to serve the ground devices.

In this paper, we propose a new and novel approach called UAV-Direct. The UAV has two main functions: The first one is to optimize the resource and power allocations in D2D communication between devices in its coverage area; and secondly, it works as a relay if needed to maintain or improve the communication links between the devices within or outside of communication range of each other. In fact, thanks to their mobility, UAVs can be more robust than legacy cellular infrastructure against environmental changes and their trajectories can be optimized based on devices' dynamic locations. To the best of our knowledge, the use of UAVs to organize D2D communication is reported in this paper for the first time.

The rest of the paper is organized as follows. Section 2 presents the UAV-based communication system model and Management scheme. The problem formulation is given in Section 3. Problem solution and proposed algorithm is presented in Section 4. Section 5 discusses selected numerical results. Finally, the paper is concluded in Section 6.

2 SYSTEM MODEL

We consider a wireless system composed with one UAV and multiple mobile pair devices $u = 1, .., U$ aiming to exchange data between each other using D2D communication link (i.e., D2D devices) or via the UAV (i.e., relay devices) as shown in Fig. 1. Denoted N and M by the total pairs of devices that communicate using direct D2D link and relay link, respectively. We assume that the UAV manages the

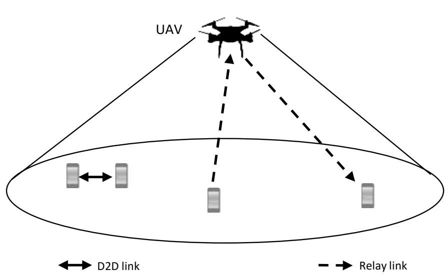

Figure 1. System Model.

resource allocations (i.e., power and bandwidth allocations) for both D2D and relay links. We consider a 3D coordinate system where the coordinate of the UAV and device u are given, respectively as $\mathbf{J}_0 = [x_0, y_0, z_0]^t$ and $\mathbf{J}_u = [x_u, y_u, 0]^t$, where $[.]^t$ is the transpose operator. We assume that the total bandwidth B is divided into two main fractions: B^d for the D2D link and B^r for the relay link. Further, we assume that all D2D users use B^d at the same time while B^r is divided to non-overlapping subfractions B^r_m such that $\sum_{m=1}^{M} B^r_m = B^r$, where B^r_m is the subfractional bandwidth assigned to the relay device m. This is a plausible assumption since the transmit power used of D2D devices is much less than the transmit power of the relay devices; and hence, using the same bandwidth for D2D devices will not cause a large interference compared to relay devices.

2.1 Channel Model

In this paper, we distinguish two channel models depending on the transmission link.

2.1.1 Ground-to-Air Path Loss Model (Relay Link). The Path Loss (PL) of ground-to-air link is a weighted combination of two PL links: Line-of-Sight (LoS) and Non Line-of-Sight (NLoS) links. This is due to the mobility and ability of UAVs to serve devices from high altitude as compared to ground base stations. In this case, there will be a probability to obtain an LoS link between the UAV and devices in the relay link [3]. The PL between the UAV positioned at a position $\mathbf{J}_0$ and a ground device m in urban environments for LoS and NLoS is given, respectively as [3]:

$$PL^{\text{LoS}}_{m,0} = \xi_{\text{LoS}} \left(\frac{4\pi\delta_{m,0}}{\lambda_0} \right), \tag{1}$$

$$PL^{\text{NLoS}}_{m,0} = \xi_{\text{NLoS}} \left(\frac{4\pi\delta_{m,0}}{\lambda_0} \right), \tag{2}$$

where $\delta_{m,0} = ||\mathbf{J}_0 - \mathbf{J}_m||$ is the distance between the UAV and the device m. λ_0 is the wavelength of the system. ξ_{LoS} and ξ_{LoS} are the additional loss to the free space propagation loss for LoS and NLoS links, respectively. The LoS probability is given by [4]:

$$p^{\text{LoS}}_{m,0} = \frac{1}{1 + \nu_1 \exp(-\nu_2[\theta_{m,0} - \nu_1])}, \tag{3}$$

where $\theta_{m,0} = \frac{180}{\pi} \sin^{-1}\left(\frac{z_0}{\delta_{m,0}}\right)$ is the elevation angle between the UAV and the device m in (degree). ν_1 and ν_2 are constant values that depend on the environment. The NLoS probability is, then, equal to $1 - p^{\text{LoS}}_{m,0}$. Therefore, the average PL for ground-to-air link is given by

$$\text{PL}_{m,0} = p^{\text{LoS}}_{m,0} PL^{\text{LoS}}_{m,0}[n] + (1 - p^{\text{LoS}}_{m,0}) PL^{\text{NLoS}}_{m,0}. \tag{4}$$

Given the PL model, the channel gain between device m and the UAV in the relay link is given as

$$h^r_{m,0} = \frac{1}{\text{PL}_{m,0}}. \tag{5}$$

2.1.2 Ground-to-Ground Channel Model (D2D Link). We assume D2D links are LoS, thus the PL between device n and the associated device $\acute{n}$ is given by the average PL for the LoS link and expressed as given in (1). Therefore, the channel gain between device n and device $\acute{n}$ in the direct link is given as

$$h^d_{n,\acute{n}} = \frac{1}{\text{PL}^{\text{LoS}}_{n,\acute{n}}}. \tag{6}$$

2.2 Rate Calculation

2.2.1 Relay link. The transmission rate from device m to the UAV in the relay link can be expressed as

$$R^r_{m,0} = B^r_m \log_2 \left(1 + \frac{P^r_{m,0} h^r_{m,0}}{B^r_m N_0}\right), \tag{7}$$

where B^r_m is the transmission bandwidth allocated to device m in the relay link, and N_0 is the noise power. Note here, in the relay link case, we assume that all devices work sparsely (allocate different bandwidth to different device, thus, no interference between devices). Similarly, the transmission rate from UAV to device $\acute{m}$ (the associated pair with device m) can be expressed as

$$R^r_{0,\acute{m}} = B^r_m \log_2 \left(1 + \frac{P^r_{0,\acute{m}} h^r_{0,\acute{m}}}{B^r_{\acute{m}} N_0}\right). \tag{8}$$

Therefore, the end-to-end maximum transmission rate at the destination (i.e., $\acute{m}$) using decode-and-forward (DF) approach where the UAV decodes the signals first before broadcasting it to the destination can be expressed as[11]

$$R^r_m = \frac{1}{2} \min \left(R^r_{m,0}, R^r_{0,\acute{m}}\right), \tag{9}$$

2.2.2 D2D link. The transmission rate from device n to its associated $\acute{n}$ in the D2D link can be expressed as

$$R^d_n = B^d \log_2 \left(1 + \frac{P^d_{n,\acute{n}} h^d_{n,\acute{n}}}{\sum\limits_{\substack{k=1 \\ k \neq n}}^{N} P^d_{k,\acute{k}} h^d_{k,\acute{n}} + B^d N_0}\right), \tag{10}$$

where $\sum_{\substack{k=1 \\ k \neq n}}^{N} P^d_{k,\acute{k}} h^d_{k,\acute{n}}$ is the interference power signal from other D2D devices.

2.3 UAV-Direct Protocol Design

In our UAV-Direct architecture, the UAV must implement a software protocol to manage the resource allocations of ground devices in addition to its trajectory. There needs to be a control link between the UAV and each devices, i.e., a UAV-Device link, so that the UAV can keep track of the devices under its coverage area. Therefore, establishing UAV-Device links by assigning portion of the bandwidth to the ground devices and maintaining these links is required (this portion is reserved only for protocol management and will not be discussed in this paper). Next, we briefly describe a protocol to manage the UAV-Device links.

2.3.1 Establishing the UAV-Device Link. To search for new devices in the UAV coverage area, the UAV periodically broadcasts a SEARCH frame. Once the ground device receives the SEARCH frame, it sends back an ACK frame. This ACK includes the Ethernet/MAC address of the device. The UAV might receive multiple ACK frames from different devices. A collision handling protocol will need to be used to resolve multiple ACKs arriving at the UAV. After receiving the ACK frames from devices, the UAV first groups the devices into two: relay devices and D2D devices (e.g., depending on the signal strength threshold); and secondly it manages the resource allocation between all devices by informing them with best power and bandwidth configurations. In addition, the UAV moves to an optimized trajectory that gives the best performance (see Section 4 for more details).

2.3.2 Maintaining the UAV-Device Link. Once a communication link is established between the UAV and a device, that device is added to a "device table" the UAV maintains. This table is updated via periodic exchange of SEARCH-ACK messages as described in the previous subsection. When there is a change in a UAV-Device link, the UAV needs to update its device table and re-optimize the resource allocations and its trajectory.

2.3.3 Terminating the UAV-Device Link. When a device does not respond with an ACK or its power goes down, the UAV needs to update the neighbor table and resolve the optimization again taking into consideration this change. possible ways to terminate a UAV-Device link:

- *Graceful Leave*: The device tells the UAV that its battery is powering down by sending a CLOSE frame to the UAV.
- *Ungraceful Leave*: The device terminates without informing the UAV (either in purpose or unexpected powering down). In this case, the UAV will keep sending its SEARCH frames, and will timeout on leaving device after μ SEARCH frames without an ACK, where μ is the maximum number of search frames without ACK from a device. Note that μ value can be chosen based on the application

3 PROBLEM FORMULATION

Let $\mathcal{U}(R^d_n, R^d_m)$ denote the rate utility (i.e., objective function metric) of all devices. A key goal of UAV-Direct is to maximize the utility of all devices. In this section, we formulate an optimization problem aiming to maximize the rate utility over all devices by tuning the following parameters: 1) transmit power levels of the devices ($P^d_{n,\acute{n}}, P^r_{m,0}$) and UAV ($P^r_{0,\acute{m}}$), 2) bandwidth allocation to each device D2D devices (B^d) and relay device (B^r_m), and 3) trajectory of the UAV. Therefore, the optimization problem can be formulated as follows

$$\underset{\substack{B^d, B^r_m, \mathrm{J}_0, \\ P^r_{m,0}, P^r_{0,\acute{m}}, P^d_{n,\acute{n}}}}{\text{maximize}} \quad \mathcal{U}(R^d_n, R^d_m) \tag{11}$$

subject to:

$$0 \leq P^r_{m,0} \leq \bar{P}, \quad \forall m, \tag{12}$$

$$0 \leq P^d_{n,\acute{n}} \leq \bar{P}, \quad \forall n, \tag{13}$$

$$\sum_{m=1}^{M} P^r_{0,\acute{m}} \leq \bar{P}_0, \quad \forall m, \tag{14}$$

$$B^d + \sum_{m=1}^{M} B^r_m \leq \bar{B}, \quad \forall m, \tag{15}$$

$$B^d, B^r_m, \geq 0, \quad \forall m, \tag{16}$$

where constraints (12), (13), and (14) represent the peak power constraints at relay devices, D2D devices, and UAV, respectively. Constraint (15) and (16) are to ensure the system bandwidth bounds. In this work, we select to use Max-Min utility. The Max-Min utilities are a family of utility functions attempting to maximize the minimum data rate in the network $\mathcal{U}(R_n^d, R_m^d) = \min_{m,n}(R_n^d, R_m^d)$ [6]. By increasing the priority of devices having lower rates, Max-Min utilities lead to more fairness in the network. In order to simplify the problem for this approach, we define a new decision variable $R_{\min} = \min_{m,n}(R_n^d, R_m^d)$. Therefore, our optimization problem becomes as follows

$$\underset{\substack{B^d, B_m^r, \mathrm{J}_0, R_{\min},\\ P_{m,0}^r, P_{0,\acute{m}}^r, P_{n,\acute{n}}^d}}{\text{maximize}} \quad R_{\min} \tag{17}$$

subject to:

$$\frac{1}{2} R_{0,\acute{m}}^r \geq R_{\min} \quad \forall m = 1, .., M, \tag{18}$$

$$\frac{1}{2} R_{m,0}^r \geq R_{\min} \quad \forall m = 1, .., M, \tag{19}$$

$$R_n^d \geq R_{\min} \quad \forall n = 1, .., N, \tag{20}$$

$$(12), (13), (14), (15), (16). \tag{21}$$

4 PROPOSED SOLUTION

The formulated optimization problem is a non-convex problem due to constraints (18)- (20) and its optimal closed-form solution remains unsolved. For this reason, we propose to solve it in three iterative steps. We firstly optimize the power allocations by assuming fixed bandwidths and UAV trajectory. As a result, we propose an approximated solution to convert our formulated problem to a convex one. We, then, optimize the bandwidth allocations for both D2D and relay devices with a similar approximation technique. Finally, we employ a recursive search algorithm to optimize the UAV trajectory. These steps are repeated until this solution converge.

4.1 Transmit Power Allocations

Since the relay devices operate sparsely, the optimal value of their transmitted power to enhance their throughput is equal to $P_{m,0}^r = \bar{P}$. Even after finding the optimal solution for $P_{m,0}^r$, the optimization problem is still non-convex with respect to other power variables. For fixed bandwidth allocations and UAV trajectory, the optimization problem can be given as

$$\textbf{(P1):} \underset{P_{0,\acute{m}}^r, P_{n,\acute{n}}^d, R_{\min}}{\text{maximize}} \quad R_{\min} \tag{22}$$

subject to:

$$(13), (14), (19), (20). \tag{23}$$

The objective function and all constraints of **P1** are convex functions except constraint (20). This constraint is neither concave nor convex with respect to $P_{n,\acute{n}}^d$. We can expand the left hand side of constraint (20) as follows:

$$\begin{aligned} R_n^d =& B^d \log_2 \left(\frac{B^d N_0 + \sum_{k=1}^{N} P_{k,\acute{k}}^d h_{k,\acute{n}}^d}{\sum_{\substack{k=1\\k\neq n}}^{N} P_{k,\acute{k}}^d h_{k,\acute{n}}^d + B^d N_0} \right) \\ =& \underbrace{B^d \log_2 \left(B^d N_0 + \sum_{k=1}^{N} P_{k,\acute{k}}^d h_{k,\acute{n}}^d \right)}_{\tilde{R}_{n,1}^d} \\ & \underbrace{- B^d \log_2 \left(\sum_{\substack{k=1\\k\neq n}}^{N} P_{k,\acute{k}}^d h_{k,\acute{n}}^d + B^d N_0 \right)}_{\tilde{R}_{n,2}^d}. \end{aligned} \tag{24}$$

Our goal is to convert (24) to a concave form in order for **P1** to become convex. Note that $\tilde{R}_{n,1}^d$ is concave, because the log of an affine function is concave [9]. Also, it can be noticed that the $\tilde{R}_{n,2}^d$ is a convex function, and thus, it needs to be converted to a concave function. To tackle the non-concavity of $\tilde{R}_{n,2}^d$, the Successive Convex Approximation (SCA) technique can be applied where in each iteration, the original function is approximated by a more tractable function at a given local point. Recall that $\tilde{R}_{n,2}^d$ is convex in $P_{n,\acute{n}}^d$ and since any convex function can be globally lower-bounded by its first order Taylor expansion at any point. Therefore, given $P_{n,\acute{n}}^d(r)$ in iteration r, we obtain the following lower bound for $\tilde{R}_{n,2}^d$(r):

$$\tilde{R}_{n,2}^d(r) \geq -B^d \log_2 (\psi(r)) - \frac{h_{k,\acute{n}}^d}{\ln(2)\psi(r)} (P_{k,\acute{k}}^d - P_{k,\acute{k}}^d(r)) \tag{25}$$

where $\psi(r) = \sum_{\substack{k=1\\k\neq n}}^{N} P_{k,\acute{k}}^d(r) h_{k,\acute{n}}^d + B^d N_0$. Now, **P1** is a convex optimization and optimal solution can be found using SCA.

4.2 Bandwidth Allocations

For given power allocations and UAV trajectory, the optimization problem that optimizes the bandwidth allocations can be given as

$$\textbf{(P2):} \underset{B^d, B_m^r, R_{\min}}{\text{maximize}} \quad R_{\min} \tag{26}$$

subject to:

$$(15), (16), (18), (19), (20). \tag{27}$$

The objective function and all constraints of **P2** are convex functions except constraints (18)-(20). These constraints are neither concave nor convex with respect to the bandwidth allocations. We can apply the same approximation technique used in Section 4.1 to convert this problem to a convex one. Analysis is omitted here due to the space limitation.

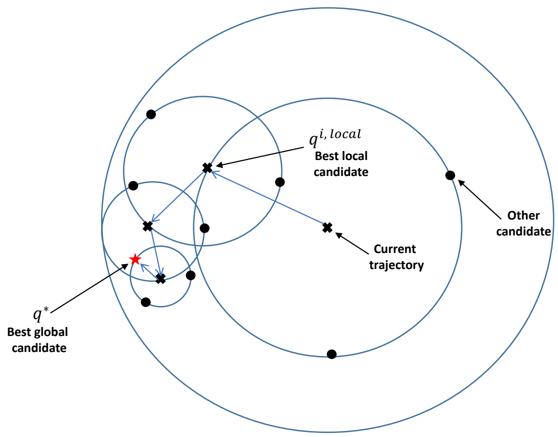

Figure 2. Shrink-and-realign process.

4.3 UAV Trajectory Optimization

In this subsection, we consider optimizing the trajectories of the UAV for fixed resource allocations (i.e., transmit powers and bandwidth allocations). Even with fixed resource allocations, the problem is still non-convex and it is very difficult to find an approximate solution due to the channel expression given in (5). Therefore, we introduce a quick and efficient heuristic algorithm based on a shrink-and-realign process. The main advantages of this approach over other heuristic algorithms can be summarized as follows: (i) it is easy to implement by using a simple search process with few parameters to manipulate, (ii) it has low computational cost, and (iii) it provides a fast convergence to a close-to-optimal solution.

We propose a Recursive Uniform Search (RUS) algorithm to optimize the UAV trajectories. In a simplifying approach, the problem of UAV trajectory optimization can be reduced to selecting the next position where the UAV will go to. Our algorithm starts by generating initial Q high efficiency next position candidates $\mathbf{J}_0^q,\ q = 1 \cdots Q$ to identify promising candidates and to form initial populations $\mathcal{Q}$. We select to distribute the candidates uniformly over the surface of a sphere (we start by assuming the radius of this sphere r_0 equal to half of the UAV coverage radius) and the initial candidate is its center. Then, it determines the objective function achieved by each candidate by solving **P1** and **P2**, this will guide us to the direction of the best candidate. After that, it finds the initial best local candidate $q^{i,\text{local}}$ that provides the highest solution for iteration i. Then, we start recursive sampling with uniform distribution over a new sphere with radius equal to half of the previous sphere and $q^{i,\text{local}}$ is the center of the new sphere. Using this shrink-and-realign of sample spaces, the algorithm progresses to find the best solution q^* and the corresponding trajectory $\mathbf{J}^{q^*}$. The shrink-and-realign procedure is repeated until the size of the sample space decreases below a certain threshold or reach maximum iteration I_{iter}. Fig. 2 shows a 2-D example.

Note that RUS is a modified version of RUS algorithm described in [7] and Recursive Random Search (RRS) algorithm described in [15], where it has been tested on a suite of well-known and difficult benchmark functions. The results in [15] showed that in terms of quickly locating a âĂIJgoodâĂİ solution, RRS outperforms other search algorithms, such as multistage pattern search and controlled random search. The details of the joint optimization approach are given in Algorithm 1.

Table 1. System parameters

Parameter	Value	Parameter	Value
ν_1	9.6	ν_2	0.29
λ (m)	0.125	$\bar{B}$(MHz)	5
ξ_{LoS} (dB)	1	ξ_{NLoS} (dB)	12
Q	8	I_{iter}	10

Algorithm 1 Joint optimization algorithm

```
Generate an initial population 𝒬 composed of Q candidates J_0^q, q = 1···Q.
while Not converged or reached maximum iteration do
    for q = 1···Q do
        Initial P^r_{m,0}, P^r_{0,ṁ}, P^d_{n,ń}, B^d, B^r_m
        while Not converged do
            Find P^r_{m,0}, P^r_{0,ṁ}, P^d_{n,ń}, B^d, B^r_m by solving P1 and P2 optimization problems for candidate q after using the approximation approaches described in Section 4-A and Section 4-B to convert the problems to convex optimization problems.
            Compute R_min given in (17) .
        end while
    end for
    Find (q^{i,local}) = arg max_q R_min, (i.e., q^{i,local} indicates the index of the best local candidate that results in the highest objective function for iteration i).
    Start recursive sampling with uniform distribution over a sphere with center and radius equal to q^{i,local} and r_0/2, respectively.
    Update the radius r_0 = r_0/2 to prepare for the next iteration.
end while
```

5 SELECTED NUMERICAL RESULTS

In this section, selected numerical results are provided to demonstrate the benefits of our UAV-Direct approach for optimizing the D2D communication throughput by tuning transmit power and UAV trajectory. We consider a system with $U = 10$ ground devices consisting of $M = 6$ pairs of relay devices and $N = 4$ pairs of D2D devices distributed randomly within an area of 200m × 200m. The UAV is flying at a fixed altitude $z_0 = 60$ m. The peak transmit power of the UAV and ground device are $\bar{P}_0 = 36$ dBm and $\bar{P} = 20$ dBm, respectively, unless otherwise stated. The noise power N_0 is assumed to be 2.5×10^{-25} W/Hz. In Table 1, using the values in [5], we summarize the values of the remaining environmental parameters.

Fig. 3 shows achieved minimum device throughput versus devicesâĂŹ transmit power $\bar{P}$ with the UAV peak transmit power $\bar{P}_0 = 6$ dBm. We compare our proposed solution to two other solutions: 1- trajectory exhaustive search, and 2- uniform resources. The exhaustive search solves P1 and P2 similar to our proposed one, in addition to that, it discretizes the coverage area to very large number of candidates $\tilde{Q}$ in order to find the best UAV trajectory. The uniform resources approach considers a uniform allocation where the power and the bandwidth are divided equally among all devices

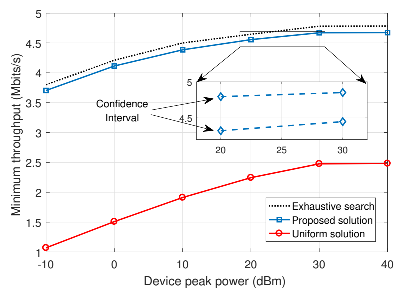

Figure 3. The minimum throughput versus $\bar{P}_0 = 36$ dBm, $M = 6$ and $N = 4$.

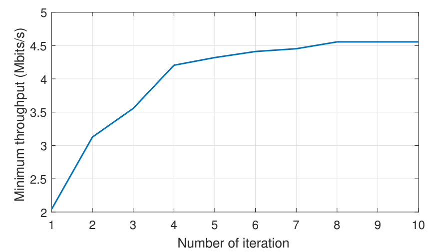

Figure 4. Convergence speed for $\bar{P}_0 = 4$ W, $M = 6$ and $N = 4$

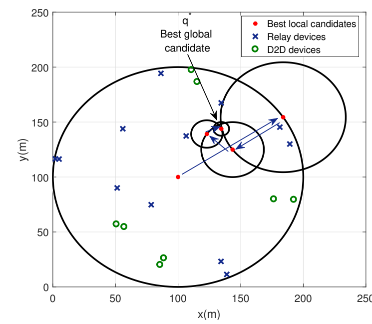

Figure 5. The proposed trajectory algorithm example with $\bar{P}_0 = 36$ dBm, $\bar{P} = 20$ dBm, $M = 6$ and $N = 4$.

(i.e., $P^r_{m,0} = P^d_{n,\acute{n}} = \bar{P}$ dBm, $P^r_{0,\acute{m}} = \bar{P}_0/M$, $B^r = B^d = \bar{B}/(M+N)$), in addition to that it uses the proposed RUS algorithm (given in Section 4.3) to find the best UAV trajectory. This figure shows that our proposed algorithm is close in performance to exhaustive search (i.e., optimal trajectory) with complexity of order $O(QQ_pI_{\text{iter}})$ compared to $O(\tilde{Q}Q_p)$ complexity order for exhaustive search, where Q_p is the complexity of solving both P1-P2. Furthermore, the improvement of our proposed algorithm over the uniform resources approach is shown clearly. For instance, using $\bar{P} = 20$ dBm, our proposed solution can improve the throughput by around 50% over the uniform resources approach by achieving 4.5 MBits/s instead of 2.3 MBits/s. Another remark can be deduced from this figure, that the achievable throughput is improving with the increase of $\bar{P}$ up to a certain point, due to the fact that the minimum throughput also depends on the $R^r_{0,\acute{m}}$ that is independent on $\bar{P}$.

Finally, the convergence speed of our proposed algorithm is shown in Fig. 4 and Fig. 5. In Fig. 4, we plot the minimum throughput versus the number of iterations to solve P1 and P2. Note that an iteration in Fig. 4 corresponds to one iteration of the âĂIJwhile loopâĂİ given in Algorithm 1 (i.e., line 6-7). While Fig. 5 shows the required number of iterations to reach the optimal UAV trajectory. In other words, it corresponds to the shrink-and-realign iteration of Algorithm 1 (i.e., 3-12). In this figure, it shows that we require only 4 iterations to achieve a near optimal solution.

6 CONCLUSIONS

In this paper, we proposed a new approach called UAV-Direct that manages the power and bandwidth allocation of ground devices. A new UAV-Direct protocol has been designed to manage the resource allocations. Furthermore, an approximation solution was proposed to maximize the minimum throughput of the ground devices. Moreover, an efficient algorithm based on a recursive shrink-and-realign process is proposed to optimize the optimal UAV trajectory. Results showed the behavior of our proposed approach and its significant impacts on the devices' throughput. In our next challenging task, multiple UAVs will be considered to serve users in multiple cells. This will add more complexity to the problem, but on the other hand, it will further improve the performance. In addition to that, developing a synchronization technique among all devices will be investigated.

ACKNOWLEDGEMENT

This work was funded in part by the following grants: NSF 1663761, NSF 1647189, and NIST 70NANB17H188.

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