Low Overhead Drone Relaying in Urban and Suburban Environments

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***Abstract*—This paper studies a drone relay assisted cooperative wireless communication system. Specifically, a drone is used as the relay node to establish communication between the base station and an aerial mobile terminal under realistic channel models with the consideration of line-of-sight probability. The total transmission time is divided into smaller time slots and in each time slot the relay uses decode-and-forward protocol to forward the received information to the mobile terminal. Then, an optimization problem is formulated where the objective is to maximize the sum rate over the whole transmission time. The formulated problem is non-convex. However, we show that for several cases the global optimal solution can be achieved. Moreover, we develop a low-complexity algorithm to find suboptimal solutions for the other cases.**

***Index Terms*—Drone communications, sum rate maximization, resource allocation.**

I. Introduction

In recent years, drones have attracted a lot of attention from different sectors such as commerce, health, and security among others for improving the service quality in terms of reduced delivery time, and improved surveillance capability. The most attractive features of drones include reduced physical size/cost, flexibility in operation and ease of deployment. Owing to these desirable attributes of drones, the wireless communication research community is also exploring the possibilities of drone deployments in wireless networks for improving the key performance metrics in wireless communication systems (WCS).

Specifically, much recent research effort has been focused toward developing optimization techniques for fully utilizing the drones potential in wireless communication systems. The existing literature on drone assisted WCS can be divided into two main categories: (i) channel modeling and performance evaluation; and (ii) performance optimization studies. The first category deals with channel modeling techniques for air-to-ground, air-to-air channels, and throughput, coverage issues analysis. In the later category, performance optimization studies deal with the positioning, trajectory and resource allocation optimization techniques for maximizing the performance of the drones assisted WCS.

In order to gain the benefit from the mobility feature of the drones, several efficient trajectory optimization techniques have been developed. In this regard, resource allocation and trajectory optimization techniques for maximizing the sum rate of a drone-relay assisted link were proposed in [1]. This work was then extended in [2] for assisting multi-cell communication, in [3] and [4] by incorporating frequency allocation issues in the system model. More recently, a multi-objective optimization technique which maximizes the sum rate while satisfying the minimum surveillance performance was proposed in [5].

While trajectory optimization is an effective approach for improving the communication performance, it requires lot of coordination at the back-end to avoid mid-air collisions due to two dimensional movement of drones. Another approach that minimizes the continuous back-end coordination is based on positioning optimization of drones. In this context, a 3D positioning and resource allocation scheme was proposed in [6], where the proposed algorithm leverages the geographical information of the service area to obtain the optimal position of the drone relay. For multiple drone scenario, alternating optimization based resource allocation, clustering and positioning for maximizing the sum rate was proposed in [7]. In [8], a joint drone placement and resource allocation scheme was developed to minimize the sum power consumption.

Although placement optimization of the drones according to the communicating entities channel gains and positions can improve the communication performance, it may not be practically possible to place the drones at the obtained optimal positions. For instance, it is usually desirable to place the drones at a location where recharging of their batteries can be performed quickly to avoid longer down-times of the network. Moreover, in urban environments, the optimal position for the drone could be in the no-fly zone.

To address the above issues, in this paper, we propose to adjust the height profile of the drone at a fixed horizontal position while considering a practical path loss model for the environments [9]. Specifically, we consider a drone relay link between the base station and a downlink user where direct link between the base station and downlink user is unavailable due to building blockages. Then, our goal is to design a joint resource allocation and drone height profile optimization scheme to maximize the total amount of data transferred over the relay link during a finite time duration. To this end, we propose an alternating optimization based iterative algorithm where in each iteration the power allocations and the height profile of the drone relay are alternately optimized over all the time slots. Our analysis shows that among the 10 possible scenarios for the initial drone height, the proposed algorithm can obtain the global optimal solution for 4 scenarios. For the remaining 6 scenarios, we propose a low complexity algorithm, where for a fixed height profile of the drone, power allocations are obtained from the closed-form expressions and the height profile is obtained by solving a single variable convex optimization problem.

II. System Model and problem formulation

A. Deployment scenario

The considered system model in this paper consists of a small base station (SBS), a drone relay (DR) and a mobile terminal (MT). We consider an urban/suburban environment, which is densely populated with buildings. Hence, we assume that there communication between SBS and MS is only possible with the help of a DR. The considered scenario is depicted in Fig. 1. In the following, we denote the height of the DR at i-th time instant with $h_D(i)$, and that of SBS and MT over all the time instants are denoted by h_S, h_M, respectively. While the DR can change its height, the horizontal positions of DR, SBS, MT are fixed for the whole duration of communication due to the reasons explained in Introduction section. We assume that the maximum ascent/descent velocity of the DR is V_{max}. The horizontal distance between SBS and DR, DR and MT, are denoted by d_{SD}, d_{DM}, respectively.

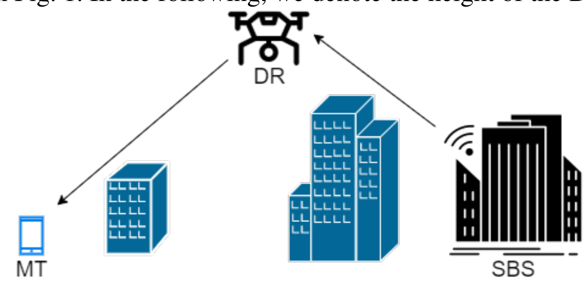

Fig. 1. System model with DR, SBS and MT, where direct link is blocked due to buildings.

B. Path loss model

Following the propagation model introduced in [9], we assume that the path loss between any two communicating nodes is dependent on several factors such as: distance, height, line of sight (LoS) probability and the environmental parameters. Specifically, the LoS probability between node $k, l \in \{S, D, M\}$, where S denotes SBS, D denotes DR and M denotes MT, is given as [9]

$$P_{kl}^{LoS}(i) = \left[1 + a \exp\left(-b\left(\arctan\left(\frac{h_{kl}(i)}{d_{kl}}\right) - a\right)\right)\right]^{-1}, \quad (1)$$

where a, b are dependent on the environment. Moreover, h_{kl} represents the absolute height difference between the heights of node k and node l. Using the LoS probability in (1), we can write the overall path loss in dB at the operating frequency f experienced between communicating nodes $k, l \in \{S, D, M\}$ can be written as [9]

$$PL_{kl}(i) = (\eta_{LoS} - \eta_{NLoS}) P_{kl}^{LoS}(i) + 10 \log\left(h_{kl}^2 + d_{kl}^2\right) + B, \quad (2)$$

where η_{LoS}, η_{NLoS} are the excessive path losses for LoS and non-LoS paths, respectively and $B = 20\log(f) + 20\log\left(\frac{4\pi}{c}\right) + \eta_{NLoS}$ with c being the speed of light. An example path loss depiction is presented in Fig. 2. It can be observed that the path loss first decreases with the increase in the relative height of DR and then increases with the increase in relative height of DR. The initial decrease is due to the higher probability of LoS while the later rise is caused by the increased overall distance due to height increase. A similar phenomenon is also observed in many previous works. As noted in Fig. 1, the optimal height at which the path loss is minimum is dependent on the horizontal distance. In the following, we use h_M^*, h_S^* to denote the optimal height of DR with respect to MT and SBS, respectively. Moreover, we use V_{min}^h to denote the minimum ascent/descent velocity needed to reach from height $h_s = h_D(0)$ to height h within I time slots.

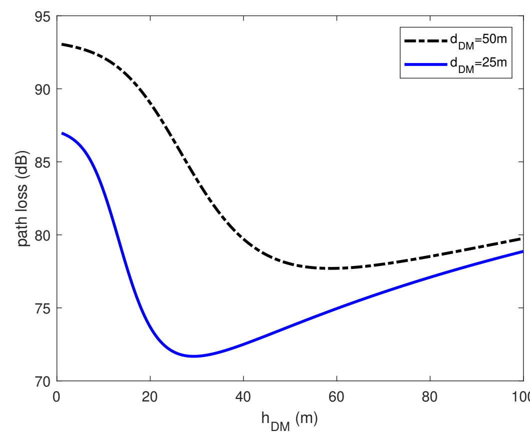

Fig. 2. Path loss with respect to relative height of the DR.

C. Communication performance metric

We consider a half-duplex decode and forward (DF) relay protocol where during the i-th time slot, the SBS transmit its signal to the DR with transmit power $p_S(i)$. Without loss of generality, we assume that the duration of each time slot is $\Delta t = 1$ second. Hence, the received signal to noise ratio (SNR) at the DR can be written as

$$\gamma_{SD}(i) = \frac{p_S(i)\mathcal{PL}_{SD}(i)}{N_0}, \ \forall\ i \ \in \{1, \cdots, I-1\}, \quad (3)$$

where N_0 is the sum of noise power and minor interference at DR, $\mathcal{PL}_{kl}(i) = 10^{\frac{PL_{kl}(i)}{10}}$, for $k, l \in \{S, D, M\}$ and I is the total number of time slots. Moreover, in the i-th time slot, for $i \in \{2, \cdots, I\}$, the DR transmits the decoded signal to the MT with transmit power $p_D(i)$. Hence, the received SNR at the MT can be written as

$$\gamma_{DM}(i) = \frac{p_D(i)\mathcal{PL}_{DM}(i)}{N_0}, \ \forall\ i \ \in \{2, \cdots, I\}. \quad (4)$$

With the help of (3), (4) the data rates between SBS and DR can be written as

$$R_{SD}(i) = \log\left(1 + \gamma_{SD}(i)\right) = \log\left(1 + \frac{p_S(i)\mathcal{PL}_{SD}(i)}{N_0}\right). \quad (5)$$

Similarly, the data rate between DR and MT is given as

$$R_{DM}(i) = \log\left(1 + \gamma_{DM}(i)\right) = \log\left(1 + \frac{p_D(i)\mathcal{PL}_{DM}(i)}{N_0}\right). \quad (6)$$

Then, the overall data transferred to MT over I time slots can be written as

$$\sum_{i=2}^{I} R_{DM}(i) = \sum_{i=2}^{I} \log\left(1+\frac{p_D(i)\mathcal{PL}_{DM}(i)}{N_0}\right). \quad (7)$$

Moreover, the DR can only retransmit that data in any given time slot which it has already received during the previous time slots. Thus, the amount of data transferred from DR to MT over $j \in \{2, \cdots, I\}$ time slots should be smaller than the amount of data transferred from SBS to DR over $j \in \{1, \cdots, I-1\}$ time slots. Mathematically, this condition can be written as

$$\sum_{j=2}^{i} \log(1+\gamma_{DM}(j)) \leq \sum_{j=1}^{i-1} \log(1+\gamma_{SD}(j)),\ \forall\ i \in \{2, \cdots, I\}. \quad (8)$$

It is clear from (1)-(8) that the total amount of data transferred to MT is dependent on the height of the DR in each time slot and the transmit powers of SBS and DR in each time slot. Therefore, it is important to find the optimal value of $h_D(i), p_S(i), p_D(i)$ for maximizing the data transfer to MT. In this context, we formulate following optimization problem:

P1:

$$\begin{aligned}
\underset{p_S(i), p_D(i), h(i)}{\text{maximize}} \quad & \sum_{i=2}^{I} \log_2(1+\gamma_{DM}(i)) \\
\text{subject to} \quad & C1: \sum_{j=2}^{i} \log(1+\gamma_{DM}(j)) \leq \sum_{j=1}^{i-1} \log(1+\gamma_{SD}(j)), \\
& C2: \ \sum_{i=1}^{I-1} p_S(i) \leq E_S, \\
& C3: \ \sum_{i=2}^{I} p_D(i) \leq E_D, \\
& C4: \ p_S(i) \geq 0, \quad p_D(i) \geq 0, \\
& C5: \ |h(i+1) - h(i)| \leq V_{max}\Delta t, \\
& C6: \ h_d(0) = h_s.
\end{aligned}$$

In **P1**, $C1$ represents the data causality constraint (8), $C2$, $C3$ are the constraints on the total energy consumed during I time slots, $C4$ imposes the non-negativity constraint on the transmission powers, $C5$ represents the maximum speed limit of the DR ascent/descent. Finally, $C6$ impose the constraint on initial height of the DR. It is clear that **P1** is a non-convex optimization problem due to the coupling of optimization variables. In the next section, we propose an alternating optimization based iterative algorithm for solving **P1**.

III. Proposed solution

In the proposed alternating optimization based approach, first we perform optimization with respect to the SBS and DR transmit powers for a fixed height profile of DR. Then, we perform optimization with respect to the height profile of DR with fixed transmit powers of SBS and DR. The details of these procedures is given in the following subsections.

A. Transmit Power Optimization for SBS and DR with Fixed Height Profile of DR

For a given height profile of DR, it can be shown that **P1** can be equivalently written as

P1.2:

$$\begin{aligned}
\underset{p_S(i), p_D(i)}{\text{maximize}} \quad & \sum_{i=2}^{I} R_{DM}(i) \\
\text{subject to} \quad & C8: \quad \sum_{j=2}^{i} R_{DM}(j) \leq \sum_{j=1}^{i-1} \log_2(1+\gamma_{SD}(j)), \\
& C9: \quad R_{DM}(i) \leq \log_2(1+\gamma_{DM}(i)), \\
& C10: \quad C2 - C4.
\end{aligned} \quad (9)$$

Since **P1.2** is a convex optimization problem and the Slater conditions are satisfied, we can use Karush Kuhn Tucker conditions to find its solution [10]. Assuming that λ_i is the dual variables associated with i-th constraint in $C8$, it can be shown that the optimal transmit powers for SBS and DR that solve **P1.2** are given as [1]

$$p_S^*(i) = \max\left(\eta\beta_i - \frac{1}{\gamma_{SD}(i)}, 0\right), \quad (10)$$

$$p_D^*(i) = \max\left(\zeta\nu_i - \frac{1}{\gamma_{DM}(i)}, 0\right), \quad (11)$$

where $\beta_i = \sum_{j=i+1}^{I} \lambda_i, \nu_i = 1 - \sum_{j=i}^{I} \lambda_i$, and η, ζ are chosen such that $\sum_{j=1}^{I-1} p_S^*(j) = E_S$ and $\sum_{j=2}^{I} p_D^*(j) = E_D$, respectively.

B. Height Profile Optimization of DR for Fixed Transmit Powers of SBS and DR

In order to perform optimization with respect to DR height profile, and to analyze the global optimality of the proposed solution we need to consider following two cases: (1) S1: $h_M^* \geq h_S^*$, and (2) S2: $h_S^* \geq h_M^*$. First, we assume $h_M^* \geq h_S^*$, then there can be following three sub-cases in S1: (1.1) S1-1: $h_s = h_D(0) \in [0, h_S^*)$, (1.2) S1-2: $h_s = h_D(0) \in (h_M^*, \infty)$, (iii) S1-3: $h_s = h_D(0) \in [h_S^*, h_M^*]$. For S1-1 there are further two possibilities: (1.1.1) S1-1-1: $V_{max} < V_{min}^{h_S^*}$ or (1.1.2) S1-1-2: $V_{max} \geq V_{min}^{h_S^*}$. The overall possible cases are summarized in Table I below. Before proceeding further, we present following lemma for sub-case S1-1-1.

TABLE I
Possible cases for initial DR height and the maximum velocity of DR.

S1: $h_M^* \geq h_S^*$	S1-1: $h_s = h_D(0) \in [0, h_S^*)$	S1-1-1: $V_{max} < V_{min}^{h_S^*}$
		S1-1-2: $V_{max} \geq V_{min}^{h_S^*}$
	S1-2: $h_s = h_D(0) \in (h_M^*, \infty)$	S1-2-1: $V_{max} < V_{min}^{h_M^*}$
		S1-2-2: $V_{max} \geq V_{min}^{h_M^*}$
	S1-3: $h_s = h_D(0) \in [h_S^*, h_M^*]$	S1-3: $h_s = h_D(0) \in [h_S^*, h_M^*]$
S2: $h_S^* \geq h_M^*$	S2-1: $h_s = h_D(0) \in [0, h_M^*)$	S2-1-1: $V_{max} < V_{min}^{h_M^*}$
		S2-1-2: $V_{max} \geq V_{min}^{h_M^*}$
	S2-2: $h_s = h_D(0) \in (h_S^*, \infty)$	S2-2-1: $V_{max} < V_{min}^{h_S^*}$
		S2-2-2: $V_{max} \geq V_{min}^{h_S^*}$
	S2-3: $h_s = h_D(0) \in [h_M^*, h_S^*]$	S2-3: $h_s = h_D(0) \in [h_M^*, h_S^*]$

Lemma 1. *For any fixed transmit power allocations, the global optimal height profile of DR for sub-case S1-1-1 is given as*

$$h_D^*(0) = h_s, h_D^*(i) = h_s + iV_{max}. \quad (12)$$

Proof. We can proof this lemma with the help of contradiction. Assume that the optimal height profile is given as $\hat{h}_D(i)$. Furthermore, assume that for $j \in \{1, 2, \cdots, \hat{i}\}$, $\hat{h}_D(j) = h^*_D(j)$, where $h^*_D(j)$ is given in (12), while $\hat{h}_D(\hat{i}+1) < h^*_D(\hat{i}+1)$ then we can increase the ascent velocity to simultaneously reduce the path loss for SBS as well as for MT. Thus, a higher data rate can be achieved for both links in time slot $\hat{i}+1$ by replacing $\hat{h}_D(\hat{i}+1)$ by $h^*_D(\hat{i}+1)$. This contradicts the assumption that $\hat{h}_D(i)$ is the optimal height profile. Hence, the lemma is proved. □

With the help of Lemma 1, we can also obtain the optimal height profile of the DR for some other cases as summarized in following corollary.

Corollary 1. *The optimal height profile for*

- *case S1-2-1 is given as*

$$h^*_D(0) = h_s, h^*_D(i) = h_s - iV_{max}, \tag{13}$$

- *case S2-1-1 is given as*

$$h^*_D(0) = h_s, h^*_D(i) = h_s + iV_{max}, \tag{14}$$

- *case S2-2-1 is given as*

$$h^*_D(0) = h_s, h^*_D(i) = h_s - iV_{max}. \tag{15}$$

Proof. The proof follows the same line of reasoning as in the proof of Lemma 1, and hence omitted for brevity. □

Before we proceed further to find the optimal height profile for cases S1-1-2, S1-2-2, S1-3, S2-1-2, S2-2-2 and S2-3, we present an important result for the optimal height profile of DR for fixed transmission powers when constraints $C6$ is relaxed in **P1**.

Lemma 2. *Assuming that $h^*_S \leq h^*_M$ the optimal height profile for the relaxed **P1** can be characterized by following three special scenarios (SSs)*

- *SS1: DR hovers only at height h^*_S.*
- *SS2: DR hovers only at height h^*_M.*
- *SS3: DR hovers at height h^*_S for some time slots and then move with the highest velocity toward h^*_M.*
- *SS4: DR hovers neither at height h^*_b nor h^*_M.*

Moreover, the height profiles for SS1-SS4 are given as

- *For SS1: $h_D(i) = h^*_S \quad \forall i \in \{1, \cdots, n_1\}$, and $h_D(i) = h^*_S + iV_{max}, \quad \forall i \in \{n_1+1, \cdots, I\}$.*
- *For SS2: $h_D(i) = h^*_M \quad \forall i \in \{n_2, \cdots, I\}$ and $h_D(i) = h^*_M - iV_{max}, \quad \forall i \in \{1, \cdots, n_2 - 1\}$.*
- *For SS3: $h_D(i) = h^*_S \quad \forall i \in \{1, \cdots, n_3\}$, $h_D(i) = h^*_M, \quad \forall i \in \{n_3 + \frac{h^*_M - h^*_S}{V_{max}}, \cdots, I\}$, and $h_D(i) = h^*_S + iV_{max}, \quad \forall i \in \{n_3 + 1, \cdots, n_3 + \frac{h^*_M - h^*_S}{V_{max}} - 1\}$.*
- *For SS4: $h_D(i)$ can be obtained using Bisection search for the first time slot height over the search span (h^*_S, h^*_M).*

The optimal values of n_1, n_2, n_3 can be obtained from Bisection search.

Proof. The proof can be obtained using a similar approach as used in [1]. □

Note that when $h^*_M \leq h^*_S$, the expression iV_{max} should be replaced by $-iV_{max}$ in Lemma 2.

From Lemma 2, it can be observed that whenever the DR moves, it moves with a constant velocity. We use this observation to devise a sub-optimal algorithm to find the height profile for **P1** with fixed transmit power allocations. In this direction, first we obtain the optimal solution for the height profile of **P1** with C6 relaxed. Then, we use a similarity maximization approach to find the height profile of DR for cases S1-1-2, S1-2-2, S1-3, S2-1-2, S2-2-2, and S2-3 as described in the following.

Let us denote the optimal height profile for the relaxed **P1** by $h^*_D(i)$, then we devise the following similarity maximization approach to find the suboptimal height profile **P1**[1]

$$\begin{aligned} &\underset{v}{\text{minimize}} && \|\hat{\mathbf{h}}^* - \mathbf{H}[1 \;\; v]^T\|_2^2 \\ &\text{subject to} && |v| \leq V_{max}, h_D(0) = h_s \end{aligned} \tag{16}$$

where $\hat{\mathbf{h}}^* = [h^*_D(2), \cdots, h^*_D(I)]$ is the optimal height profile of the relaxed problem of **P1**, and the i-th row of $\mathbf{H}$ is given as $[h_s, \; i]$. In essence, the goal in (16) is to obtain a sub-optimal height profile of the drone during the whole transmission length by ascending/descending the drone at a constant velocity so that the difference between the sub-optimal height profile and the optimal height profile is minimum. Note that (16) is a convex optimization problem which can be efficiently solved with the help of off-the-shelf optimization tools such as CVX [11].

Based on the above analysis, we have devised an optimization algorithm for solving **P1**.

Algorithm 1: Proposed algorithm for **P1**.

Set the scenario under consideration as S;
if $S \in \{S1\text{-}1\text{-}1, S1\text{-}2\text{-}1, S2\text{-}1\text{-}1, S2\text{-}2\text{-}1\}$ **then**
  Obtain the optimal height profile according to Lemma 1;
  Obtain the optimal transmit power allocation at the SBS and DR according to (10), (11);
else
  Obtain the optimal height profile and transmit power allocation for the relaxed problem **P1**;
  Obtain the sub-optimal height profile for **P1** according to (16);
  Set the transmit power allocation according to (10), (11);
end

IV. Numerical Results

For numerical results, we assume that the $d_{SD} = 50$m and $d_{DM} = 25$m, $E_S = E_D = 10$dBm, $N_0 = -100$dBm, $a = 11.95, b = .136$, $(\eta_{Los}, \eta_{NLos}) = (.1, 21)$, $f = 2$ GHz [9].

[1]Note that we have ignored the difference caused by the height at the first time slot due to the fact that it will be a constant for the constraint $h_D(0) = h_s$ and will not affect the solution of (16).

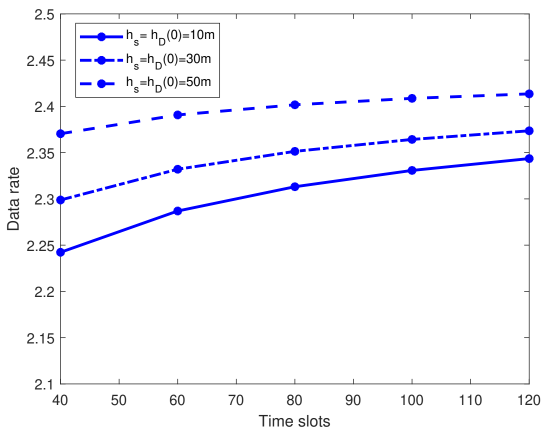

Fig. 3. Total data rate for different number of time slots.

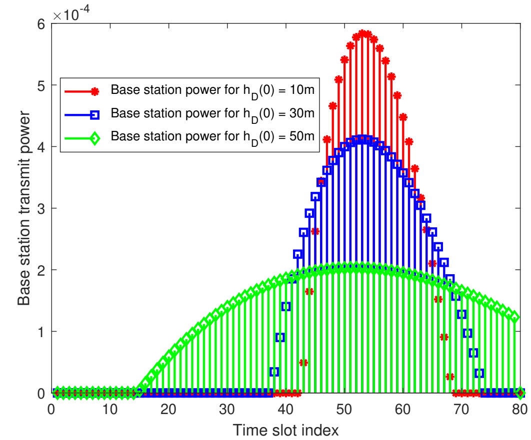

Fig. 4. Base station transmit powers for different time slots when $I = 80$.

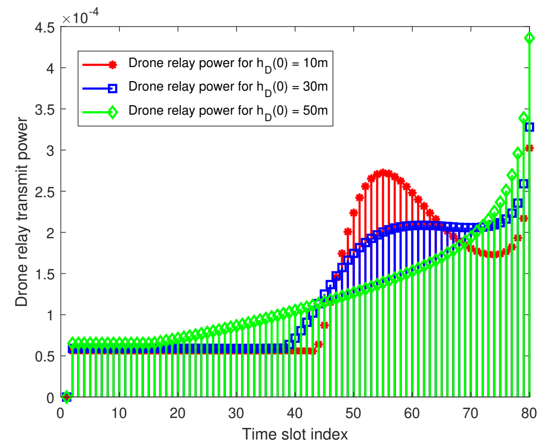

Fig. 5. Drone relay transmit powers for different time slots when $I = 80$.

With these parameter settings, first we present the total data rate results for different number of time slots and then we present the power allocation distribution at the SBS and DR.

The total data rate results for different initial heights of the DR are presented in Fig. 3. It can be seen that as the total number of time slots increase, the achieved total data rate also increases. Moreover, the data rate performance for $h_D(0) = 50$m is is superior to the other initial heights of DR. This is due to the fact that the optimal height of the DR with respect to SBS is 59m and with respect to MT is 29m and thus significantly less loss is observed between both links as compared to the case when $h_D(0) = 10$m. On the other hand, the higher rate for $h_D(0) = 50$m case as compared to $h_D(0) = 30$m case is caused by the data causality constraint which limits the amount of data transferred on SBS-DR link during the initial time slots when the channel conditions of SBS-DR link are good.

Fig. 4 and Fig. 5 show the transmit power profile for SBS and DR, respectively. From Fig. 4, we observe that the SBS transmit powers have smaller values during the initial time slots when the path loss is higher. However, SBS allocates more transmit power at the later time slots when the DR has become closer to optimal height h_S^* for utilizing the better channel conditions between SBS and DR. On the contrary, in Fig. 5, the allocation of transmit powers at DR is also higher for later time slots instead of initial time slots. This is because the data received from SBS in the initial time slots is not enough to fully utilize the better channel conditions between DR and MT during the initial time slots.

V. Conclusions

This paper considered a DR assisted communication system between SBS and MT in urban environments. Particularly, LoS probability is considered while finding the height profile of DR, and power allocations at SBS and MT for maximizing the sum rate performance. Despite the non-convexity of considered problem, an efficient low-complexity algorithm is developed which can obtain the global optimal solution for multiple scenarios.

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