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Optimal Placement of a UAV to Prolong the Lifetime of Indoor Wireless Devices [1]

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Abstract Unmanned aerial vehicles (UAVs) can be used as aerial wireless base stations when cellular networks go down. Prior studies on UAV-based wireless coverage typically consider outdoor scenarios, where a UAV and wireless devices are outdoor. In this paper, the problem of UAV placement is studied, where the goal is to find the optimum location of a single UAV that prolongs the lifetime of indoor wireless devices. First, a realistic Indoor-Outdoor path loss model is presented and the tradeoff introduced by this model is described. Then, the problem of UAV placement is formulated, where the goal is to find the optimum UAV location that prolongs the lifetime of indoor wireless devices. It can be proven that the constraint sets of the problem can be represented by a convex set in terms of three variables. To this end, an algorithm to find the optimum UAV location is proposed. Simulation results are presented to validate the effectiveness of the proposed algorithm.

Keywords Unmanned Aerial Vehicles (UAVs), Indoor-to-Outdoor Path Loss Model, Lifetime of Wireless Network, Emergency Response, Convex Optimization

1 Introduction

During disaster situations, UAVs can be deployed to provide continuous wireless coverage when the terrestrial network goes down [1]. They can also be used to provide seamless wireless coverage when the cellular network service is not available or it is unable to serve all wireless devices[2].

Prior studies on UAV-based wireless coverage typically consider outdoor scenarios, where a UAV and wireless devices are outdoor. Only a few studies consider the indoor scenarios in which an outdoor UAV is used to provide wireless coverage for indoor wireless devices. The authors in [3] suggest using a single UAV to provide indoor wireless coverage under disaster situations, where the placements of indoor wireless devices are symmetric across the dimensions of each floor, and apply the gradient descent algorithm to find an efficient placement of the UAV that minimizes the transmit power. In [4], the authors assume that the placements of indoor wireless devices are uniformly distributed in each floor and apply the particle swarm optimization algorithm to find an efficient location of a single UAV that minimizes the transmit power required to cover the indoor wireless devices. The authors in [5] minimize the number of UAVs required to provide indoor wireless coverage and prove that this problem is NP-complete. Due to the intractability of the problem, they apply clustering to minimize the number of UAVs required for indoor wireless coverage. In [6], the authors maximize the indoor wireless coverage using UAVs equipped with directional antennas. They propose two methods for the placements of UAVs; providing indoor wireless coverage from one building side and from two building sides. However, the authors of these research studies assume downlink scenarios from UAVs to indoor users.

In post-disaster scenarios such as earthquakes or floods, wireless devices may not be able to connect with remote-undamaged terrestrial cellular network due to the limited transmit power of these devices [7]. Due to physical damage to energy infrastructure, they may also not be able to recharge their batteries as shown in Figure 1. In the case of Hurricane Irma, at the peak of the power blackout following Hurricane Irma, over 36% of all accounts in Florida were without electricity [9]. In case of an emergency, one of the first things we do is to pick up our mobile phones to learn about the emergency event, locate family and friends, and report their safety [10]. In this paper, the motivation is to explore how the location of a single UAV can prolong the time durations of uplink transmissions of indoor wireless devices when a UAV is used to provide indoor wireless coverage under disaster situations. The authors in [7] and [8] study this problem under the assumption that the users are outdoor. To the best of our knowledge, this is the first work that proposes using a single UAV to prolong the sum of time durations of uplink transmissions under disaster situations, where the indoor users are not able to recharge their wireless devices due to physical damage to energy infrastruc-

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[1] Part of this work was presented in IEEE IWCMC 2018 [7].

Figure 1. Downed power lines following Hurricane Irma [14].

ture. The main contributions are summarized as follows:

- A realistic Indoor-Outdoor path loss model is presented and the tradeoff introduced by this model is described.
- The problem of UAV placement is formulated, where the goal is to find the optimum UAV location that prolongs the lifetime of indoor wireless devices.
- The constraint sets of the problem are proved that can be represented by a convex set in terms of three variables and an algorithm is proposed to find the optimum location of UAV.

The rest of this paper is organized as follows. In Section 2, the system model is described. In Section 3, the problem of UAV placement is formulated, where the goal is to find the optimum UAV location that prolongs the lifetime of indoor wireless devices. In Section 4, an algorithm is proposed to find the optimum UAV location. Finally, the numerical results are presented in Section 5 and concluding remarks are made in Section 6.

2 System Model

2.1 System Settings

In Figure 2, $|U|$ indoor wireless devices are assumed to be placed inside a building, and (x_k, y_k, z_k) is used to represent the placement of indoor wireless device $k \in U$. The dimensions of the building are $X^b \times Y^b \times Z^b$. Also, let (X^u, Y^u, Z^u) denote the placement of the UAV, let D_k^u be is the 3D outdoor path-length between the UAV and the external wall, let θ_k be the incidence angle, and let $d_{in,k}$ be the 2D indoor distance of wireless device k inside the building. Each wireless device $k \in U$ has a residual energy e_k with maximum transmit power P^{max}. The indoor wireless devices must be served by the aerial base station to collect the information. An uplink scenario is assumed in which the indoor wireless devices utilize a frequency division multiple access (FDMA) technique to send information to the UAV at a desired data rate r. FDMA allocates one subchannel to each wireless device for transmission and hence the channels do not interfere with one another. Also, each indoor device $k \in U$ is considered to be served by the aerial base station for a time t_k seconds and this time depends on the residual energy of the wireless device e_k. The time duration of uplink transmission t_k must be greater than or equal to t_{th}. The indoor wireless devices can send the values of residual energies to the UAV using control messages [11].

2.2 Indoor-Outdoor Path Loss Model

The Outdoor-Indoor path loss model, certified by the ITU [12], is not appropriate when the uplink scenario for indoor users is considered, because this model assumes that the transmitter is outdoor and the receivers are indoor. In this paper, the Indoor-Outdoor path loss model is adopted [13]. The path loss between indoor user k and the UAV is given as follows:

$$\begin{aligned} L_k^u = L_o + L_b + L_i = (w_1 + w_2 \log_{10}(D_k^u + d_{in,k})) \\ +(w_3 + w_4(1-\cos\theta_k)^2) + (w_5 d_{in,k} + w_6 q) \end{aligned} \quad (1)$$

where L_o is the outdoor propagation loss, L_b is the building penetration loss and L_i is the indoor loss. Also, $d_{in,k}$ is the indoor horizontal path-length, D_k^u is the 3D outdoor path-length, θ_k is the incidence angle on the external wall, q is the number of apartment or office separations along the indoor horizontal path and $w_1 - w_6$ are constants.

2.3 Path Loss Model Tradeoff

There is a key tradeoff in the Indoor-Outdoor path loss model when the horizontal distance between the aerial base station and an indoor wireless device changes. When this horizontal distance increases, the outdoor propagation loss (i.e., L_o) increases as D_k^u increases, while the building penetration loss

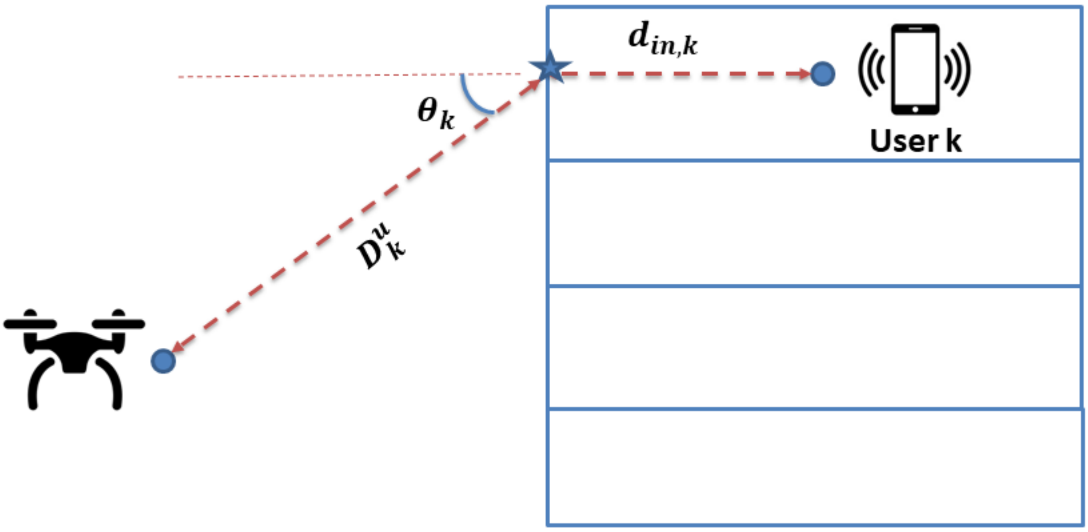

Figure 2. Indoor user transmitting data to a UAV.

(i.e., L_b) decreases as the incident angle (i.e., θ_k) decreases. Similarly, when this horizontal distance decreases, the outdoor propagation loss (i.e., L_o) decreases as D_k^u decreases, while the building penetration loss (i.e., L_b) increases as the incident angle (i.e., θ_k) increases.

Under the assumption that the locations of indoor wireless devices and the location of the UAV are fixed, the path loss between indoor wireless device k and the UAV can be represented as a function of the incidence angle θ_k:

$$\begin{aligned} L_k^u(\theta_k) = (w_1 + w_2 \log_{10}(\frac{\Delta H_k^u}{\sin\theta_k} + d_{in,k})) + (w_3 + \\ w_4(1-\cos\theta_k)^2) + (w_5 d_{in,k} + w_6 q) \end{aligned} \qquad (2)$$

where ΔH_k^u is the altitude difference between the UAV and the indoor wireless device k. In Figure 3, the minimum transmit power of the indoor wireless device required to achieve the threshold Signal-to-noise ratio (SNR) is demonstrated. The minimum transmit power of indoor wireless device is given by:

$$P_{tx,min}(dB) = P_{rx,th} + L_k^u \qquad (3)$$

$$P_{rx,th}(dB) = N + \nu \qquad (4)$$

Here, $P_{rx,th}$ is the minimum received power, N is the noise power (equals -120 dBm) and ν is the threshold SNR (equals -37 dBm). The numerical results show that there is an optimum incidence angle that minimizes the total transmit power of the indoor wireless device k. The optimum incident angle θ that minimizes the transmit power required to satisfy the threshold SNR between the indoor wireless device and the UAV is 48^o. Note that this angle is also the optimum angle for the downlink scenario, from the UAV to an indoor wireless device [3].

3 Problem Formulation

Consider a transmission between an indoor wireless device located at (x_k, y_k, z_k) and a UAV located at (X^u, Y^u, Z^u). The data rate for indoor wireless device k is given by:

$$C_k = B_k log_2 \left(1 + \frac{p_k/L_k}{N}\right) \qquad (5)$$

where B_k is the transmission bandwidth of indoor wireless device k, p_k is the transmit power from indoor wireless device k to the UAV, L_k is the path loss between indoor wireless device k and the UAV and N is the noise power.

Let us assume that all indoor wireless devices have the same data rate r and each indoor wireless device has a channel with bandwidth equals $B/|U|$, where B is the UAV bandwidth and $|U|$ is the number of indoor wireless devices. Then, the minimum power required to satisfy this data rate for each indoor wireless device is given by:

$$p_k = \left(2^{\frac{r.|U|}{B}} - 1\right).N.L_k \qquad (6)$$

Our goal is to find the optimum placement of the UAV such that the lifetime of indoor wireless devices defined by S is prolonged. Here, the lifetime S represents the sum of time durations of uplink transmissions of indoor wireless devices. Our problem can be formulated as:

$$\begin{array}{lll} \max\limits_{(X^u,Y^u,Z^u),t_k} S = \sum\limits_{k=1}^{|U|} t_k = \sum\limits_{k=1}^{|U|} \frac{e_k}{p_k} & & \\ \quad subject\ to & & \\ \qquad p_k \le P^{max} & \forall k \in U & (7.a) \\ \qquad t_k \ge t_{th} & \forall k \in U & (7.b) \\ \qquad t_k.p_k \le e_k & \forall k \in U & (7.c) \\ \qquad X^u \in [x_{min}, x_{max}] & & (7.d) \\ \qquad Y^u \in [y_{min}, y_{max}] & & (7.e) \\ \qquad Z^u \in [z_{min}, z_{max}] & & (7.f) \end{array} \qquad (7)$$

Here, constraint set (7.a) guarantees that the transmit power of each indoor wireless device is not exceed its maximum transmit power P^{max}. Constraint set (7.b) ensures that each indoor wireless device $k \in U$ is served by aerial base station for a time greater than t_{th} seconds. Constraint set (7.c) guarantees that the total energy consumed by indoor wireless device is not exceed its residual energy e_k. Constraints (7.d-7.f) show the maximum and minimum allowed values for X^u, Y^u and Z^u. Despite the optimization problem has a number of nonlinear constraints, it can be solved by proving that the constraint sets of the problem can be represented by the intersection of convex sets.

Theorem 1 *Under the assumption that the altitude of a UAV is fixed, the constraint sets in optimization problem (7) can be represented by the intersection of convex sets and the region formed by this intersection is also a convex set.*

Proof 1 *Let us assume that the altitude of a UAV Z^u is fixed. From (2) and (6), the transmit power of indoor wireless device k is given by:*

$$p_k = \left(2^{\frac{r.|U|}{B}} - 1\right).N.L_k(\theta_k) = Q.L_k(\theta_k) \tag{8}$$

where Q is a constant and equals $\left(2^{\frac{R.|I|}{B}} - 1\right).N$. Now, to satisfy constraint set (7.a), p_k must be less than P^{max}. From (8), the range of incidence angles θ_1 that satisfies the constraint set (7.a) is given by:

$$L_k(\theta_k) \leq \frac{P^{max}}{Q} \tag{9}$$

The range of incidence angles θ_1 (less than 90^o) represents a convex set. To satisfy constraint sets (7.b) and (7.c), p_k must be less than $\frac{e_k}{t_{th}}$. From (8), the range of incidence angles θ_2 that satisfies constraint sets (7.b) and (7.c) is given by:

$$L_k(\theta_k) \leq \frac{e_k}{t_{th}.Q} \tag{10}$$

The range of incidence angles θ_2 also represents a convex set. The range of distances that satisfies constraint sets (7.d) and (7.e) is given by a 2D plane. The constraint sets in optimization problem (7) can be represented by the intersection of convex sets and the region formed by this intersection is a convex set [15].

From Theorem 1, the constraints of the optimization problem (7) can be represented as a convex set, when the altitude of a UAV is fixed. In the next theorem, the objective function is proved that it is concave when the altitude of a UAV is fixed. This theorem enables us to find the optimum location for UAV.

Theorem 2 *The objective function of (7) is concave when the altitude of a UAV is fixed.*

Proof 2 *The nonnegative weighted sums preserve the concavity of function [15]. Since $e_k > 0, \forall k \in U$, we need to prove that (11) is a concave function.*

$$F = \frac{1}{L_k(\theta_k)}, \forall k \in U \tag{11}$$

From Figure 3, we can notice that $L_k(\theta_k)$ is a convex function and hence (11) is a concave function.

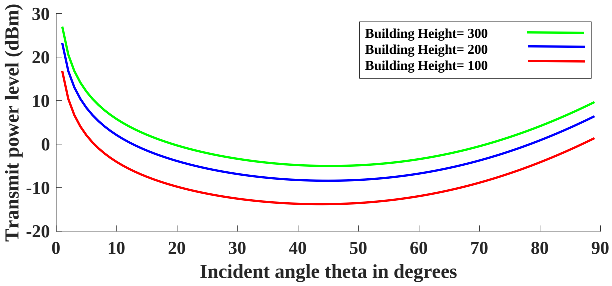

Figure 3. Minimum transmit power of indoor wireless device.

Theorem 2 enables us to find the optimum 2D location for the UAV (X^u, Y^u), when the altitude of UAV Z^u is fixed. In order to the optimum 3D location of a UAV, the optimum UAV placement algorithm is proposed in the next section.

4 Optimum UAV Placement Algorithm

The proposed algorithm to find the optimum location for a UAV is shown in Algorithm 1 as follows: The inputs are the locations of indoor wireless devices, the maximum transmit power, the residual energy of each indoor wireless device, the data rate, the total bandwidth, the noise power and the threshold time duration of uplink transmission. In steps (9-10), the convex sets V_k at different altitudes of a UAV are found. In steps (11-17), the gradient projection algorithm is used to find the optimum 2D location of a UAV $(X^u, Y^u)_{opt}$ at each altitude z_k where n is the iteration number, γ is a positive step size, ∇F is the gradient of the objective function in (7) and $[\,]^+$ denotes the orthogonal projection of a vector onto a convex set. In steps (18-19), the optimum 3D location of a UAV that prolongs the lifetime of indoor wireless devices is found.

Algorithm 1 The Optimum UAV Placement Algorithm

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1: Input:
2: The locations of $|U|$ indoor wireless devices.
3: The maximum transmit power of wireless device $P^{max}$.
4: The residual energy of each wireless device $e_k$.
5: The data rate $r$.
6: The total bandwidth $B$.
7: The noise power $N$.
8: The threshold time duration of uplink transmission. $t_{th}$.
9: For $z_k = z_{min} : z_{max}$
10: Find $V_k$
11: Initialize $(X^u, Y^u)$
12: For $n$=1,2,..., $n_{max}$
13: $(X^u, Y^u)^{n+1} = [(X^u, Y^u)^n + \gamma.\nabla F((X^u, Y^u)^n))]^+$
14:         If $\| (X^u, Y^u)^n - (X^u, Y^u)^{n+1} \| < \epsilon$
15:     Return: $(X^u, Y^u)_{opt} = (X^u, Y^u)^{n+1}$
16: End for
17: Output:$(X^u_{opt}, Y^u_{opt}, z_k)$
18: End for
19: Find the $(X^u_{opt}, Y^u_{opt}, Z^u_{opt})$ that gives the maximum lifetime.
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5 Numerical Results

In Figure 4.a, 400 indoor wireless devices (blue dots) are uniformly distributed in a building with dimensions $20m \times 50m \times 100m$, then Algorithm 1 is used to find the optimum location of the UAV that prolongs the sum of time durations of uplink transmissions. The optimum location for the UAV is $(30, 25, 57)$ and the optimum lifetime for all indoor devices is 316130 seconds. The average lifetime for each indoor wireless device will be 13.17 minutes. In Figure 4.b, the convergence speed of the Algorithm 1 is showed when the indoor wireless devices are uniformly distributed. The projection of the optimum point is located near the center of the building. This is because the indoor wireless devices that have the highest path losses are placed at the corners of the building and placing the projection of UAV near the center prolongs the total lifetime. Table I lists the parameters used in the numerical analysis.

In Figure 4.c, 400 indoor wireless devices are non-uniformly distributed in the building. To find the optimum location of the UAV that prolongs the sum of time durations of uplink transmissions, Algorithm 1 is used. The optimum location for the UAV is $(30, 32, 66)$ and the optimum lifetime for all indoor devices is 421570 seconds. The average lifetime for each indoor wireless device will be 17.56 minutes. In Figure 4.d, the convergence speed of the Algorithm 1 is showed when the indoor wireless devices are non-uniformly distributed. The UAV location is near the high density region.

In Figure 4.e, the definition of the lifetime of wireless devices is changed. The new definition of the lifetime represents the time duration of uplink transmission until the first wireless device runs out of energy (Max-Min). Under the disaster situation, it is necessary that we keep all of the indoor wireless devices up as much as we can due to physical damage to energy infrastructure. Therefore, instead of prolonging the lifetime of all indoor wireless devices, the lifetime as defined above is prolonged. The optimum location for the UAV is $(52, 24, 44)$ and the optimum lifetime is 219 seconds, when the indoor wireless devices are uniformly distributed in the building. As can be seen from the figures, the optimum horizontal point X^u increases. This is to recompense the increased building penetration loss due to an increased incident angle. In Figure 4.f, the convergence speed of the algorithm is showed when the indoor wireless devices are uniformly distributed.

In Figure 4.g, the indoor wireless devices are non-uniformly distributed in the building. The objective is finding the optimum location of the UAV that prolongs the time duration of uplink transmission until the first wireless device runs out of energy (Max-Min). The optimum location for the UAV is $(57, 34, 61)$ and the optimum lifetime is 300 seconds. In Figure 4.h, the convergence speed of the algorithm is showed when the indoor wireless devices are non-uniformly distributed.

6 Conclusions

In this paper, the problem of UAV placement is studied, where the goal is to find the optimum location of a single UAV that prolongs the lifetime of indoor wireless devices. First, a realistic Indoor-outdoor path loss model is presented and the tradeoff introduced by this model is described. Then, the problem of UAV placement is formulated, where the goal is to find the optimum UAV location that prolongs the lifetime of indoor wireless devices. The constraint sets of problem are proved that can be represented by a convex set in terms of three variables and an algorithm is proposed to find the optimum location of UAV. The analysis is validated by simulations and the effectiveness of the proposed algorithm is demonstrated under different cases. In order to model more realistic scenarios, different types of user distribution can be considered as future work. Also, the problem of prolonging the lifetime of wireless devices can be studied using multiple UAVs.

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Table 1. Parameters in numerical analysis

Dimensions of the building	$20m \times 50m \times 100m$
Number of wireless devices U	400 devices
Maximum number of iterations n_{max}	100
Maximum transmit power of wireless device P^{max}	0.5 watt
Energy of each wireless device e_k in joule	4500+13500*rand(200,1)
Data rate r	1 Mbps
Total bandwidth B	50 MHz
The noise power N	1×10^{-14}
The carrier frequency	2 Ghz
Threshold time duration of uplink transmission t_{th}	200 seconds
$[x_{min}, x_{max}]$	[25,100]
$[y_{min}, y_{max}]$	[0,50]
$[z_{min}, z_{max}]$	[10,100]

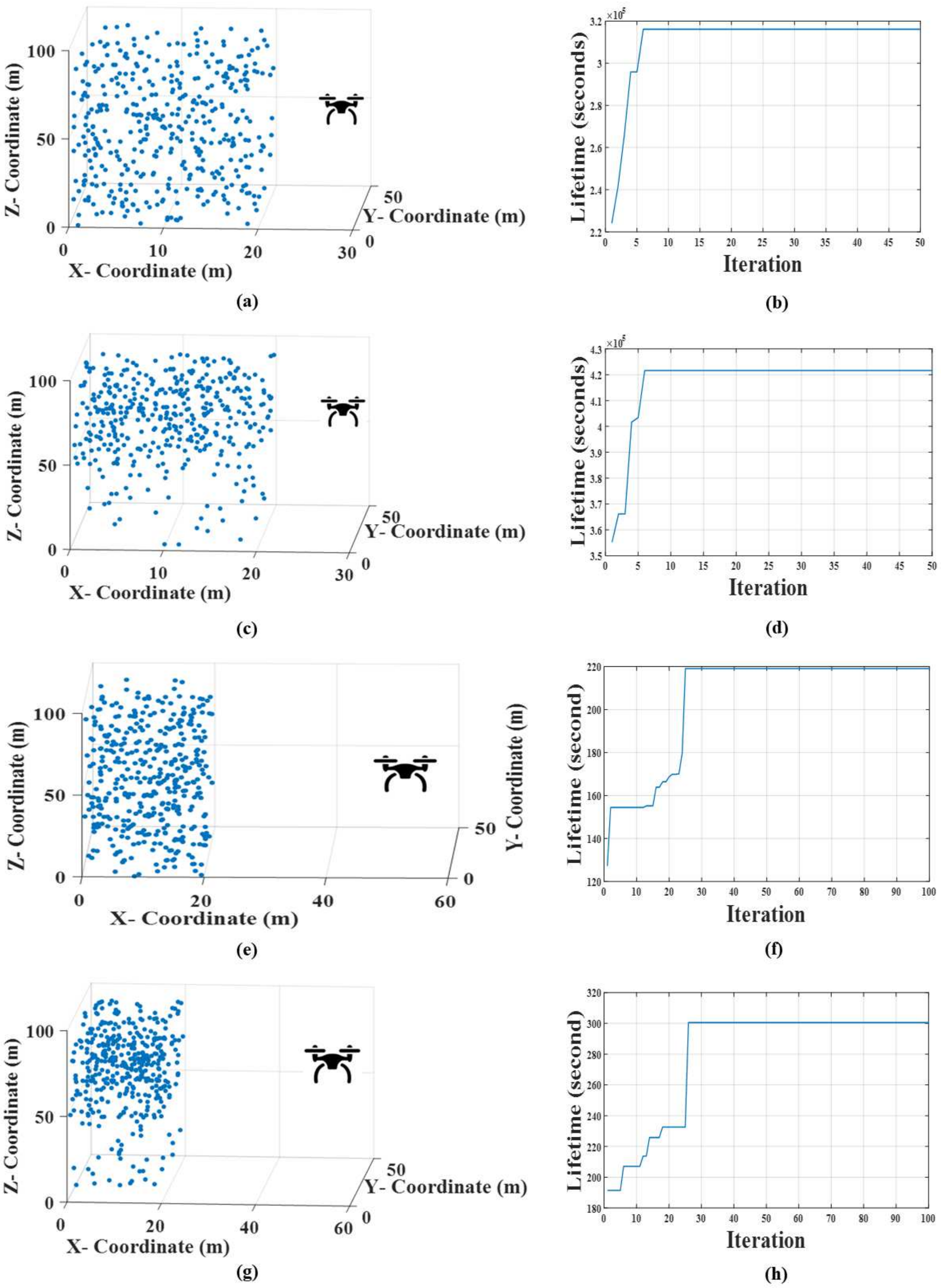

Figure 4. The optimum 3D placement of the UAV and the convergence speed of the algorithm.

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