Optimal Deployment Strategy for Relay Based UAV Assisted Cooperative Communication for Emergency Applications

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***Abstract*—There has been a lot of research in the last decade on UAV assisted wireless communication networks. Due to its ability of fast deployment, it is seen as a potential solution to establish communication under emergency scenarios like natural disasters. The mobile nature of the UAVs offers a lot of flexibility, which can be harnessed to improve the QoS of a wireless communication network. In this paper UAV assisted cooperative communication to serve different user clusters distributed in a geographical location is considered. These user clusters do not have access to any conventional base station which is typically a scenario under natural disasters. Each cluster is served by two types of UAVs: cluster UAV which hovers on the top of the cluster centroid and relay UAV which relays information between a central base station (CBS) and cluster UAV. To achieve the required QoS, which is serving a maximum number of users with limited available power, two major parameters have to be optimized apart from other parameters. These are the height of the cluster UAV and trajectory of the relay UAV. To solve this problem, a three-step approach is considered in this paper. In the first step, an unsupervised learning algorithm is used to find the horizontal location parameters of cluster UAVs. Then using convex optimization to find the optimal height of the cluster UAV under power constraints and capacity requirement. Finally using a heuristic algorithm to find the optimal trajectory with minimum distance to be traveled by the relay UAVs. The wireless channel considered here is a simple line of sight (LoS) with a path loss. Computer simulations are performed to prove the validity of the proposed approach in comparison with random deployment.**

***Index Terms*—Unmanned Aerial Vehicles (UAV), power optimization, 3-D Deployment, QoS, Relay UAV.**

I. Introduction

UAVs are used as a potential solution to enhance the coverage area, to improve the quality of service (QoS), and to reduce the traffic on conventional cellular networks [1]-[3]. QoS includes the maximum number of users to be served, robustness of the communication link, data rate, and low latency. Therefore UAV based base stations (UAV-BSs) are considered to be a vital part of future 5G communication systems and IoT applications owing to their versatile and cost effective nature. During emergency scenarios such as natural disasters, where a conventional communication system is damaged or unavailable, UAVs can quickly establish a communication network due to their ability of fast deployment. Moreover, they can also create a network amongst themselves to make sure that the fidelity of the communication is high. Optimal deployment of UAV leads to an increase in the number of covered users under limited resource constraints.

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A. Related Work

Over the last few years, there have been many works on UAV based communication network. These works address some of the challenges in deploying UAV for a particular scenario and they are summarised here. A comprehensive overview of UAV based wireless network and their challenges is presented in [4]. Placement and positioning of UAVs play an important role in achieving the desired QoS and is modeled as a 3-D placement problem [4] with the third dimension being height. The tradeoff between UAV height, coverage area, and pathloss is studied in [5],[6] for a single UAV acting as a base station. The work in [7] proposes a framework for calculating the 3-D location of the UAV-BSs that uses minimum transmit power to cover maximum users by decoupling the deployment problem into vertical and horizontal dimensions. Similar work is proposed in [8] where a mathematical solution is formulated to find the optimal position of a single UAV to minimize required transmit power to serve a fixed set of users. In [9], a single UAV is used to serve a set of ground users with different quality of experience (QoE) requirements, by jointly optimizing user communication schedule, UAV trajectory, transmit power, and bandwidth allocation. All the works discussed so far [5]-[9] considered only a standalone UAV to augment the performance of an existing network.

In [10], a multiple UAV placement problem is presented to maximize the number of covered users by formulating an equivalent quadratic constraint mixed integer non-linear optimization problem (MINLP). The authors in [11] proposed a deployment of multiple UAV-BSs in a geographical area to cover maximum users by using k-means algorithm. In [10]-[11], only horizontal deployment of UAVs is considered. The deployment of UAVs is sequential and not collective. Also, the UAVs have to be in the range of the ground base station. A grid search algorithm by considering the availability of reliable wireless backhaul links was proposed in [12] to solve a backhaul-aware 3-D deployment problem. In [13], a single UAV along with an existing conventional communication network is used to improve the QoS of users with mobility, by using a reinforcement learning algorithm. In both [12]-[13], users are served by a conventional network, and UAVs

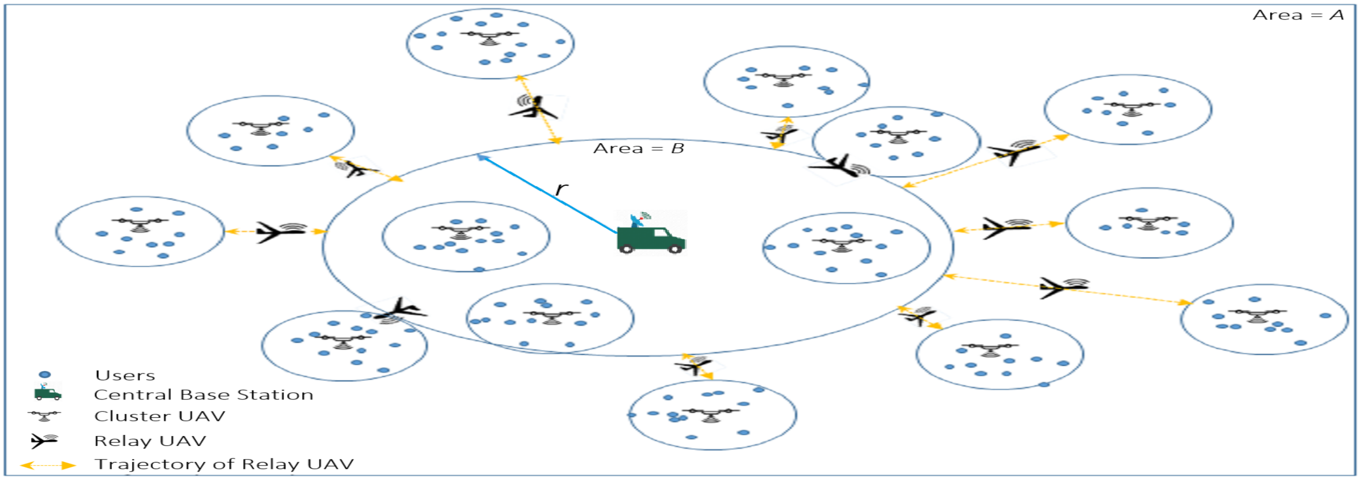

Figure 1: Typical scenario of network deployment in emergency scenario with cluster UAV, relay UAV, and central base station

are added as a backup to improve the QoS of the conventional network. The UAVs primarily serve the mobile users who go out of the coverage area of the conventional network.

In [14] a method was proposed to maximize the number of covered users with power constraints and different QoS requirements defined in terms of SNR. In [15], a low latency solution to optimal 3D deployment of multiple UAVs problem is presented by dividing the geographical area into clusters in order to enhance the QoS in terms of network capacity. The authors in [16] proposed a wireless charging UAV-BSs, where a joint optimization for user association, resource allocation, and base station placement are investigated to maximize the downlink sum rate. So here the assumption was unlimited energy resources due to wireless charging. In all these papers, UAV is assumed to be in the range of the conventional network.

The work in [17] proposed a genetic algorithm that finds the trajectory with minimum energy requirement of a single UAV to provide backhaul connectivity to multiple trunk-mounted BSs in an area affected by natural disasters. In [18], UAV is used as a relay to transfer information from source to destination with maximum throughput via wireless power transfer mechanism. In [19], to maximize the throughput by providing efficient communication link to cell edge users by jointly optimizing the height, power and channel of a single UAV used.

B. Contribution of Paper

In this paper, a multiple UAV 3-D deployment algorithm is proposed for emergency scenarios. Based on the motivation of work done in [17], the UAVs are categorized into two: cluster UAVs and relay UAVs. Typical network deployment is shown in figure 1. The central base station (CBS) in figure 1 can be a fixed one or a temporary one depending on the scenario and resources available. The relay UAVs can move between the coverage area of cluster UAV and CBS. One major disadvantage of the existing UAV based network is overcome by using relay UAVs. That is the UAVs serving the users need not be in the coverage range of CBS. To the best of our knowledge, this is the first work in 3-D deployment of multiple UAVs with some UAVs acting as relays. The optimal deployment here not only involves finding the horizontal coordinates and height but also finding the optimal trajectory for the relay UAVs. For this, a three step approach is proposed: finding the horizontal location parameters of cluster UAVs, finding the optimal height of the cluster UAV under power constraints and capacity requirement, and finding the optimal trajectory with minimum distance to be traveled by the relay UAVs.

The paper is organized as follows: System model and assumptions are presented in Section II. The proposed algorithm is presented in section III. Simulation results are discussed in section IV followed by conclusion in section V.

II. System Model and Assumptions

As mentioned earlier, a 3-D deployment strategy is proposed for a relay based UAV assisted cooperative communication for emergency scenarios. The objective is to serve maximum number of users in a geographical area where a conventional network may not exist. The scenario is illustrated in figure 1 where it can be seen that there are two kinds of UAVs namely cluster UAVs and relay UAVs. The cluster UAV serves the users in the cluster and relay UAV transfers the information between CBS and cluster UAV. The CBS can be a mobile base station (can also be UAV with more resources) or a fixed one and can be deployed anywhere in the area.

The number of users in an area 'A' is considered to be 'N' and they are grouped into 'K' clusters. This is a typical scenario in the rural and semi-urban regions. The user/population density is modeled by sampling the data points from a 2D Gaussian mixture model by specifying mean, variance, and mixing probability. In figure 1 the CBS is illustrated at the center of the geographical area, however, it can be placed anywhere in the area. The coverage area of CBS is modeled as a circle of radius 'r' with an area of 'B'. For better communication, please note that CBS is used only to serve the

UAVs not users. The users not in the coverage area of CBS are served by cluster UAVs and relay UAVs. The users in the coverage area of CBS are served by cluster UAVs alone. The cluster UAVs are denoted as UAV_{C_i} $(i = 1, ..., K)$ and relay UAVs are denoted as UAV_{R_i} $(i = 1, ..., L)$ with $L \leq K$ which are the UAVs assigned to i^{th} cluster.

The cluster UAVs are static in the horizontal direction and moves in a vertical direction based on the population density within the cluster and pathloss. The relay UAVs are static in the vertical direction and moves in a horizontal direction based on the location of the cluster UAVs of which it serves. Please note that it is considered that all the UAVs in the air are having the same receiver characteristics and the same is the case of users on the ground. The wireless links between the CBS and UAVs are considered to be LoS and same is the the case for the link between cluster UAV and its users.

The path loss for LoS connection is [6]:

$$L_{LoS}(dB) = 20\ log(\frac{4\pi f_c d}{C}) + \xi_{LoS} \tag{1}$$

where L_{LoS} is the average path loss for LoS links, ξ_{LoS} is the average additional loss to the free space propagation which depend on the urban environment, C is the speed of light, f_c is the carrier frequency and d is the distance between the UAV and ground user. The cluster UAVs are serving the users inside the cluster using multiple access techniques such as FDMA or TDMA. There is no constraint placed on the bandwidth resources. The problem to be solved here is to find the optimum height and optimum transmitting power for cluster UAVs and to find the optimum trajectory for relay UAVs with minimum possible travel distance. Here the number of users covered is calculated based on the capacity of each user which depends on the received signal to noise ratio (SNR).

III. Proposed Method

A three-step approach is proposed in this method to solve the optimal UAV deployment, power-height optimization, and trajectory optimization problem. In the first step, the entire population density is clustered into K clusters using an unsupervised learning algorithm. One such popular algorithm is K-means which creates K clusters depending on the data spread. Please note that K is a user defined value. Once clusters are formed, a centroid of each cluster is found. Let the centroids of each cluster be C_i which would be the 2-D planar (horizontal) location of the cluster UAVs. Therefore UAV_{C_i} are placed above each of these centroids.

Once the horizontal location of UAV_{C_i} are decided, we solve for the optimal height of the UAV_{C_i}. As height increases, the coverage area of the UAV increases as the coverage area is considered to be a cone shaped projection from the UAV. Also as the height increases, the probability of line of sight connection increases. Therefore more number of users will be covered as height increases. While the increase in the coverage area is an advantage, due to an increase in height, the power required to transmit data is also increasing due to the increment of pathloss for line of sight (LoS) connections. As it can be observed in equation 1, the pathloss is proportional to height. Since UAVs operate on batteries and have limited power, to make sure that UAV is able to stay in the air for a longer duration, it is not feasible to increase height and required transmit power. So the trade off between height and required transmit power is to be optimized for UAV_{C_i} to increase the number of covered users without any inter-UAV interference.

Based on the above discussion, the following cost function is proposed to find the optimal height of the UAV_{C_i} with optimal transmit power. This will be solved for each of the users in each cluster for each UAV assigned to that particular cluster.

$$\begin{aligned} \min_{P_{UAV}, H} \quad & \beta P_{UAV} + (1-\beta) H \\ \text{s.t.} \quad & 0 \leq P_{UAV} \leq P_{Threshold} \\ & H \geq H_{Threshold} \\ & W_{UAV} * log(1 + \frac{P_{UAV}}{(d_{User_j})^{\alpha}\ N}) \geq C_{Threshold} \end{aligned} \tag{2}$$

where P_{UAV}, H, β are the power utilized by the UAV_{C_i}, the height of the UAV_{C_i} and the tradeoff factor between power and height respectively, for the UAV assigned to that population cluster i. $P_{Threshold}$ is the maximum power that the UAV_{C_i} can utilize for communication and $H_{Threshold}$ is the lowest height the UAV_{C_i} can be allowed to move down to. One more rational reason behind having a lower height threshold is that there may be skyscrapers or natural obstacles that may get in the way of the communication of the UAV which would hinder the LoS communication. Naturally, the UAV should be flying above that height. The number of users per cluster is fixed to 'M'. Also, d_{User_j} $(j = 1, ..., M)$ is the distance between the UAV_{C_i} assigned to that cluster and user j. $C_{Threshold}$ is the minimum channel capacity that is required for communication to occur which depends on received SNR. α is the path-loss exponent and N is the variance of the AWGN noise. This constrained optimization problem is convex and can be easily solved by convex optimization solvers [20]. If the constraints are violated then the user will not be served by the UAV assigned to that cluster.

One of the major drawbacks of solving the above optimization problem is that it has to be solved for each user which is computationally expensive to solve. Instead, we propose an iterative algorithm $Algorithm$ 1 that leverages the fact that if the solution of the optimization problem satisfies the constraints for an arbitrary user j then the solution is valid for all other users closer to the UAV than user j.

Here the reason behind placing the CBS at the mean of all the K centroids is to reduce the minimum distance traveled by UAV_{R_i}. It should be noted that UAV_{C_i} may not be in the coverage area of CBS. hence, UAV_{R_i} are used to transmit data between UAV_{C_i} and CBS. If CBS is placed at any one corner, then the UAV_{R_i} serving the other end clusters need to

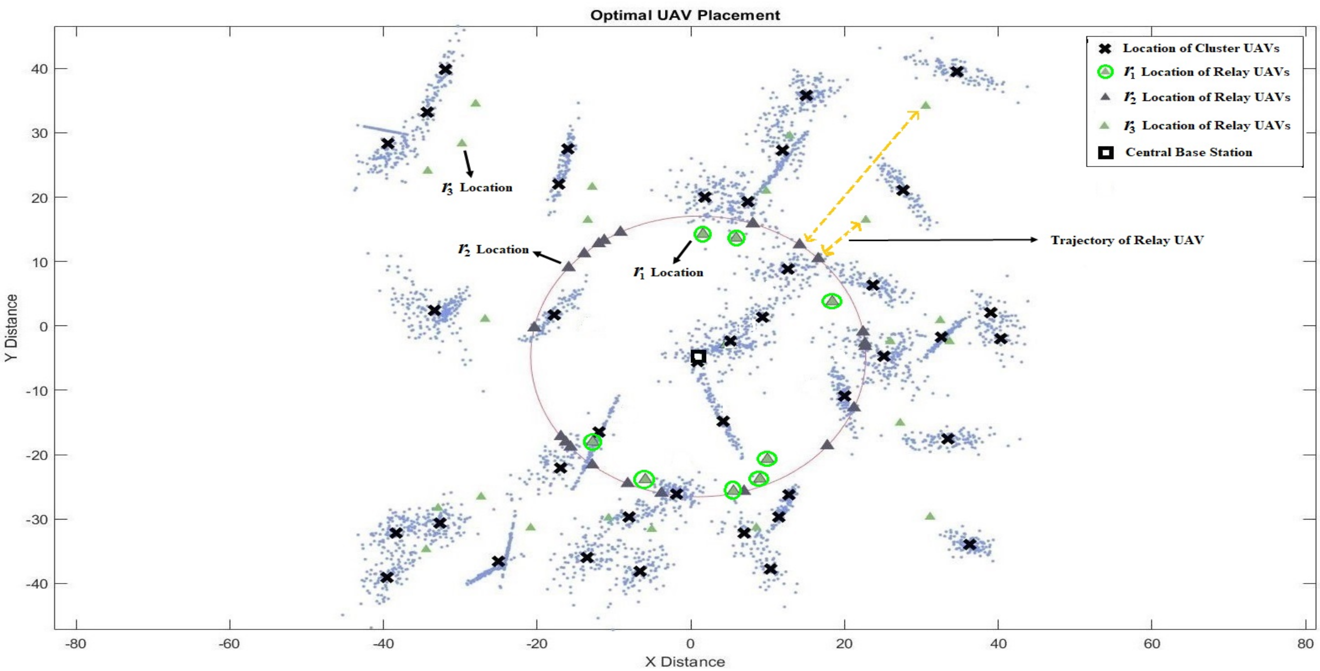

Figure 2: Snapshot of a typical deployment of CBS, UAV_{C_i}, and UAV_{R_i} using the proposed method

Algorithm 1 Power and Height Optimization Algorithm

Use the K-Means Algorithm to get the K centroids of the overall users
Place the base station at the mean of all the K centroids
Place the UAV_{C_i} at the centroids of each of these K clusters.
for $i = 1$ to K (for each cluster) **do**
  Sort all the users assigned to cluster i in the descending order of distance from the UAV (from 1 to M)
  for $j = 1$ to M **do**
    Solve the optimisation problem for $User_j$ using Equation 2 and obtain solutions P_{UAV_j} and H_j
    if P_{UAV_j} and H_j satisfy the constraints in Equation 2 **then**
      Save P_{UAV_j} and H_j as the optimal values (P_{UAV}, H) for UAV_{C_i} and terminate the inner for loop.
    end if
  end for
end for

travel for longer distances which can be visualized from figure 1 or 2. Therefore the third step is to optimize the trajectory of these UAV_{R_i}.

UAV_{R_i} should be placed in a such a way that the channel capacity between the CBS and UAV_{R_i} as well as UAV_{R_i} and UAV_{C_i} is above a certain threshold. This allows better communication between the CBS and all the UAV_{C_i} as the UAV_{R_i} act as relays. Let $C_{R_i}^{BS}$ be the channel capacity between CBS and UAV_{R_i} and the channel capacity between UAV_{R_i} and UAV_{C_i} is $C_{C_i}^{R_i}$. The permissible channel capacity threshold is considered to be C_T. In order to optimize the trajectory, the UAV_{R_i} are placed such that the following two constraints are satisfied.

$$C_{R_i}^{BS} = W_{CBS} * log(1 + \frac{P_{CBS}}{(d_{R_i}^{BS})^{\alpha}\ N}) \geq C_T \tag{3}$$

$$C_{C_i}^{R_i} = W_{UAV} * log(1 + \frac{P_{UAV}}{(d_{C_i}^{R_i})^{\alpha}\ N}) \geq C_T \tag{4}$$

where W_{CBS} and P_{CBS} are the bandwidth of the frequency channels used and the transmission power of the CBS respectively. Whereas W_{UAV} and P_{UAV} are the bandwidth of the frequency channels used and the transmission power of the relay (or cluster) UAV respectively. Also, $d_{R_i}^{BS}$ is the distance between the CBS and the UAV_{R_i} and $d_{C_i}^{R_i}$ is the distance between UAV_{R_i} and UAV_{C_i}. α is the path-loss exponent and N is the variance of the AWGN noise.

$Algorithm$ 2 is proposed to optimize the location and trajectory of the UAV_{R_i}. First, the equation 3 and 4 are solved collectively to get the optimal location of UAV_{R_i} as r_1 location of relay UAVs which are shown in figure 2. It should be noted that in some cases, it may so happen that it is impossible to place the UAV in such a manner that both the channel capacities are above C_T. In such scenarios, $C_{R_i}^{BS} = C_T$ is to be solved to get the r_2 location of relay UAVs, and $C_{C_i}^{R_i} = C_T$ is to be solved to get the r_3 location of relay UAVs which are shown in figure 2. Therefore the UAV_{R_i} either stays in the r_1 location or flies back and forth between the r_2 location and r_3 location which is the trajectory of the UAV_{R_i} covering minimum possible distance. With this 3rd step, the optimized 3-D deployment of cluster UAVs and

Algorithm 2 Optimal UAV Placement Algorithm

for $i = 1$ to K **do**
  if ($C_{R_i}^{BS} = C_{C_i}^{R_i} \geq C_T$ at a certain location) **then**
    Solve $C_{R_i}^{BS} = C_{C_i}^{R_i}$ to get the optimal location r_1.
    Place UAV_{R_i} at r_1.
  else
    Solve $C_{R_i}^{BS} = C_T$ and get the location r_2
    Solve $C_{C_i}^{R_i} = C_T$ and get the location r_3
    Make UAV_{R_i} move to and fro from r_2 to r_3 and also make sure that UAV_{R_i} stays r_2 and r_3 for a particular time duration.
  end if
end for

optimized trajectory of relay UAVs is obtained. The results of all three steps can be visualized in figure 2.

IV. Simulation Results

To analyze the performance of the proposed 3-D deployment algorithm, MATLAB simulations are carried out. The population size is taken as 4000 and is distributed around 40 clusters. To simulate the population distribution, data points were sampled from a Gaussian mixture Model where the mean and variance for each Gaussian distribution was derived from a uniform random distribution. The power threshold of the CBS is fixed to 50 dB. The height of the UAV_{C_i} is varied ranging from 0.5 to 6.5 Kms. The height of the UAV_{R_i} is fixed to 1 Km for all i. The power threshold of the UAV_{C_i} and UAV_{R_i} is considered to be the same for all i and is varied between 6 dB to 14 dB. The tradeoff factor β is taken as 0.5. Four different experiments are carried out to test the validity of this approach. The total number of users served, and the percentage of power saved are the performance metrics considered. The results of the proposed algorithm are compared with the results of the random deployment. Unit noise variance is considered for the first three experiments.

A. Experiment 1

In this experiment, the effect of the power threshold ($P_{Threshold}$) on the performance is analyzed. Here the population spread is fixed to 40 km x 40 km and the height threshold of the UAV_{C_i} is fixed to 0.5 kms. The number of users served with the proposed optimal UAV placement algorithm is compared with the number of users served via random placement. Also, the percentage of power saved using the proposed power and height optimization algorithm is observed as shown in figure 3. The power saved is calculated by adding the P_{UAV} of all clusters for both random placement method and proposed optimal placement method and by taking the difference.

As observed in figure 3, as the power threshold of the UAV increases, a larger number of users are served using both the methods. However, it can be seen that, there is a significant difference in the percentage of users served using proposed algorithm. Moreover, it can be observed that the percentage of

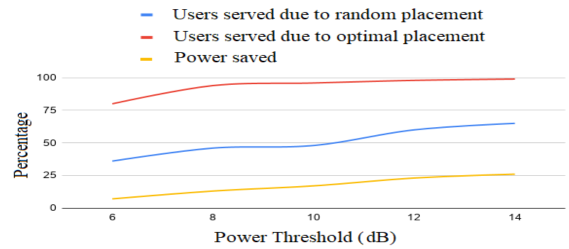

Figure 3: Effect of power threshold on number of users served

power saved also increases as the power threshold increases. This can be justified as more the power threshold, the more would be the power saved to serve all the users.

B. Experiment 2

In this experiment, the effect of height threshold ($H_{Threshold}$) of the UAV_{C_i} on the number of users served is analyzed. Here the population spread is again fixed to 40 km x 40 km and the power threshold of the UAV is fixed to 10 dB.

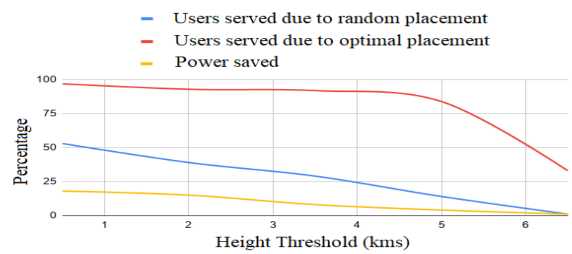

Figure 4: Effect of height threshold on number of users served

As observed in figure 4, as the height threshold of the UAV increases, a lesser number of users are served using both the methods. But, it can be seen that the percentage of users served significantly reduces using a random placement method while the height threshold increases. It can also be observed that the proposed optimal placement method performs better by a huge margin for each height threshold. Moreover, it can be observed that the power saved also reduces as the height threshold increases. This can be justified as more the height threshold, the more is the distance between the UAV and user, which would lead to the UAV consuming more power to communicate with the user.

C. Experiment 3

Here, the effect of population spread is investigated while fixing the $P_{Threshold}$ as 10 dB and $H_{Threshold}$ as 0.5 kms. Therefore simulations were done for the different population spread values. The results for this setup are observed as follows.

As observed in figure 5, as the spread of the population increases, a lesser number of users are served using both the methods. However, it can be seen that using the proposed optimal placement algorithm, there is a significant difference in the percentage of users served, as the spread of the population

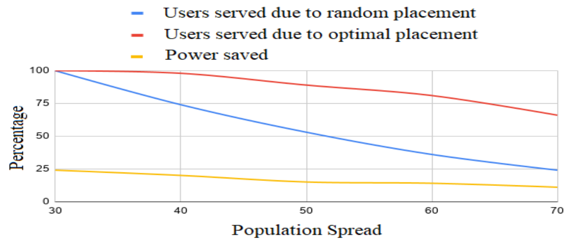

Figure 5: Effect of population spread on number of users served

increases. Moreover, it can be observed that the power saved also reduces as the spread of the population increases. This can be justified as more the spread, the more would be the power required to serve all the users.

D. Experiment 4

In this experiment, the effect of noise variance is investigated by fixing the population spread to 40 km x 40 km, power threshold of the UAV to 10 dB, and height threshold of the UAV_{C_i} to 0.5 kms.

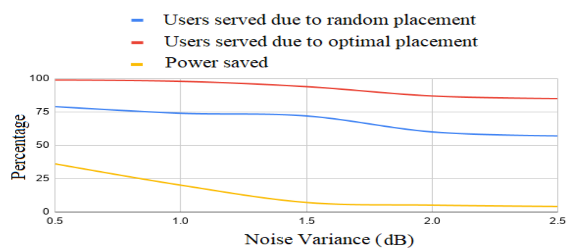

Figure 6: Effect of noise variance on number of users served

As observed in figure 6, as the noise variance increases, a lesser number of users are served using both the methods. However, it can be seen that using the optimal placement algorithm, there is a marginal difference in the percentage of users served while the noise variance increases. Moreover, we can observe that the power saved also reduces as the noise variance increases. This can be justified as more the noise, less the signal to noise ratio, and hence less capacity.

V. Conclusion and Limitations

In this work, a 3-D UAV deployment algorithm is proposed for establishing a communication network under emergency situations. The network consists of both relay UAVs and cluster UAVs to serve the users who are distributed in a geographical area. A three-step approach is proposed to find the horizontal location of cluster UAVs, power-height optimization under capacity requirement, and trajectory optimization of relay UAVs. The Effect of various parameters on performance metrics was analyzed and compared with random deployment. In this work, the channel model considered was simple LoS model, antenna parameters were not considered, bandwidth constraints were not imposed, and inter-user interference was considered to be negligible. In future work, the effect of these parameters on the performance metrics is to be investigated.

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