Failure Aware Deployment of Drone Base Stations

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***Abstract*—The use of drone base stations in wireless networks is studied by many researchers and it is shown that DBSs offer significant potential for meeting user demands in various wireless communication scenarios. However, the scenario where a DBS becomes out of function during the communication operation has not been investigated. This scenario is particulary important when the requirements of public safety and tactical communications networks are considered. In this paper, we propose a failure-aware deployment strategy to alleviate the impact of a DBS loss. We have shown that the proposed failure-aware DBSs positioning algorithm performs better than the comparison algorithm, k-means clustering, in terms of number of users served and the timeout duration where even the basic communication services are not provided to the users.**

***Index Terms*—Drone Base Station, Clustering, Failure Awareness, Emergency Networks, Battlefield Networks**

I. INTRODUCTION

Drone base stations (DBSs) have attracted many researchers in the recent years and there is an increasing interest for the DBS research. This interest mainly stems from two inherent advantages of the DBS-based communications. First, the DBS is positioned in the sky where the probability of line-of-sight (LoS) between the user and the DBS is high compared to the LoS probability provided by the terrestrial base stations. Secondly, the fixed communication infrastructure may not be able to handle user demands in the case of unexpected events such as a disaster where the communication infrastructure gets damaged or a network congestion caused by events such as sporting events, concerts and fairs [1], [2]. In these scenarios, a fleet of DBSs may be used to mitigate communication problems unexpectedly arising in the network instead of heavily investing to the fixed communication infrastructure considering all contingency operations. The utilization of DBSs in the battlefield is also a very promising application [3], [4].

In the public safety and tactical networks, the reliable flow of information among users is critical. The interruption in the communication may lead to significant consequences which can not be restored later. In these scenarios, the deployment of DBSs offers a promising solution to satisfy the strict user demands capitalizing on good channel conditions and flexible positioning in the open sky. However, there are challenges that needs to be addressed. First, a DBS as being a complex electro-mechanical system is prone to system failures. In addition to that in the tactical networks, the DBSs may be targeted by the adversaries and there may not be redundant DBSs to revert the network to its initial state.

The deployment and placement of DBSs have been studied extensively [1]. In [5], considering the fairness among users, we investigated the positioning of DBSs in 3-Dimension (3D). A new application of DBSs was introduced in [3] where we proposed a DBSs placement algorithm taking into account the challenges of urban warfare. The authors in [6] derived the optimal altitude of a single aerial platform in order to achieve maximum coverage. In [7], the deployment of two interfering DBSs was investigated. The same authors in [8] also studied the placement of multiple DBSs using circle packing theory. In [9], the minimum number of DBSs and their positions under the coverage and capacity constraints were investigated. The work [10] and [11] modeled a single DBS placement problem as a multiple circles placement problem and proposed optimal placement algorithms. The authors in [12] and [2] analyzed the impact of the altitude and the number of DBSs on the coverage probability in a post-disaster situation.

In this paper, considering the requirements of the public safety and tactical networks, we propose a failure aware deployment of DBSs. In this concept, the DBSs are initially positioned taking into consideration that a DBS may become nonfunctional. After a DBS failure occurs, the remaining DBSs start to move to the final positions minimizing the total distance travelled. To the best of our knowledge, this scenario has not been studied in the literature before.

II. SYSTEM MODEL AND ASSUMPTIONS

We consider a network where DBSs are deployed to provide single-frequency TDMA-based downlink service to the users who are distributed uniformly in the cell. It is assumed that all DBSs are positioned at the same altitude and the output powers are equal. We denote the sets of users and DBSs by $\mathcal{U} = \{1, ..., U\}$ and $\mathcal{D} = \{1, ..., D\}$ respectively. The set $\mathcal{D}_j$ represents the users associated with the jth DBS. The positions of the user i and the DBS j are denoted by (x_i^u, y_i^u) and (x_j^d, y_j^d) where $i \in \mathcal{U}$, $j \in \mathcal{D}$, respectively.

There are two phases for the deployment. In the first phase, the positions of DBSs are determined and drones move to their final positions and start serving the users. After then, a DBS becomes nonfunctional and the second phase starts. In this phase, the new positions of DBSs are determined and the remaining DBSs fly to the final positions with speed v while continuing the transmission. The second phase ends when all DBSs reach to their final destinations. The second phase is divided into timeslots of Δt seconds and user data rates are calculated at each time slot. A system model is illustrated in Fig. 1 which exemplifies the deployment of 3 DBSs.

As for the channel model, we adopt the probabilistic path loss model defined in [6] and [13]. The LoS and NLoS

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978-1-5386-7171-9/18/©31.00 2018 IEEE

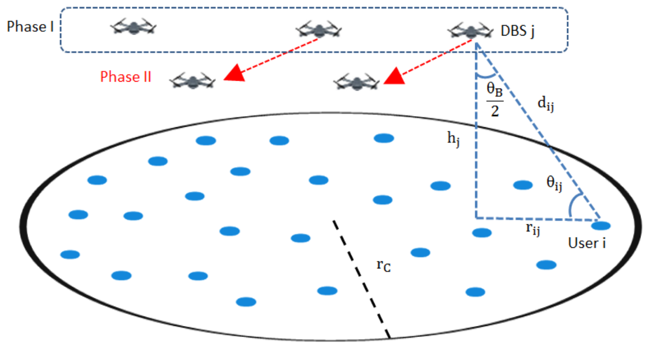

Fig. 1: System model. In this illustration there are 3 DBSs in the phase I. The phase II starts after a DBS failure occurs. The remaining DBSs move to their final positions while serving the users.

components between the user i and the DBS j are formulated as:

$$PL^{ij}_{LoS} = 10\log\left(\frac{4\pi d_{ij} f_c}{c}\right)^{\gamma} + \eta_{LoS} \tag{1}$$

$$PL^{ij}_{NLoS} = 10\log\left(\frac{4\pi d_{ij} f_c}{c}\right)^{\gamma} + \eta_{NLoS} \tag{2}$$

where d_{ij} is the distance between the ith user and the jth DBS, γ is the path loss exponent, f_c is the operating frequency (Hz), c is the speed of light (m/s), η_{LoS} and $\eta NLoS$ are the mean additional losses (in dBs) for the LoS and NLoS connections, respectively.

The probability of LoS between the ith user and the jth DBS is given by [6]:

$$p^{ij}_{LoS} = \frac{1}{1+\alpha\exp(-\beta(\frac{180}{\pi}arctan(\frac{h_j}{r_{ij}})-\alpha))} \tag{3}$$

where r_{ij} is the distance between the user i and the DBS j in the horizontal plane and calculated as $\sqrt{(x_i-x_j)^2+(y_i-y_j)^2)}$, α and β are environment-dependent parameters, h_j is the altitude of jth DBS.

Finally, the mean path loss is formulated as follows:

$$\overline{PL_{ij}} = PL^{ij}_{LoS} p^{ij}_{LoS} + PL^{ij}_{NLoS}(1-p^{ij}_{LoS}) \tag{4}$$

In our model, we assume that DBS-user association is based on the received signal power. Let α_i be the DBS selected by the ith user,

$$\alpha_i = \arg\max_j R_{ij}(x_j, y_j, h_j), \tag{5}$$

where $R_{ij}(x_j, y_j, h_j)$ is the received signal power from the DBS j at the user terminal i and expressed as

$$R_{ij}(x_j, y_j, h_j) = 10^{\frac{P_T+G_{ij}-\overline{PL_{ij}}}{10}}, \tag{6}$$

where P_T is the transmission power (in dBm) of a DBS and G_{ij} is given by [14],

$$G_{ij} = \begin{cases} \frac{29000}{\theta_B^2}, & \text{if } r_{ij} \leq \ h_j \tan\frac{\theta_B}{2} \\ 0, & \text{if } r_{ij} > h_j \tan\frac{\theta_B}{2} \end{cases}, \tag{7}$$

where θ_B is the half power beamwidth of the DBS antenna. For the user antenna, we consider the use of a zero gain omnidirectional antenna. We assume that the capacity of a DBS is equally shared amongst the users. Let N_j, be the total number of users connected to the DBS j.

$$N_j = \sum_{i\in U} I(\alpha_i = j), \quad \forall j \in \mathcal{D}, \tag{8}$$

where $I(\alpha_i = j) \in \{0, 1\}$ defined as,

$$I(\alpha_i = j) = \begin{cases} 1, & \text{if} \quad \alpha_i = j, \\ 0, & \text{otherwise.} \end{cases}$$

Finally, the data rate of the user i is formulated as

$$DR_i = \frac{W}{N_{\alpha_i}} \log_2\left(1 + \frac{R_{i\alpha_i}(x_{\alpha_i}, y_{\alpha_i}, h_{\alpha_i})}{N_0 W + \sum\limits_{j\neq\alpha_i} R_{ij}(x_j, y_j, h_j)}\right) \tag{9}$$

III. FAILURE-AWARE DEPLOYMENT OF DBSS

In the emergency and tactical networks, deployment planning time is generally limited and the computation resources are limited. In [5], we have shown that fast k-means clustering provides good performance when the users are unifomly distributed in the cell and the number of DBSs for the deployment is not chosen excessively. For this reason, we modified k-means clustering to determine initial positions of DBSs. We also use k-means clustering as a benchmark in our simulations.

In the first phase of our proposed algorithm, k-means clustering is applied to the user positions. The algorithm finds the centroids and associated users. Instead of placing DBSs above these centroids, we apply a simple method to find the final positions of DBSs. In this approach, the position of each DBS is recalculated as follows:

$$x^d_j = \frac{\sum_{i\in\mathcal{D}_j} x^u_i + g\sum_{z\in\mathcal{D}, z\neq j} x^{0d}_z}{|\mathcal{D}_j| + g(D-1)}, \tag{10}$$

$$y^d_j = \frac{\sum_{i\in\mathcal{D}_j} y^u_i + g\sum_{z\in\mathcal{D}, z\neq j} y^{0d}_z}{|\mathcal{D}_j| + g(D-1)} \tag{11}$$

where (x^{0d}_z, y^{0d}_z) is the position of the zth DBS, $z \in \mathcal{D}$, found by k-means clustering method.

After a DBS failure occurs, the second phase starts. First, the positions of the remaining $D-1$ DBSs are calculated using k-means clustering method. Then, the DBSs are appointed to their new positions by solving the assignment problem given in Equation 12. The costs are based on the direct paths between the DBSs and the new positions. We applied Hungarian algorithm to match each each DBS with each of the final positions. The speed of the decision process is critical because the users served by a failed DBS is at high risk of service outage. Therefore, the DBSs are required to start moving as quick as possible.

$$\begin{aligned} &\min \sum_{l=1}^{D-1}\sum_{k=1}^{D-1} d_{lk} c_{lk} \\ &\text{subject to} \\ &\sum_{l=1}^{D-1} c_{lk} = 1, \quad k = 1, .., D-1 \\ &\sum_{k=1}^{D-1} c_{lk} = 1, \quad l = 1, .., D-1 \end{aligned} \tag{12}$$

TABLE I: Simulation Parameters

Parameter	Definition	Value
U	Number of users	100
f_c	Carrier frequency	$2GHz$
r_C	Radius of cell	$2000m$
W	Bandwidth	$20MHz$
N_0	Noise power spectral density	$-170dBm/Hz$
a, b	Environmental parameters	9.61, 0.16
η_{LoS}, η_{NLoS}	Mean path loss	$1dB$, $20dB$
θ_B	DBS antenna beamwidth	$140°$
P_T	DBS transmission power	$30dBm$
N_0	Noise power spectral density	$-170dBm/Hz$
Δt	Timeslot interval	$100ms$
v	Speed of DBS	$30m/s$

where $c_{lk} \in 0, 1$ is a binary indicator variable and equals to 1 if the remaining DBS l is assigned to the new position k, d_{lk} is the distance between the remaining DBS l and the new position k. The first constraint indicates that each DBS is assigned to only one position and the second constraint shows that each position is assigned to a single DBS.

IV. SIMULATION RESULTS

In this section, we present and evaluate the results of our proposed failure aware clustering algorithm. As a benchmark, we use the k-means clustering method. The following metrics are considered for performance evaluation:

1) Minimum user data rate in the cell DR_{min}.
2) Number of users not fully served, N_{nFS}. A user, whose average data rate is less than 500Kbps, is not fully served by a DBS.
3) Maximum timeout duration of a user in the cell, T_{out}. It is the sum of time slots where a user data rate is less than 32Kbps.

The metrics 2, and 3 are not applicable for the performance evaluation of the first phase. In this phase, we only consider DR_{min} in the cell. In the second phase where the remaining DBSs fly to their new locations, the user data rates are calculated over each time slot and averaged to obtain final results. The simulation parameters are presented in Table I. The results shown in the figures are obtained by averaging the results of 100 different networks where the users are uniformly distributed. In the figures, we name our failure clustering algorihm as FACpI and FACpII and k-means clustering as KCpI and KCpII. The suffixes pI and pII denote the first phase and second phase of the DBSs deployment process, respectively. The performance of FACpII and KCpII are directly related to FACpI and KCpI, because the initial positions are found by these algorithms. Note that in the second phase, the final positions of the remaining DBSs are the same for both FACpII, KCpII and determined by k-means clustering method.

Fig. 2 shows DR_{min} performance of the algorithms in the first and second phase with respect to algorithm parameter g. Notice that g is not a parameter for k-means, hence its results are constant for varying g. The results indicate that if g is small, such as less than 2.5, the performances of KCpI and FACpI are very close to each other and FACpII provides better performance than KCpII. For example, when g equals to 2.5, FACpII provides 25% better performance than that of KCpII while incurring no performance loss in the first phase. When g is larger, we observe a performance loss in FACpI. If we consider the case where each user requires full service in the first phase, then g is selected as 5.5 for FACpI. In this case, although the excessive capacity provided by KCpI, which may not be useful considering the application needs, is lost, there is a 42% increase, in the second phase, where each bit is important for running applications. Fig. 3 also shows that when FACpII is employed ($g = 5.5$), one more user on average is fully served compared to KCpII without considerably degrading the first phase performance of FACpI.

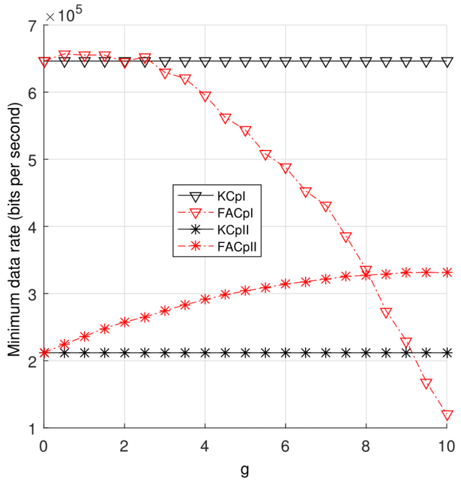

Fig. 2: Minimum data rate versus algorithm parameter g (D=4, h=450m).

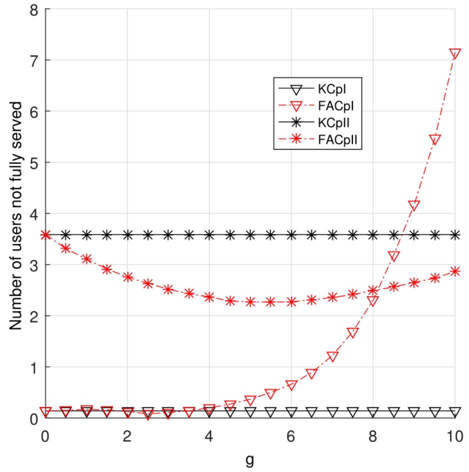

Fig. 3: Number of users not fully served versus g (D=4, h=450m).

The effect of deployment altitude is illustrated in Fig. 4. It is shown that there is an optimum altitude for the performance of FACpI. It is also observed that FACpII provides better performance than KCpII for all altitudes. As the altitude increases, there is a decrease in the number of users unserved because of higher LoS probability. However, there is a small performance loss in FACpI due to the increased interference.

In Fig. 5 and 6, N_{nFS} and T_{out} performance of the algorithms are shown. As expected, increasing D improves the performance of both algorithms ,however, FACpII achieves better results. Fig. 6 illustrates a significant decrease (25-50%) in T_{out} when FACpII is used. According to these results, the number and initial positions of DBSs needs to be determined considering the tolerable T_{out} requirement of the users.

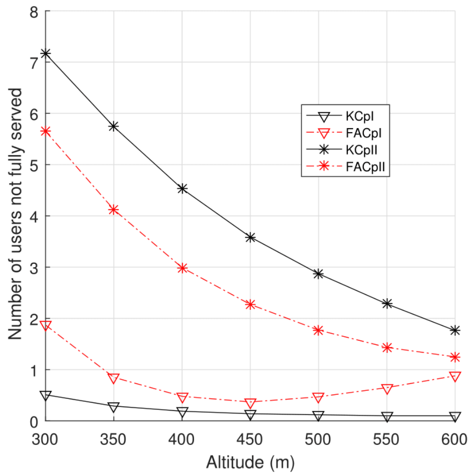

Fig. 4: Number of users not fully served versus altitude (D=4, g =5.5).

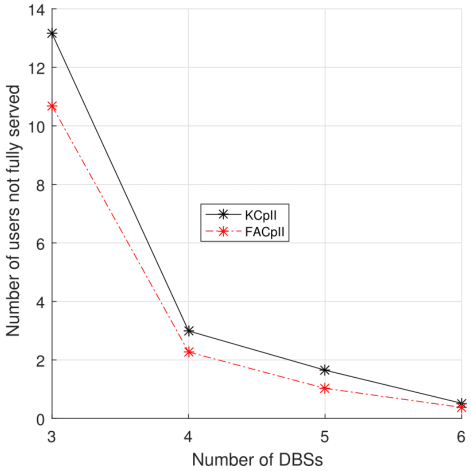

Fig. 5: Number of users not fully served versus number of DBSs (g=5.5, h=450m).

V. CONCLUSION

In this paper, we introduce a new scenario for the use of DBSs in the tactical and public safety networks where user connectivity is critical. A fast deployment algorithm based on clustering method and assignment problem is proposed. The results show that our proposed algorithm improves the minimum user data rate and user timeout performance.

ACKNOWLEDGEMENT

The work of A. Akarsu was supported by HAVELSAN Inc.

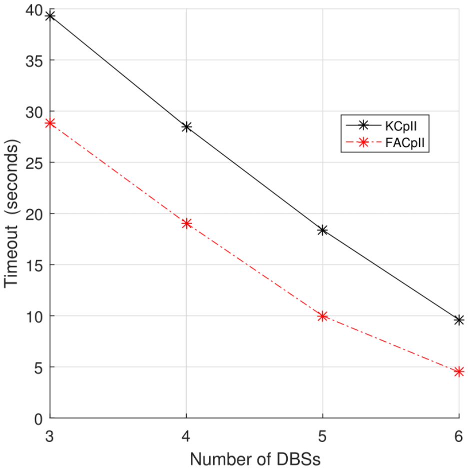

Fig. 6: Timeout (s) versus number of DBSs (g=5.5, h=450m).

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