Resilient Deployment of Drone Base Stations

Alper Akarsu and Tolga Girici
TOBB University of Economics and Technology
Department of Electrical and Electronics Engineering
06560, Ankara, Turkey
{tgirici, aakarsu}@etu.edu.tr

***Abstract*—Drone base stations have emerged as a promising solution to the requirements of future cellular networks which may not be fully met by the existing terrestrial base stations. The main reasons for the superiority of DBSs are the higher probability of line of sight (LoS) and mobility in the sky which provides better adaptation to the demands of users. However, drones are complex electro-mechanical systems and more prone to the errors compared to that of radio communication systems. With the help of onboard sensors, failure tendency of a drone can be estimated and this information can be used to determine the positions of DBSs. In this work, we address the problem of DBSs' deployment where one of the DBSs is assumed to have a high probability of failure. Our proposed algorithm jointly determines the positions of DBSs before a failure occurs and paths to be followed in order to recover the network. Our simulations show that our proposed algorithm provides significant gain in the minimum user data rate performance of the network during recovery phase with tolerable loss in the initial performance compared to the benchmark algorithm.**

***Index Terms*—Drone Base Station, Emergency Network, Battlefield Network, Particle Swarm Optimization**

I. Introduction

In the recent years, drone base stations (DBSs) have emerged as a tool to meet the requirements of various communication networks such as emergency, congested, military etc. DBSs satisfy the demand of these networks with the help of better line of sight (LoS) utilization and faster mobility compared to the conventional ground based base stations. As a result, the deployment of DBSs have been addressed by many researchers [1], [2]. However, current literature assumes that drones are extremely reliable and are able to provide service uninterruptedly. On the other hand, in practical cases, drones are vulnerable to mechanical and electrical failures which cause interruption in communication. Unless redundant DBSs are deployed, which increase operational costs, it is certain that the communication service will be negatively affected when a DBS fails. In our work, considering the high service availability and limited number of DBSs available for deployment, we propose a DBS deployment method that reduces the degrading effect of a DBS loss during the repositioning of the remaining DBSs.

The literature on DBSs can be grouped in two categories in terms of drone mobility. In the first category, the static deployment of DBSs are investigated considering various constraints. In [3], the optimal altitude of a DBS was derived to maximize the cell coverage. Authors in [4] and [5], investigated the placement of DBSs considering energy efficiency and different quality of service requirements, respectively. In [6], a metaheuristic-based algorithm was proposed to find the number of required DBSs and their positions. The same authors also studied the DBSs deployment problem with backhaul consideration [7]. In [8], positioning of multiple DBSs was studied using circle packing theory. We also investigated multiple DBS deployment problem and proposed a method that finds the optimal number and locations of DBSs for user fairness and total capacity [9].

The second category investigates the path design of DBSs by optimizing drone movement or radio parameters. In [10], the authors proposed a drone mobility algorithm to improve the spectral efficiency. In this work, drones move with a fixed speed and update their directions at regular intervals. The same authors in [11] proposed an algorithm to control the repositioning of fixed number of DBSs in response to the users' mobility. In [12], the authors studied unmanned aerial vehicle(UAV) trajectory problem with the objective of minimizing mission completion time. Their algorithm provides the set of waypoints and DBS's speed along the route. In [13], the formulated trajectory and power control optimization problem was solved by an iterative algorithm that applies the block coordinate descent and successive convex optimization techniques.

In our previous work [14], we proposed a novel clustering technique to handle a random DBS loss. In that case, our algorithm does not consider the trajectories of DBSs which causes high interference in the network. In this work, instead of considering a random DBS loss, we assume that the operational or maintenance data provide an insight about the health status of the DBSs, hence failure prone DBS can be estimated. By using this information, we proposed a new technique to mitigate the loss of failure prone DBS. Our proposed method determines the initial positions and routes of DBSs after DBS failure occurs.

II. System Model and Assumptions

We consider a network where there is a failure prone DBS and this information is known a-priori. DBSs use the same frequency band and are deployed to provide TDMA-based downlink service to static users that are uniformly distributed in the cell. It is assumed that all DBSs are positioned at the same altitude and the output powers and velocities are equal. The system model is shown in Fig. 1.

*A. Akarsu is a senior systems engineer at HAVELSAN Inc., Ankara, Turkey.

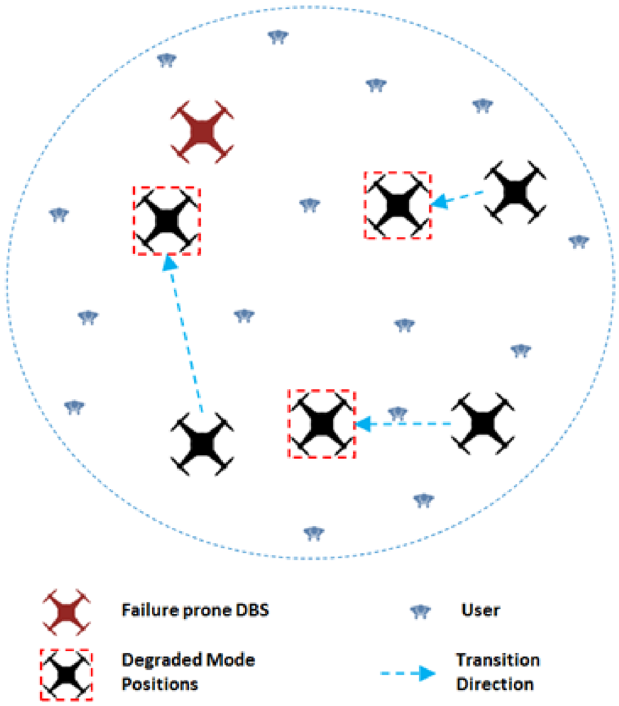

Fig. 1: System model of $|\mathcal{D}| = 4$ DBSs deployed in normal mode. Transition mode starts after the DBS failure occurs. Remaining DBSs move along the direct path to their degraded mode positions minimizing the time spent for network recovery.

There are 4 modes of the system which are illustrated in Fig. 2. In the normal mode, DBSs are deployed and provide service to the users. When the DBS failure occurs, transition mode starts. In this mode, the remaining DBSs start moving to their new positions. Transition mode finishes and degraded mode starts when all DBSs reach to their new positions. In the recovery mode, a new DBS is deployed from the operation center and DBSs move to their normal mode positions. In our study, we do not investigate the network performance of recovery mode.

We represent the sets of users and DBSs by $\mathcal{U} = \{1, ..., U\}$ and $\mathcal{D} = \{1, ..., D\}$ respectively. The set $\mathcal{D}_j$ denotes the users associated with the jth DBS. The positions of the ith user and jth DBS are denoted by (x_i, y_i) and (x_j, y_j) where $i \in \mathcal{U}$, $j \in \mathcal{D}$, respectively.

For the channel model, we use the probabilistic path loss model proposed in [15] and [3]. The LoS and NLoS components between ith user and jth DBS are as follows:

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

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

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

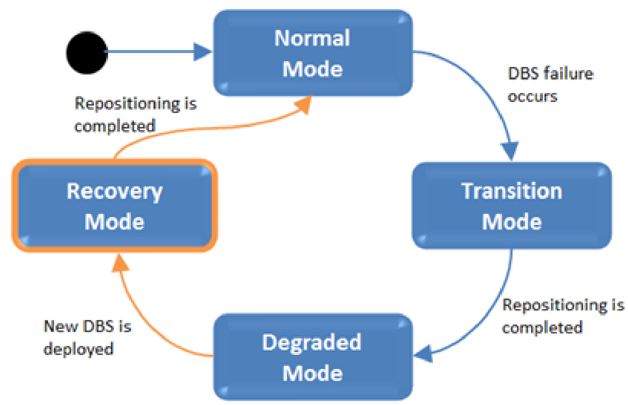

Fig. 2: System modes.

The probability of LoS between the user i and DBS j is defined by [15]

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

where r_{ij} is the distance between the ith user and jth DBS 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 DBS j.

The mean path loss is formulated as:

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

We assume that DBS-user association is based on the received signal power. Let α_i be the DBS selected by the user i,

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

where $R_{ij}(x_j, y_j, h_j)$ is the received signal power from the jth DBS at the ith user terminal 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 [16],

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

where θ_B is the half power beamwidth of the DBS antenna. The capacity of a DBS is equally shared amongst the users. Let N_j, be the total number of users connected to the jth DBS.

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

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

$$I(\alpha_i = j) = \begin{cases} 1, & \text{if} \quad \alpha_i = j, \\ 0, & \text{otherwise.} \end{cases} \tag{9}$$

Then, the data rate of the ith user is formulated as

$$DR_i = \frac{W}{N_{\alpha_i}} \log_2 \left(1 + \frac{R_{i\alpha_i}(x_{\alpha_i}, y_{\alpha_i}, h_{\alpha_i})}{N_0 W + \sum\limits_{j \neq \alpha_i} R_{ij}(x_j, y_j, h_j)} \right) \tag{10}$$

where N_0 is the noise power and W is the channel bandwidth.

In the transition mode, DBSs start to move to their new positions via the shortest route (a direct line). DBS-to-position assignment, which determines the waypoints of DBSs, is made considering the total distance travelled by DBSs is formulated as follows:

$$\begin{aligned} &\min \sum_{l=1}^{D-1} \sum_{k=1}^{D-1} d_{lk} c_{lk} \\ &\text{subject to} \\ &\sum_{l=1}^{D-1} c_{lk} = 1, \quad k = 1, .., D-1, \\ &\sum_{k=1}^{D-1} c_{lk} = 1, \quad l = 1, .., D-1, \end{aligned} \tag{11}$$

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

III. Fairness Aware Deployment of DBSs (FAD)

In our previous work, we have proposed a DBS deployment technique, which maximizes the sum of the logarithm of user data rates [9]. It is shown that with minor loss in total linear capacity (sum of user data rates), significant improvement in fairness, which is measured by Jain's fairness index, is obtained. FAD problem is formulated as

$$\begin{aligned} &\max_{\mathbf{x}, \mathbf{y}} \sum_{i \in \mathcal{U}} \log(DR_i) \\ &\text{subject to} \\ &\sqrt{x_j^2 + y_j^2} \leq r_c \qquad \forall j \in \mathcal{D}, \end{aligned} \tag{12}$$

where $\mathbf{x} = [x_1, .., x_D]$ and $\mathbf{y} = [y_1, .., y_D]$ denote the locations of DBSs and r_c is the radius of the cell. Note that altitudes of DBSs are assumed to be constant.

The solutions of Eq. 12 with $D = |\mathcal{D}|$ and $D = |\mathcal{D}| - 1$ provide the positions of DBSs in normal mode and degraded mode, respectively. In transition mode, DBS-position assignment is found by solving Eq. 11.

IV. Resiliency Aware Deployment of DBSs (RAD)

As being a complex electro-mechanical system, drone is vulnerable to failures over time caused by electrical, mechanical or software problems. Considering user demand for high availability (e.g. in emergency or military scenarios), we proposed a deployment technique to handle negative effects of a DBS failure which we assume it is known a-priori. Although, the utilization of failure-prone DBS is not preferred, the number of reliable DBSs available may not meet user demand and necessitates deployment of failure-prone DBS.

Our proposed algorithm aims to improve the network performance in transition mode, where the worst service is provided to the users, by determining normal mode positions. In transition mode, DBSs start moving towards their degraded mode positions which are determined by Eq. 12. When all DBSs reach their positions, transition mode ends and degraded mode starts. The duration of transition mode, T (sec), is determined by the DBS which travels the longest path. The following problem is formulated to optimize normal mode positions of DBSs so that network performance of transition mode is improved. Here, at each time period Δ_t sec, user data rates, $DR_i(n\Delta_t)$ where $i \in \mathcal{U}$ and $n = [1, .., N]$ where $N = \frac{T}{\Delta_t}$, are calculated using the new positions of DBSs that moves along the direct path to their degraded mode positions. Our algorithm first optimize the positions of reliable DBSs and then optimize the position of failure prone DBS denoted by D_{fp}. The first problem is formulated as follows:

$$\begin{aligned} &\max_{\mathbf{x^R}, \mathbf{y^R}} \frac{1}{N} \sum_{n=1}^{N} \sum_{i \in \mathcal{U}} \log(DR_i(nt_\Delta)) \\ &\text{subject to} \\ &\sqrt{(x_j^* - x_j^R)^2 + (y_j^* - y_j^R)^2} \leq r_S \qquad \forall j \in \{\mathcal{D} - D_{fp}\}, \end{aligned} \tag{13}$$

where (x_j^*, y_j^*) are the positions of DBSs which are found by Eq. 12 for reliable DBSs, r_S is the radius of a circle where the solution is searched and $\mathbf{x^R} = [x_1^R, .., x_{D-1}^R]$ and $\mathbf{y^R} = [y_1^R, .., y_{D-1}^R]$ are the positions of reliable DBSs which we try to optimize for improving transition mode performance. Note that both FAD and RAD use the same degraded mode positions that are found by solving Eq. 12 with $D = |\mathcal{D}| - 1$.

After finding $\mathbf{x^R}$ and $\mathbf{y^R}$, we need to update the position of failure prone DBS,so that the interference is managed and performance of normal mode operation is improved. In this case, Eq. 12 is solved given $\mathbf{x^R}$ and $\mathbf{y^R}$.

V. Simulation Results

We have performed extensive simulations to evaluate the performance of the proposed algorithm. The results are obtained by using 100 different networks, where each has 100 uniformly distributed users. The simulation parameters are presented in Table I. We use $|\mathcal{D}| = 4$ and $|\mathcal{D}| = 5$ for our simulations. For the evaluation of algorithm performance, we consider the following:

1) Minimum user data rate in normal mode, DR_{min}^N.
2) Minimum user data rate in transition mode, DR_{min}^T.
3) Number of users not fully served in transition mode, N_{out}^T. We determine a threshold of 500Kbps for this metric.

Minimum user data rate is an important metric for the evaluation of network performance, because each user needs to use services such as voice and some amount of data for

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	$500ms$
v	Speed of DBS	$30m/s$
h	Altitude	500m

TABLE II: Gains (%) in DR_{min}^N and DR_{min}^T for FAD and RAD, respectively

r_S	DR_{min}^N **for** $(D=4, D=5)$	DR_{min}^T **for** $(D=4, D=5)$
50	$(2.77, 2.46)$	$(27.04, 7.58)$
150	$(6.67, 7.76)$	$(40.8, 13.03)$
250	$(9.66, 11.08)$	$(52.55, 20.14)$

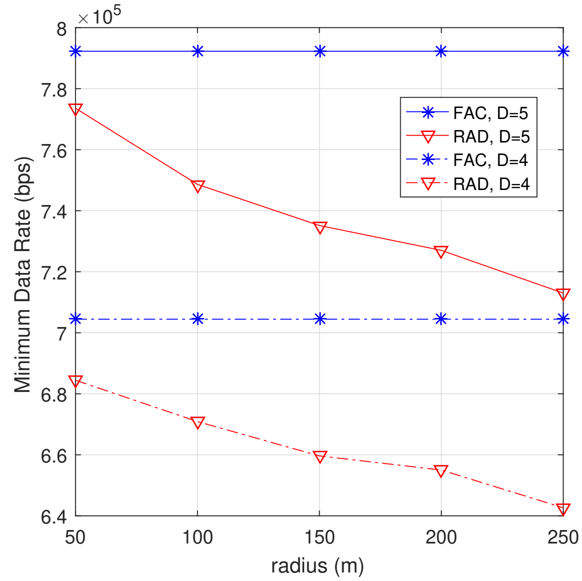

Fig. 3: Minimum user data rate in normal mode.

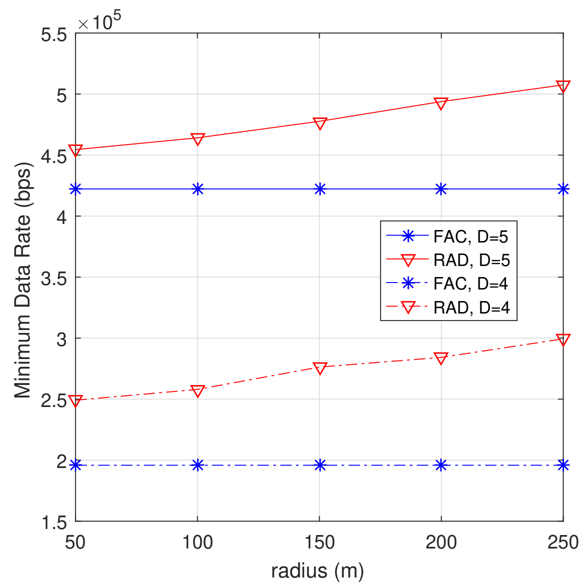

Fig. 4: Minimum user data rate in transition mode

running important applications. In emergency or high reliable networks, the main aim is to provide uninterrupted data flow to users at a rate which satisfies the critical needs of users.

Our proposed algorithm is designed to improve transition mode performance with acceptable loss in normal mode operation. To better understand tradeoff DR_{min}^N and DR_{min}^T are evaluated together. Fig. 3 and Fig. 4 illustrate the DR_{min}^N and DR_{min}^T performance in normal and transition modes, respectively. Table II presents the gains, in percentage, of FAD in normal mode and RAD in transition mode with respect to each other for $r_S = 50, 150$ and 250.

When D equals to 4 and $r_S = 150$, RAD provides a slight loss (%6.67) in DR_{min}^N but significant increase (%40.8) in the DR_{min}^T. Considering already high DR_{min}^N, some loss can be tolerated in the normal mode, however in transition mode, even a slight increase is critical to run services provided by the DBSs. When D is increased to 5, we still observe a considerable increase (%13.03 for r_S) in DR_{min}^T but it is much less than the performance increase provided by DBSs when $D = 4$. We expect to see less increase in DR_{min}^T when D is increased because the network becomes saturated. In previous work [9] we have shown that increasing D causes excessive interference at some point and leads to performance loss .

In Fig. 5, the average number of users which receive less than a threshold rate, 500Kbps, in each time slot is illustrated for FAD and RAD. When $r_S = 150$ and $D = 4$, average of 2 more users exceeds the threshold rate in each time slot. On the other hand, when $D = 5$, the gain drops considerably and only 0.47 more users in each time slot exceeds 500Kbps compared to that of FAD. As we explained, increasing D leads to loss in the performance of RAD technique.

VI. Conclusion

In this paper, we have studied the problem of DBS deployment considering a scenario, where one of the DBSs is known to be failure-prone. First, we described the behavior of a network in terms of system modes. Then we proposed a technique that determines the initial positions and routes of DBSs. The results showed that in the transition mode, the proposed algorithm provides significant increase in the minimum user data rate performance with tolerable performance decrease in normal mode.

The model can be used for communication scenarios, where uninterrupted flow of information has high priority and there is a knowledge about the health status of DBSs to be deployed on the field. Optimization of power outputs and velocities of DBSs can be studied as a future work.

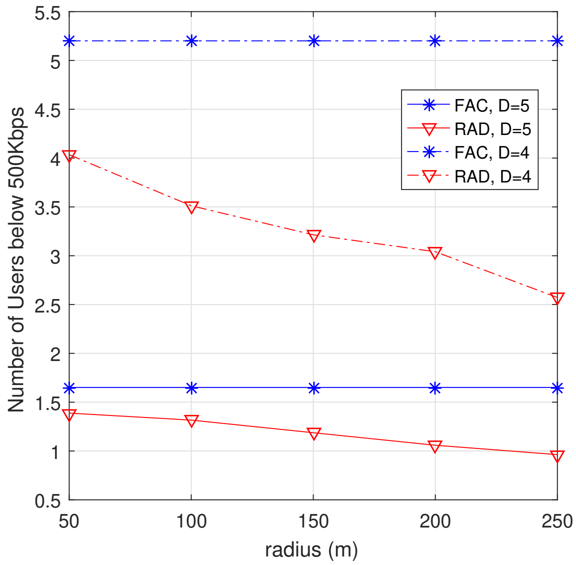

Fig. 5: Number of users having less than 500Kbps in transition mode.

References

[1] M. Mozaffari, W. Saad, M. Bennis, Y.-H. Nam, and M. Debbah, "A tutorial on uavs for wireless networks: Applications, challenges, and open problems," *arXiv preprint arXiv:1803.00680*, 2018.

[2] A. Fotouhi, H. Qiang, M. Ding, M. Hassan, L. G. Giordano, A. Garcia-Rodriguez, and J. Yuan, "Survey on uav cellular communications: Practical aspects, standardization advancements, regulation, and security challenges," *arXiv preprint arXiv:1809.01752*, 2018.

[3] A. Al-Hourani, S. Kandeepan, and A. Jamalipour, "Modeling air-to-ground path loss for low altitude platforms in urban environments," in *Global Comm. Conference (GLOBECOM), 2014 IEEE*. IEEE, 2014, pp. 2898–2904.

[4] M. Alzenad, A. El-Keyi, F. Lagum, and H. Yanikomeroglu, "3d placement of an unmanned aerial vehicle base station (uav-bs) for energy-efficient maximal coverage," *IEEE Wireless Comm. Letters*, 2017.

[5] M. Alzenad, A. El-Keyi, and H. Yanikomeroglu, "3d placement of an unmanned aerial vehicle base station for maximum coverage of users with different qos requirements," *IEEE Wireless Comm. Letters*, 2017.

[6] H. Y. E. Kalantari and A. Yongacoglu, "On the number and 3d placement of drone base stations in wireless cellular networks," in *Vehicular Technology Conference (VTC-Fall)*. IEEE, 2016, pp. 1–6.

[7] H. Y. E. Kalantari, M. Z. Shakir and A. Yongacoglu, "Backhaul-aware robust 3d drone placement in 5g+ wireless networks," in *Proc. of IEEE International Conference on Communications Workshops (ICC Workshops)*. IEEE, 2017, pp. 109–114.

[8] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Efficient deployment of multiple unmanned aerial vehicles for optimal wireless coverage," *IEEE Comm. Letters*, vol. 20, no. 8, pp. 1647–1650, 2016.

[9] A. Akarsu and T. Girici, "Fairness aware multiple drone base station deployment," *IET Communications*, vol. 12, no. 4, pp. 425–431, 2017.

[10] M. H. Azade Fotouhi, Ming Ding, "Dronecells: Improving 5g spectral efficiency using drone-mounted flying base stations," *arXiv preprint arXiv:1707.02041*, 2017.

[11] M. D. A. Fotouhi and M. Hassan, "Dynamic base station repositioning to improve spectral efficiency of drone small cells," in *18th International Symposium on A World of Wireless, Mobile and Multimedia Networks (WoWMoM)*. IEEE, 2017, pp. 1–9.

[12] X. X. Y. Zeng and R. Zhang, "Trajectory design for completion time minimization in uav-enabled multicasting," *IEEE Transactions on Wireless Communications*, vol. 17, no. 4, pp. 2233–2246, 2018.

[13] ——, "Joint trajectory and communication design for multi-uav enabled wireless networks," *IEEE Transactions on Wireless Communications*, vol. 17, no. 3, pp. 2109–2121, 2018.

[14] A. Akarsu and T. Girici, "Failure aware deployment of drone base stations," in *2018 26th Telecommunications Forum (TELFOR)*. IEEE, 2018, pp. 1–4.

[15] A. Al-Hourani, S. Kandeepan, and S. Lardner, "Optimal lap altitude for maximum coverage," *IEEE Wireless Communications Letters*, vol. 3, no. 6, pp. 569–572, 2014.

[16] C. A. Balanis, "Antenna theory: Analysis & design, john willey & sons," *Inc. Publication*, 1997.