Joint Multi-UAV Deployments for Air-Ground Integrated Networks

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***Abstract*—Unmanned aerial vehicles (UAV) can perform high-speed and reliable transmissions with the properties in air superiority, high agility and fast deployment. They have shown advantages in flexibility and reliability when the ground communication facilities cannot provide satisfactory services. In this article, a multi-UAV based air-ground integrated network (AGIN) model is established with a novel joint optimal multi-UAV deployment framework, where UAVs serve as aerial base stations (BSs) or relays. To improve the communication performance of the AGIN, the following deployment schemes are proposed: 1) a static multi-UAV BS deployment to maximize the number of covered users by user clustering; 2) a mobile multi-UAV BS deployment to maximize the transmission performance of users, which is achieved by jointly optimizing UAV trajectories and user scheduling; 3) an optimized UAV multi-hop relay deployment to minimize the number of UAV relays and the communication outage probability. Moreover, UAV formation relay is deployed as a virtual multi-antenna array to improve the relaying performance by beamforming and orthogonal space-time block coding, and some further open researches and challenges are also discussed.**

***Index Terms*—air-ground integrated networks; multi-UAV deployment; UAV base station; UAV relay**

I. INTRODUCTIONS

Recently, unmanned aerial vehicle (UAV) assisted air-ground integrated networks (AGINs) have played an important role in disaster rescue, emergency support and network expansion, and have drawn wide attention from academia and industry [1], [2]. Due to the advantages of low cost, high mobility and flexible deployment, UAV hovering in the air is easier to establish the wireless communication link than the ground fixed communication facilities [3], [4]. UAVs possess the ability to establish superior line of sight (LoS) links by air superiority. Hence, they can sufficiently approach ground terminals to transmit and receive data [5]. In the AGIN, there are mainly two types of applications of UAV: 1) UAV base station (BS), which can quickly recover the ground communications by forming an air-to-ground cellular network in the area where the ground BSs are paralyzed [6]; and 2) UAV relay, which can help the ground users suffering severe channel fading to achieve high-speed and reliable communications via better aerial LoS transmissions [7].

UAV BS has drawn lots of attention so far since it may offer wireless services to the ground users from the air without relying on the terrestrial infrastructure. In [8], Savkin *et al.* studied the network performance improved with a variety of UAV BS deployments to minimize the average UAV-user distance. To maximize the communication coverage of the UAV BS, Al-Hourani *et al.* [9] optimized the UAV altitude according to the pathloss and the statistical parameters of the urban environment. In [10], Lai *et al.* proposed a density-aware deployment scheme to maximize the number of users covered by UAV under the constraint of minimum rate for each user. Considering the UAV BSs serving cellular users, Huang *et al.* [11] tried to find the minimum number of UAVs and their deployments under the constraint of expected user coverage ratio. In [12], Kimura *et al.* proposed a distributed 3D deployment scheme for UAV BSs with on-demand coverage in a downlink network, which was performed by sensing-aided crowd density estimation and distributed push-sum algorithm. Most of the existing work has focused on the optimization of UAV deployment with limited users, while the deployment of multiple UAVs serving massive users has not been sufficiently investigated .

UAVs can also be used as relays to improve the connectivity, coverage and quality of ground networks. Considering the case that a UAV works as an amplify-and-forward (AF) relay, Zhang *et al.* [13] optimized the trajectory and transmit power of UAV as well as the mobile device by minimizing the network outage probability. In [14], Zeng *et al.* maximized the throughput of mobile relaying system by optimizing the source/relay transmit power and the UAV trajectory under the practical mobility constraints. The optimal deployment of a relaying UAV for maximum reliability is studied by Chen *et al.* [15], in which the total power loss, outage probability and bit error rate were derived as reliability measures. In [16], Li et al. jointly optimized the UAV deployment and the transmit power of users to maximize the total rate of both uplink and downlink under the constraint of the signal-to-noise ratio (SNR) on the UAV control channel. Considering that a UAV relays data for multiple user pairs in a time-division manner, Jiang *et al.* [17] maximized the minimum average rate of each communication pair by optimizing time slot, power and UAV trajectory. To maximize the capacity of UAV-relaying device-to-device (D2D) network, Zhong *et al.* [18] jointly optimized relay deployment, channel allocation and relay assignment by an alternating optimization method.

Although the deployment of single UAV or multiple non-cooperative UAVs has been settled in some work, the deployment of multiple cooperative UAVs is a more challenging issue

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and still not settled yet. This article aims to provide a joint optimal multi-UAV deployment framework for the AGIN. The following deployment schemes are proposed: a static multi-UAV BS deployment to maximize the number of covered users by user clustering; a mobile multi-UAV BS deployment to maximize the transmission performance of users by jointly optimizing UAV trajectories and user scheduling; an optimized UAV multi-hop relay deployment to minimize the number of UAV relays and the communication outage probability; an UAV formation relay deployment as a virtual multi-antenna array to improve the relaying performance by beamforming and orthogonal space-time block coding (OSTBC).

II. MULTI-UAV ENABLED AIR-GROUND INTEGRATED NETWORKS

Owing to the smaller volume, lower transmission attenuation and better communication performance, the UAV can be quickly and flexibly deployed in the AGIN without considering the terrains and ground facilities, as shown in Fig. 1. The LoS communication link of the UAV can bring more stable and reliable data transmissions for the AGIN. And the UAV can use its maneuverability to select the optimal flight path to enhance the communication link and reduce the transmission interference. In the AGIN, the UAV can perform as a base station (BS) or a relay. Since a single UAV usually does not provide the expected network capacity, the multi-UAV deployment in a collaborative manner is of great significance.

A. *UAV BS*

When the terrestrial infrastructures are completely destroyed in a disaster or the users are out of the communication coverage of the ground base station (BS), the UAV equipped with the BS module can function as an aerial BS and provide communication services to the ground users without relaying on the ground BS. Through proper location selection and trajectory design of the UAV, the transmit power of the UAV can be effectively reduced and the larger coverage under the constraints of high system capacity and low transmission interference can be achieved. The two main deployment schemes for multi-UAV BSs are below.

Static multi-UAV BS deployment: the static UAV functions as a fixed aerial BS and serves the users within its communication coverage. The coverage area of each UAV can be seen as a microcellular, where the users can exchange information via the corresponding UAV BS. The distances between the UAVs should be long enough, so that the communications of an UAV will not be disturbed by the adjacent UAVs. In addition, the UAVs should be deployed according to the distribution of the users to ensure the UAV BSs can cover as many users as possible and provide high-quality communication services to users. Therefore, the key to the deployment of the static UAV BSs is to optimize the three-dimension position of the UAVs under the constraints of energy and coverage of each UAV as well as the communication performance required by each user.

Mobile multi-UAV BS deployment: the mobile UAV serves the users as a dynamic aerial BS, which can improve the service quality by flying close to the users who need information transmissions. As the position of the UAV changes constantly, the air-to-ground channel is time-varying. To improve the communication performance, the flight trajectory of the UAV should be optimized according to the channel conditions. Since the mobile UAV BSs have no fixed serving users and each user can access any UAV, the user scheduling needs to be optimized to improve the service quality and decrease the inter-user interference. Therefore, joint optimization of UAV trajectory and user scheduling should be considered in the deployment of mobile UAV BSs.

B. *UAV Relay*

When the ground communication link is blocked by the shadow fading, due to the aerial LoS link, the UAV as a cooperative relay can forward the source information to the destination. Compared with the ground relay, the UAV relay can flexibly choose the cooperation location with the best channel states, thus improving the cooperative communication performance. There are two deployment schemes for the multi-UAV relays as follows.

UAV multi-hop relay: when the distance between the source user and the target user is relatively far, multiple UAVs are connected in turn to form a multi-hop cooperative communication link. The UAV can relay the source information by amplify-and-forward (AF) mode or decode-and-forward (DF) mode. The distance between UAVs should be selected properly. If the distance is too large, the relaying performance of the UAV will be reduced; while the number of cooperative UAVs will be increased if the distance is very small. In addition, the air-to-air channel accords with the LoS loss, whereas the air-to-ground channel is affected by the scattering and fading near the ground users. Thus, the optimal deployment should consider different channel types and reduce the number of cooperative UAVs by optimizing the cooperative locations of the UAVs with the best cooperative communication performance.

UAV formation relay: when the transmit power of a UAV is low, multiple UAVs can formate to form a multi-relay system to forward the source information. Since the UAV formation and the ground terminals form a virtual multi-input multi-output (MIMO) system, the relaying performance of the UAV formation will be significantly enhanced [19]. The MIMO capacity of the cooperative link depends on the placement of the UAV formation, which is directly affected by both the source-to-UAV and the UAV-to-destination links. Therefore, the deployment of the UAV formation should be optimized to maximize the cooperative throughput. Furthermore, the transmit beamforming and orthogonal space-time block codes (OSTBC) can be applied to the UAV formation to further improve the cooperative communication performance.

III. STATIC MULTI-UAV BS DEPLOYMENT

When the ground BS is damaged, the UAV BS with stronger environmental adaptability can provide reliable high-speed communication services to the ground users through proper operation and deployment. If a quantity of static users need to be served, multiple static UAV BSs can be deployed. To

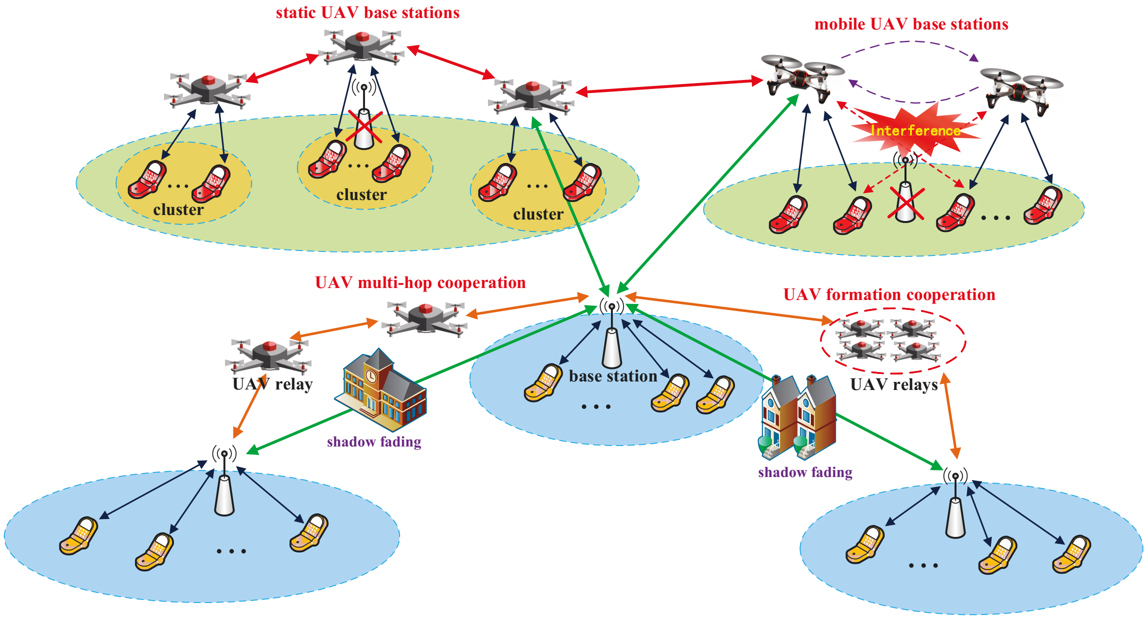


Fig. 1. Air-ground integrated network model.

achieve better communication performance under the circumstances of limited energy and resources, the optimal three-dimensional deployment locations of static UAVs should be determined according to the distribution of ground users. The static UAV BS deployment should get the following information: (1) the number of deployed UAV BSs; (2) the deployment locations of UAV BSs; (3) the expected service levels of UAV BSs.

According to the maximum number of users that accessing each UAV and the total number of ground users, we can estimate the number of deployed UAV BSs. There are two methods to estimate the number of UAVs. One is to get the coverage radius by setting the optimal height of UAV and determine the number of UAV BSs according to the total coverage area and the maximum coverage radius of UAV. The other is to estimate the number of UAV BSs according to the maximum capacity of UAV BS and the total service capacity of ground users [20]. Assuming the maximum capacity of the UAV BS is C and the user rate is r, the maximum number of accessing users is $q = \frac{C}{r}$. Therefore, the initial number of deployed UAV BSs is $N = \frac{N_T}{q}$, where N_T is the total number of ground users. By using the K-means method, the N_T ground users are divided into N clusters, each of which is managed by one UAV BS, as shown in the deployment of Fig. 2. Assume the horizontal location coordinate of each UAV is (v, μ), the location coordinate of each cluster user is (x_k, y_k), and the maximum coverage radius of UAV is R. Set $\alpha_k = \{0, 1\}$, where $\alpha_k = 1$ if user k is covered by the UAV BS, and $\alpha_k = 0$, otherwise. Then (v, μ) is obtained by solving the following optimization problem

$$\begin{aligned} &\max_{k} \sum \alpha_k \\ &s.t. (x_k - v)^2 + (y_k - \mu)^2 \leq \alpha_k R^2 + \Phi(1 - \alpha_k),\ \forall k \\ &\quad (x_k - v)^2 + (y_k - \mu)^2 \geq (1 - \alpha_k) R^2,\ \forall k \end{aligned} \tag{1}$$

where Φ is a big enough constant.

The UAV's height can be obtained by searching a tradeoff between the coverage radius, R, and the height of the UAV, h. In order to guarantee the user rate, the receiving power of the ground user must be large enough. That is, the path loss of any user in the coverage of UAV is not greater than a certain threshold. Assuming the maximum allowable path loss of the edge user in the coverage is L_{max}, we have $L_k \leq L_{max}, \forall k$. At the beginning of UAV's take-off, the coverage radius first increases with the height due to the improvement of the channel conditions. However, after the coverage radius reaches the threshold, it decreases with the height because of the great free space loss. Hence, there exists an optimal height that maximizes the coverage radius, which is achieved by $\frac{\partial R}{\partial h} = 0$.

In the simulations, the ground users are randomly distributed in the area of 2000m×2000m, which are served by 4 UAVs. The optimal coverage areas of UAVs with the coverage radius of $R = 300$m are shown in Fig. 3(a), in which the dots represent the users and the asterisks denote the UAVs. The users are divided into 4 clusters, each of which is covered by one UAV BS, and most of the users have been covered by the UAVs. The optimal height of the UAV is illustrated in Fig. 3(b). There is an optimal height to maximize the coverage radius, which is marked by the asterisk. In addition, the coverage radius increases with L_{max}, which indicates that increasing the transmit power of the UAV can expand the coverage.

IV. MOBILE MULTI-UAV BS DEPLOYMENT

When the users are dynamic, mobile UAV BSs can be deployed to guarantee the stable spectrum access. According to the distribution of the users, the mobile UAV BS can select the best flight trajectory to ensure the maximum transmission capacity for the users served during the flight. In addition,

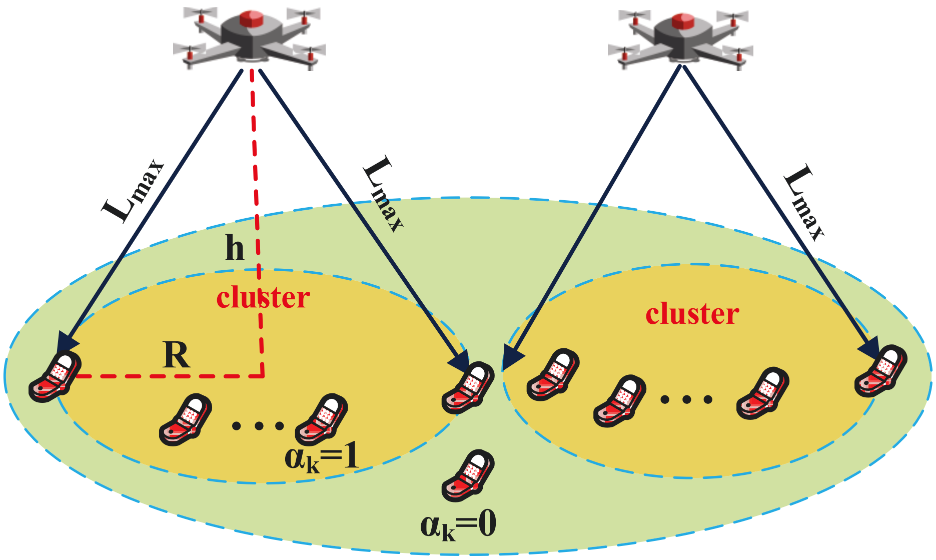
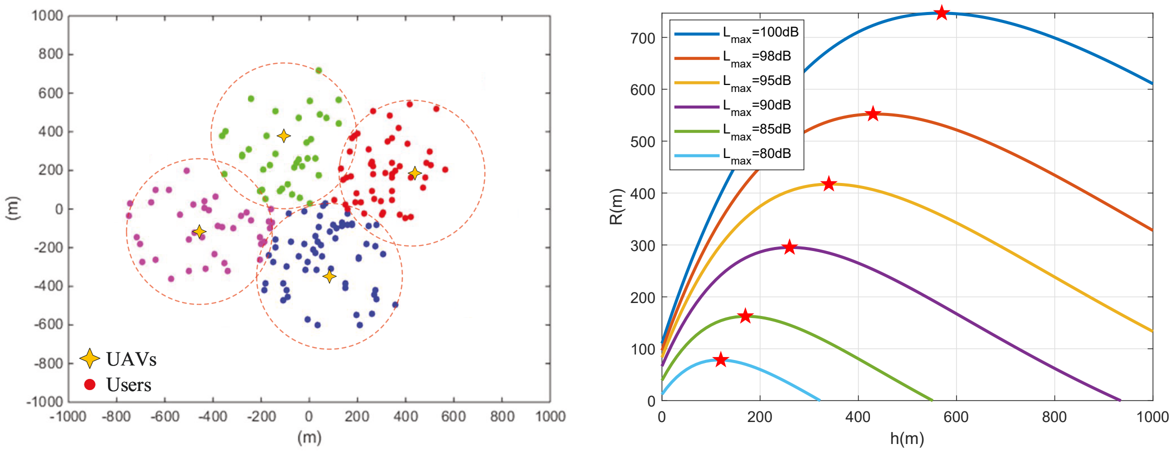


Fig. 2. Optimal deployment model of static UAV BSs.



(a) (b)

Fig. 3. Optimal deployment results: (a) optimal coverage areas of UAVs; (b) optimal height of UAVs.

since the users served by each UAV are not fixed, the user scheduling needs to be considered to avoid access conflicts.

We use the K-means method to cluster the users and update the locations of UAV BSs, such that the users can connect the UAV with the minimum transmit power. According to the optimal transmission theory, the UAV trajectory is optimized among the discrete UAV BSs, which seeks to achieve dynamic efficient communications between UAV BSs and ground users. There should be a certain flying distance between UAVs to avoid sever inter-user interferences. Assume the location update time is $t_n, n = 1, 2, ..., K$, where K is the number of updates, and the locations of UAV BSs and the associated users are known before each update. Due to user activities in different update times, the UAV BS will be re-deployed after each update. Therefore, the UAV trajectory is composed of K hovering positions [14]. Our goal is to maximize the transmission performance of the users under the constraint of the minimum interference distance between the UAVs by jointly optimizing the trajectories of UAVs and user scheduling. The optimizing model is shown in Fig. 4.

In the simulations, 9 users are randomly distributed in the area of 1000m×1000m, the transmit power of each UAV is 10dBmW, and the average noise power is -100dBmW. The total flight time within one circle is 40s, and the length of each time slot is 0.5s. The optimal trajectories of mobile UAVs are shown in Fig. 5(a). Each UAV always flies as close as possible to its served users, and any two UAVs always keep as far away from each other as possible to alleviate interference to the greatest extent. The optimal total throughput of UAVs is illustrated in Fig. 5(b). It shows that the mobile UAV may achieve a larger throughput than the statistic UAV, and the throughput can be improved by increasing the number of mobile UAVs.

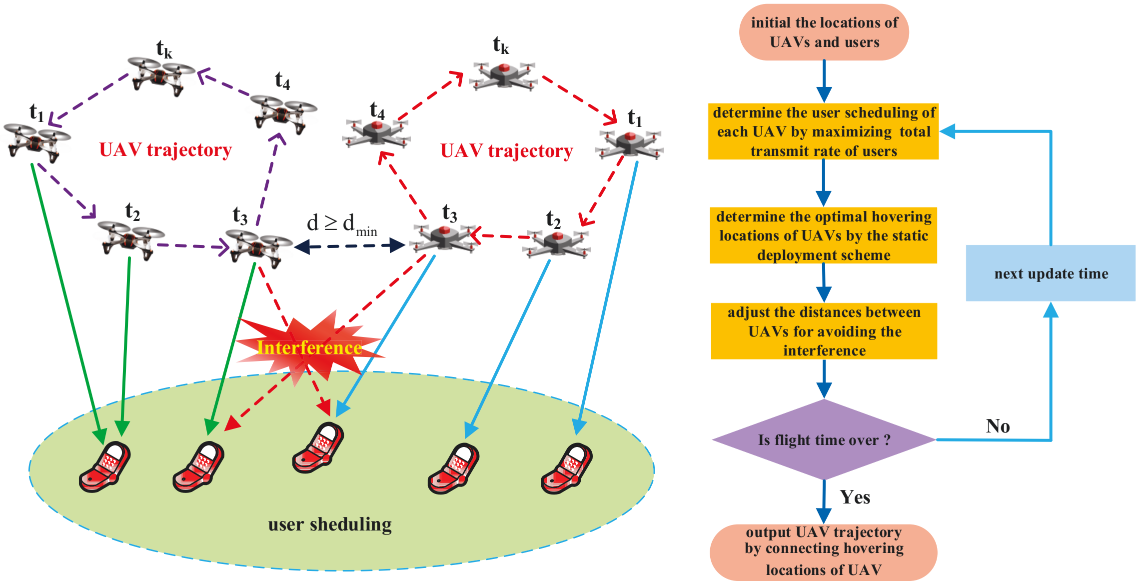
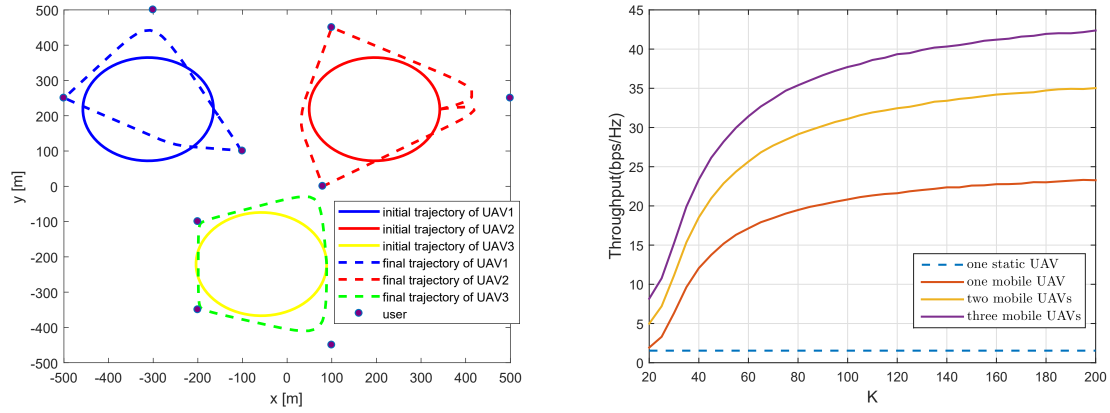


Fig. 4. Optimal deployment model for mobile UAV BSs.



(a)

(b)

Fig. 5. Optimal deployment results: (a) optimal trajectories of UAVs; (b) optimal total throughput of UAVs.

V. UAV MULTI-HOP RELAY DEPLOYMENT

Ground wireless communications are easily hindered by terrain and other factors, which leads to the communication failure between users. The aerial LoS link using UAV as cooperative relay can effectively avoid ground shadow fading and improve the transmission performance between ground users. When the users are far away, due to the limited power of a single UAV, multiple UAVs are required to form multi-hop cooperative communication to ensure long-distance transmission performance.

UAV-relaying cooperative communication needs to consider the number of UAVs, relay quality and connectivity. Therefore, the key to guarantee the cooperative communication performance is to select the number of cooperative UAVs and deployment locations of UAV relays. Our goal is to minimize the number of UAVs and the communication outage probability by determining the deployment locations of UAVs, subject to the constraints of the communication distance between users and the UAV power. In addition, other deployment constraints may also be considered. For example, the deployment of UAVs should avoid the shadow areas to ensure reliable cooperative communication; there should be a LoS path between any adjacent UAVs to avoid communication disconnection in the relay link; any UAV should be placed at the only deployment location.

In the cooperative communication link, we need consider two channel states: the air-to-air channels between UAVs conform to free space loss, and the air-to-ground channels between UAV and ground user are affected by the scattering and fading near the ground users, are shown in Fig. 6. In the air-to-ground link, LoS link loss L_{LoS} and non-LoS (NLoS) link loss L_{NLoS} appear in the probabilities of $P(\theta)$ and $1-P(\theta)$, respectively. $P(\theta)$ is decided by the elevation angle of the UAV relative to the ground user, denoted by θ. Therefore, the air-to-ground link loss can be defined as the probability sum of LoS loss and NLoS loss, denoted by $L_{LoS}P(\theta)+L_{NLoS}(1-P(\theta))$. The

UAVs can perform amplify-and-forward (AF) or decode-and-forward (DF) cooperative communication. In the AF mode, the receiving SNR of the destination user is given by [15]

$$\gamma = \left[\prod_{i=1}^{K} \left(1 + \frac{1}{\gamma_k} \right) - 1 \right]^{-1} \tag{2}$$

where γ_k is the receiving SNR of each UAV and K is the number of UAV relays. While in the DF mode, the receiving SNR of the destination user is obtained by $\gamma = \min\{\gamma_1, \gamma_2, ..., \gamma_K\}$. Then the outage probability of cooperative communication can be calculated by $P_r(\gamma < \gamma_{min})$ where γ_{min} is the minimum SNR satisfying the communication requirement.

Assume the horizontal locations of K UAV relays are (x_1, y_1), (x_2, y_2),...,(x_K, y_K), and the center location and coverage radius of shadow areas c_i are (x_{c_i}, y_{c_i}) and r_i, respectively. The deployment locations of UAV relays should satisfy

$$d_{min} <= \sqrt{(x_k - x_{k-1})^2 + (y_k - y_{k-1})^2} <= d_{max}, \tag{3}$$
$$k = 2, 3, ..., K;$$
$$\sqrt{(x_k - x_{c_i})^2 + (y_k - y_{c_i})^2} >= r_i, \forall k, i; \tag{4}$$

where d_{min} and d_{max} are the minimum interference distance and maximum communication distance between UAVs, respectively. The UAV relays can hover at these optimized locations.

In the simulations, the ground users are located in the area of 3000m×3000m where there are three shadow areas, and the maximum transmission distance of UAV is 800m. The optimal locations of UAV relays are shown in Fig. 7(a), where the fewest UAVs are deployed to keep the connectivity and avoid the shadow areas. The optimal height of UAVs is illustrated in Fig. 7(b). With the increase of the height, the outage probability first reduces due to the decrease of the NLoS probability and then rises because of the increased LoS loss in the air-to-ground link. Therefore, there exists an optimal height of UAV that minimizes the outage probability. Moreover, the outage probability increases with the decrease of $P(\theta)$, which indicates that the increase of the NLoS loss in the air-to-ground link may cause great transmission interruptions.

VI. UAV FORMATION RELAY DEPLOYMENT

Currently, point-to-point communication performance can be improved obviously by using antenna arrays with the MIMO signal processing. Multiple UAVs can formate as a virtual multi-antenna array, which can achieve MIMO capacity gains along with multiple antennas at the source and destination. The MIMO capacity of the cooperative link depends on the deployment of UAVs, which is affected by both the soruce-to-UAV and UAV-to-destination channels. Therefore, the cooperative performance can be improved by optimizing the location of the UAV formation. Furthermore, transmit beamforming and OSTBC can be applied to the UAV formation, which can improve the channel capacity and transmission distance of the UAV formation by increasing the transmit antenna gain.

In the simulations, we assume that the direct ground transmission is blocked by buildings and the UAV formation performs as a virtual MIMO enabled cooperative relay for the ground communications. As shown in the deployment model of Fig. 8, the UAV formation receives the information from the multi-antenna ground BS by data combining such as equal gain combining (EGC), selection combining (SC), maximum ratio combining (MRC) and receiving beamforming. Then using transmit beamforming or OSTBC, the UAV formation forwards the decoded symbols to the destination with the UAVs acting as virtual antenna elements [19]. Fig. 9 compares the bit-error-rate (BER) performance between the cooperative communications of 1, 2, 4 and 8 UAVs formations and the direct transmission from the source to the destination. It is seen that the UAV formation enabled cooperative communication can achieve better BER performance than the direct transmission, and the BER decreases obviously with the increased number of UAVs in the formation.

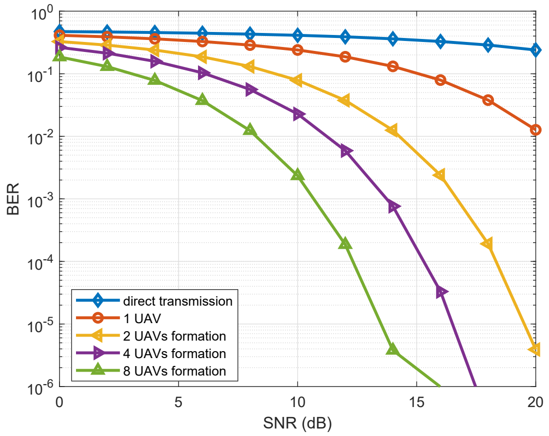


Fig. 9. BER Performance of UAV formation cooperation

Accordingly, the UAV deployment needs to consider the joint design of deployment location, altitude, and flight trajectory. Designing the optimal location and altitude can effectively expand the coverage and service quality of the UAV. While designing the optimal trajectory can make full use of the UAV mobility to achieve the optimal service quality by improving the air-ground link performance. In addition, the deployment of UAVs needs to comprehensively consider the distributions of ground users and the fading characteristics of air-ground links. By jointly optimizing deployment location, altitude, and trajectory of UAVs based on the user distribution and link fading, the coverage radius of UAV can be maximized and the air-ground communication outage can be minimized.

VII. OPEN RESEARCHES AND CHALLENGES

This article has introduced some fundamental works on joint optimal multi-UAV deployment in air-ground-integrated network, such as static multi-UAV deployment, mobile multi-UAV deployment, UAV multi-hop relay deployment and UAV formation relay deployment. However, there are still some open researches and challenges to be discussed in the future.

Hybrid deployment of static UAVs and mobile UAVs: although the coverage and transmission performance of the

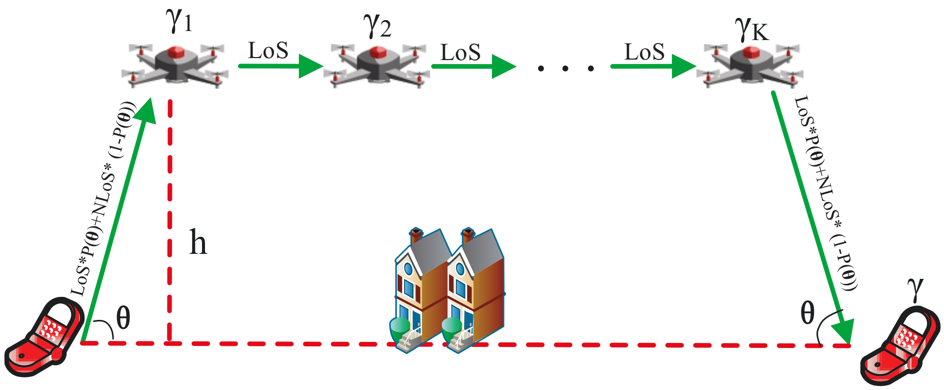
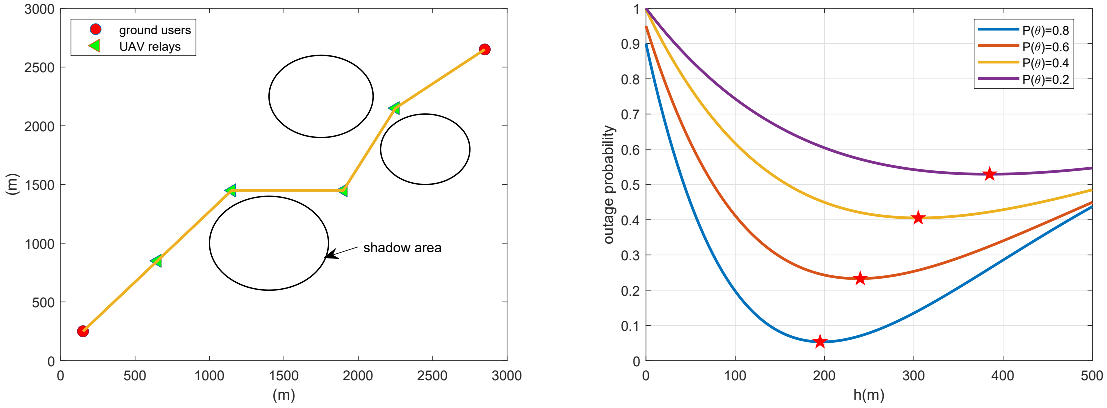


Fig. 6. UAV multi-hop relay model.



(a) (b)

Fig. 7. Optimal deployment results: (a) optimal locations of UAVs; (b) optimal height of UAVs.

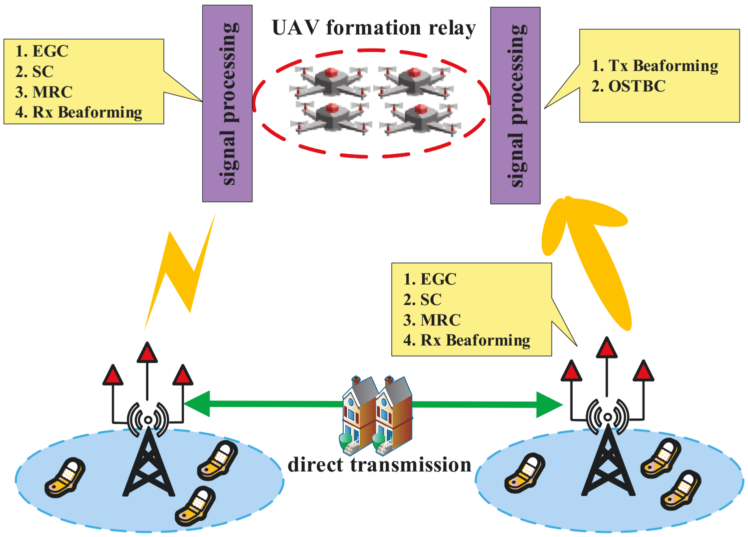


Fig. 8. Deployment model of UAV formation cooperation

static UAV is limited, it can save a lot of propulsion energy especially in the area where the users are densely distributed. Therefore, according to the distribution of the ground users, the hybrid deployment of static UAVs and mobile UAVs can be investigated to guarantee the communication performance with less energy consumption.

Inter-UAV interference suppression: when multiple UAVs communicate with the ground users, there will be severe inter-

UAV interference. However, if the distance between UAVs is set far enough to avoid interference, some users will not be covered by the UAVs. Therefore, spread spectrum communication, interference alignment, adaptive antenna and other anti-jamming technologies can be applied to the UAVs to reduce the communication interference.

Massive-UAVs formation communications: massive-UAV formation communication can be regarded as massive MIMO, which can improve the transmission performance by achieving greater spatial diversity gain. Some key technologies for massive MIMO such as channel estimation, precoding and antenna selection etc. can be investigated in the massive-UAV scenario.

Energy-efficient UAVs deployment: the traditional UAVs deployment focuses on improving the coverage and transmission quality of UAVs, but ignores the energy consumption of the UAVs during the flight and communications. Therefore, the energy-efficient UAVs deployment should be investigated to reduced the energy consumption of UAVs.

UAVs deployment for mobile users: the current UAVs deployment mostly provide services for fixed ground users, ignoring the impact of user mobility on UAV deployment. When the ground users moves at a high speed, the UAVs are difficult to provide real-time coverage and continuous communications for the users. Therefore, based on the mobile trajectory of ground users, the dynamic UAVs deployment for mobile users can effectively improve the communication performance.

UAV communication security: because of the open and LoS characteristics of wireless channels between UAVs and ground users, UAV communication is more vulnerable to eavesdropping attacks from malicious eavesdroppers than the traditional ground communications. To improve the confidentiality of UAV communications, some communication security technologies, such as information encryption, physical layer security, etc, should be adopted to provide an effective solution.

VIII. CONCLUSIONS

In this article, a multi-UAV based AGIN, where the UAVs serve as aerial BSs and relays, is proposed to achieve high-speed and reliable communications when the ground communications are paralyzed or in fading. To improve the transmission performance of the AGIN, we have studied the joint multi-UAV deployment including static multi-UAV BS deployment, mobile multi-UAV BS deployment, UAV multi-hop relay deployment and UAV formation relay deployment. We also discuss some open researches and challenges in the future, such as hybrid deployment of static UAVs and mobile UAVs, inter-UAV interference suppression, massive-UAV formation communications, etc.

REFERENCES

[1] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Optimal transport theory for power-efficient deployment of unmanned aerial vehicles," in *2016 IEEE International Conference on Communications (ICC)*, pp. 1–6, 2016.

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

[3] E. Kalantari, H. Yanikomeroglu, and A. Yongacoglu, "On the number and 3D placement of drone base stations in wireless cellular networks," in *2016 IEEE 84th Vehicular Technology Conference (VTC-Fall)*, pp. 1–6, 2016.

[4] S. Kim, P. Silson, A. Tsourdos, and M. Shanmugavel, "Dubins path planning of multiple unmanned airborne vehicles for communication relay," *Proceedings of the Institution of Mechanical Engineers Part G Journal of Aerospace Engineering*, vol. 225, no. 1, pp. 12–25, 2011.

[5] N. Cheng, W. Xu, W. Shi, Y. Zhou, N. Lu, H. Zhou, and X. Shen, "Air-ground integrated mobile edge networks: Architecture, challenges, and opportunities," *IEEE Communications Magazine*, vol. 56, no. 8, pp. 26–32, 2018.

[6] J. Lu, S. Wan, X. Chen, Z. Chen, P. Fan, and K. B. Letaief, "Beyond empirical models: Pattern formation driven placement of UAV base stations," *IEEE Transactions on Wireless Communications*, vol. 17, no. 6, pp. 3641–3655, 2018.

[7] H. Baek and J. Lim, "Time mirroring based CSMA/CA for improving performance of UAV-relay network system," *IEEE Systems Journal*, vol. 13, no. 4, pp. 4478–4481, 2019.

[8] A. V. Savkin and H. Huang, "Deployment of unmanned aerial vehicle base stations for optimal quality of coverage," *IEEE Wireless Communications Letters*, vol. 8, no. 1, pp. 321–324, 2019.

[9] 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.

[10] C. Lai, C. Chen, and L. Wang, "On-demand density-aware UAV base station 3D placement for arbitrarily distributed users with guaranteed data rates," *IEEE Wireless Communications Letters*, vol. 8, no. 3, pp. 913–916, 2019.

[11] H. Huang, C. Huang, and D. Ma, "A method for deploying the minimal number of UAV base stations in cellular networks," *IEEE/CAA Journal of Automatica Sinica*, vol. 7, no. 2, pp. 559–567, 2020.

[12] T. Kimura and M. Ogura, "Distributed collaborative 3d-deployment of UAV base stations for on-demand coverage," in *IEEE INFOCOM 2020 - IEEE Conference on Computer Communications*, pp. 1748–1757, 2020.

[13] S. Zhang, H. Zhang, Q. He, K. Bian, and L. Song, "Joint trajectory and power optimization for uav relay networks," *IEEE Communications Letters*, vol. 22, no. 1, pp. 161–164, 2018.

[14] Y. Zeng, R. Zhang, and T. J. Lim, "Throughput maximization for uav-enabled mobile relaying systems," *IEEE Transactions on Communications*, vol. 64, no. 12, pp. 4983–4996, 2016.

[15] Y. Chen, N. Zhao, Z. Ding, and M. Alouini, "Multiple UAVs as relays: Multi-hop single link versus multiple dual-hop links," *IEEE Transactions on Wireless Communications*, vol. 17, no. 9, pp. 6348–6359, 2018.

[16] L. Li, T. Chang, and S. Cai, "Uav positioning and power control for two-way wireless relaying," *IEEE Transactions on Wireless Communications*, vol. 19, no. 2, pp. 1008–1024, 2020.

[17] X. Jiang, Z. Wu, Z. Yin, W. Yang, and Z. Yang, "Trajectory and communication design for UAV-relayed wireless networks," *IEEE Wireless Communications Letters*, vol. 8, no. 6, pp. 1600–1603, 2019.

[18] X. Zhong, Y. Guo, N. Li, and Y. Chen, "Joint optimization of relay deployment, channel allocation, and relay assignment for UAVs-aided D2D networks," *IEEE/ACM Transactions on Networking*, vol. 28, no. 2, pp. 804–817, 2020.

[19] R. C. Palat, A. Annamalau, and J. R. Reed, "Cooperative relaying for ad-hoc ground networks using swarm UAVs," in *MILCOM 2005 - 2005 IEEE Military Communications Conference*, vol. 3, pp. 1588–1594, 2005.

[20] Y. Li, J. Zhao, and Z. Wei, "Energy-efficienct deployment of unmanned aerial vehicle base station," *Computer Applications and Software*, vol. 39, no. 5, pp. 153–159, 2022.

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