2018 IEEE 19th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)

Energy-Efficient UAV Deployment with Flexible Functional Split Selection

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***Abstract*—In this paper, we consider the deployment of unmanned aerial vehicles (UAVs) along a straight road, and aim to minimize the total energy consumption of UAVs, including the baseband processing energy, the wireless fronthauling energy and the constant circuit energy. Specifically, the horizontal location, vertical location, coverage radius and the functional split scheme selection of UAVs are jointly optimized. Both the user data rate and the total delay consisting of baseband processing and fronthaul transmission are guaranteed. To reduce the optimization complexity, we further derive the upper and lower bounds of the optimal number of UAVs. Numerical results show that, with flexible functional split, the energy consumption of UAVs can be considerably reduced compared with fixed functional split. We also observe that more baseband functions should be placed at the UAV side when the distance between the UAV and the baseband units (BBU) on the ground is larger.**

***Index Terms*—Functional split, UAV deployment, Cloud-Radio Access Network (C-RAN), fronthaul.**

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) have recently gained growing attentions due to their flexibility to provide better coverage, good mobility and high probability of line-of-sight (LoS) channels [1]. UAVs can be rapidly deployed to provide coverage in emergency scenarios, or assist the ground networks when they are overloaded. Batteries are often used on UAVs, to support the communication power, the mobility power, and etc. The power consumption of communications can limit the flying time of UAVs due to their limited battery capacity [2], [3].

Some key factors like the coverage size, transmitting power and on-board circuit power are recently explored for energy efficient UAV deployment. In [4], an analytical approach is proposed to get the optimal vertical location of a single UAV to maximize the coverage. A 3-D energy efficient UAV deployment algorithm is proposed in [5], jointly considering the vertical location and the coverage size of UAVs. The overall UAV transmission power of multiple UAVs is minimized while satisfying the users' data requirement in [6]. In [7], the energy efficient UAV deployment considering the user density and the on-board circuit power is analyzed.

By centralizing some baseband functions at the baseband units (BBU) on the ground, the computation complexity of a UAV can be reduced in the context of cloud radio access network (C-RAN), and thus the processing energy introduced by baseband processing at UAVs can potentially be saved [8]. However, UAVs need to communicate with the BBU through wireless fronthaul under limited rate. Flexible functional split can tradeoff between the baseband processing complexity of UAVs and the wireless fronthaul rate requirement [9]. As illustrated in Fig. 1(b), with more baseband functions at the UAV, i.e., at the right side of the blue line corresponds to each split scheme, the required fronthaul rate is smaller, but the baseband processing complexity is larger, consuming more baseband processing energy, and introducing larger processing delay [10]. In short, the functional split scheme affects both the energy efficiency and the delay performance of the UAV communication system. Note that the path loss of the wireless fronthaul is affected by the distance between the UAV and the BBU. The locations of UAVs, including the horizontal locations and the vertical locations, affect the channel state of the wireless fronthaul, which will potentially affect the functional split scheme. The locations of UAVs have different effects on the user data rate and the wireless fronthaul, and thus the UAV deployment and the functional split should be jointly optimized.

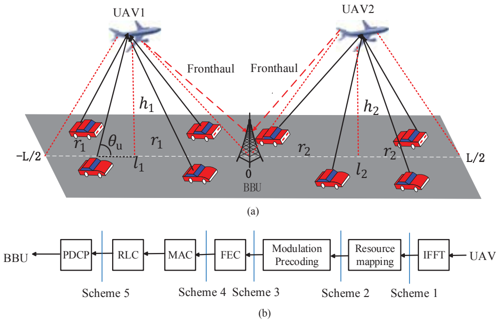

Fig. 1. (a) UAV deployment along a straight road with two UAVs. (b) Illustration of the flexible functional split in the uplink.

In this paper, we investigate the energy-efficient UAV deployment jointly with the functional split selection. The uplink scenario is considered, and we aim to minimize the total energy consumption of all the UAVs, including the baseband processing, the wireless fronthaul and the constant circuit energy consumption, while guaranteeing the given user data rate, the processing and fronthauling delay constraints. We further analyze the minimum number of UAVs to guarantee the coverage, and the upper bound of the optimal number of

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UAVs, based on which, the optimal energy consumption is obtained with reduced complexity. Numerical results validate the gain brought by the joint optimization of flexible functional split and UAV deployment over the fixed functional split scheme.

The paper is organized as follows. The system model is described in Section II. The energy-efficient UAV deployment problem is formulated and analyzed in Section III. The numerical results are presented in Section IV. The paper is concluded in Section V.

II. SYSTEM MODEL

We consider the deployment of UAVs for the uplink, where the UAVs serve as access points and receive the data from the users, and then transmit the corresponding baseband signals to the BBU on the ground with wireless fronthaul, as illustrated in Fig. 1.

A. *UAV Coverage*

We aim to cover a straight and horizontal road of length L. The vertical location of the road is denoted as 0, and the horizonal range of the road is from $-\frac{L}{2}$ to $\frac{L}{2}$. The vertical locations of all the users are assumed to be 0, as they correspond to vehicles on the road. The BBU is placed at the center of the coverage area, and thus both the vertical and the horizonal locations are denoted by 0.

We assume that N UAVs are needed to guarantee the coverage, and the horizontal locations of the UAVs are denoted by $\boldsymbol{l} = \{l_1, l_2, ..., l_N\}$, where l_n is the horizontal location of UAV-n, and $l_n < l_{n+1}$ for $1 \leq n \leq N-1$. The coverage radius of UAV-n is denoted by r_n, i.e., the coverage range of UAV-n is $[l_n - r_n, l_n + r_n]$. Assume that there is no overlap between the coverage areas of UAVs, and we thus have $l_{n+1} - l_n = r_n + r_{n+1}$ for $1 \leq n \leq N-1$, and $l_1 - r_1 = -\frac{L}{2}$, $l_N + r_N = \frac{L}{2}$. The vertical location of UAV-n is h_n. Denoted by $\boldsymbol{r} = \{r_1, r_2, ..., r_N\}$ the coverage radius of all the UAVs, and $\boldsymbol{h} = \{h_1, h_2, ..., h_N\}$ the vertical locations of all the UAVs.

B. *Channel Model*

To guarantee the quality of services of users, the channel capacity between the user and the serving UAV should be no smaller than a given transmission rate R_u. According to [4], [11], the channel between the user and the UAV can be classified into LoS condition and non-line-of-sight (NLoS) condition. Let $\xi = 0$ represent LoS link, $\xi = 1$ represent NLoS link, the path loss is expressed as

$$L_\xi^\mathrm{u}(d_\mathrm{u}) = \begin{cases} \eta_0 \left(4\pi f_\mathrm{u} d_\mathrm{u}/c\right)^2, & \xi = 0 \quad \text{(1a)} \\ \eta_1 \left(4\pi f_\mathrm{u} d_\mathrm{u}/c\right)^2, & \xi = 1 \quad \text{(1b)} \end{cases}$$

where η_0 and η_1 are constant parameters related to the environment, d_u is the distance between the UAV and the user, f_u is the carrier frequency of the air interface, and c is the light speed. According to [4], [11], the probability that the channel is LoS can be expressed as

$$P_0(\theta_\mathrm{u}) = \frac{1}{1 + ae^{-b(\theta_\mathrm{u} + a)}}, \tag{2}$$

where θ_u is the elevation angle between the user and the UAV, a and b are constant parameters. The average path loss between the user and the UAV is

$$\bar{L}^\mathrm{u}(d_\mathrm{u}, \theta_\mathrm{u}) = P_0(\theta_\mathrm{u}) L_0^\mathrm{u}(d_\mathrm{u}) + (1 - P_0(\theta_\mathrm{u})) L_1^\mathrm{u}(d_\mathrm{u}). \tag{3}$$

To guarantee the user data rate R_u, the transmission power of the user, denoted by $P_{\mathrm{u},\xi}(d_\mathrm{u})$, should satisfy

$$R_\mathrm{u} = \log_2\left(1 + \frac{P_{\mathrm{u},\xi}(d_\mathrm{u})}{L_\xi^\mathrm{u}(d_\mathrm{u}) N_0}\right), \tag{4}$$

where N_0 is the noise power. The transmission power of the user can be expressed as

$$P_{\mathrm{u},\xi}(d_\mathrm{u}) = L_\xi^\mathrm{u}(d_\mathrm{u}) N_0 (2^{R_\mathrm{u}} - 1). \tag{5}$$

The average transmission power of the user is then

$$\begin{aligned} P_\mathrm{u}(d_\mathrm{u}, \theta_\mathrm{u}) &= P_0(\theta_\mathrm{u}) P_{\mathrm{u},0}(d_\mathrm{u}) + (1 - P_0(\theta_\mathrm{u})) P_{\mathrm{u},1}(d_\mathrm{u}) && (6) \\ &= N_0 (2^{R_\mathrm{u}} - 1) \bar{L}^\mathrm{u}(d_\mathrm{u}, \theta_\mathrm{u}). && (7) \end{aligned}$$

The average transmission power $P_\mathrm{u}(d_\mathrm{u}, \theta_\mathrm{u})$ increases with the distance between the user and the UAV d_u, and decreases with the elevation angle θ_u. The maximum average transmission power of the user is achieved at the edge of each UAV cell. For the user at the edge of the cell coverage of UAV-n, we have

$$d_{\mathrm{u},n} = \sqrt{h_n^2 + r_n^2}, \theta_{\mathrm{u},n} = \left(180 \tan^{-1}(h_n/r_n)\right)/\pi, \tag{8}$$

and note that h_n is the vertical location of UAV-n, and r_n is the coverage radius of UAV-n. To guarantee that the average transmission power of any user is no larger than a given power threshold P_th, the user transmission power constraint of UAV-n can be expressed as

$$P_\mathrm{u}(d_{\mathrm{u},n}, \theta_{\mathrm{u},n}) \leq P_\mathrm{th}. \tag{9}$$

The channel conditions of the wireless fronthaul can also be classified into LoS and NLoS. The wireless fronthaul path loss of UAV-n can be expressed as

$$L_{\xi,n}^\mathrm{f}(d_{\mathrm{f},n}) = \begin{cases} \eta_0 \left(4\pi f_\mathrm{f} d_{\mathrm{f},n}/c\right)^2, & \xi = 0 \quad \text{(10a)} \\ \eta_1 \left(4\pi f_\mathrm{f} d_{\mathrm{f},n}/c\right)^2, & \xi = 1 \quad \text{(10b)} \end{cases}$$

where f_f is the carrier frequency of the wireless fronthaul, and $d_{\mathrm{f},n}$ is the distance between the BBU and UAV-n, expressed as $d_{\mathrm{f},n} = \sqrt{h_n^2 + l_n^2}$. Accordingly, the probability of LoS channel between UAV-n and the BBU can be expressed as

$$P_0(\theta_{\mathrm{f},n}) = \frac{1}{1 + ae^{-b(\theta_{\mathrm{f},n} + a)}}, \tag{11}$$

where $\theta_{\mathrm{f},n}$ is the elevation angle of UAV-n,

$$\theta_{\mathrm{f},n} = \left(180 \tan^{-1}(h_n/|l_n|)\right)/\pi. \tag{12}$$

The average path loss between UAV-n and the BBU is

$$\bar{L}^\mathrm{f}(d_{\mathrm{f},n}, \theta_{\mathrm{f},n}) = P_0(\theta_{\mathrm{f},n}) L_{0,n}^\mathrm{f}(d_{\mathrm{f},n}) + (1 - P_0(\theta_{\mathrm{f},n})) L_{1,n}^\mathrm{f}(d_{\mathrm{f},n}).$$

The wireless fronthaul rate of UAV-n $R_{\mathrm{f},n}$ and the transmission power $P_{\mathrm{f},n}$ satisfy that $R_{\mathrm{f},n} = \log_2\left(1 + \frac{P_{\mathrm{f},n}}{\bar{L}^\mathrm{f}(d_{\mathrm{f},n}, \theta_{\mathrm{f},n}) N_0}\right)$.

C. Delay Constraint

We assume that the distribution of the active users is modeled by a uniform distribution with density λ, i.e., the active users covered by each UAV is proportional to the coverage radius. Each UAV can be configured with one of K candidate functional split schemes. Given the selected functional split scheme k, the computation complexity on the UAV to process the baseband signals of one user in each subframe is c_k, the corresponding data of baseband signals to be transmitted via the fronthaul, as measured by bits, is s_k. We assume that with larger k, more baseband functions are placed at the UAV, and thus the computation complexity to process the baseband signals is larger, but less baseband signals need to be transmitted via the fronthaul to the BBU, i.e., $c_k < c_{k+1}$ and $s_k > s_{k+1}$ for $1 \leq k \leq K-1$.

For UAV-n, its selected functional split scheme is denoted by k_n. Denoted by $\boldsymbol{k} = \{k_1, k_2, ..., k_N\}$ the functional split scheme for all UAVs. The computation operations required to process the baseband signals is $2\lambda r_n c_{k_n}$, and the data amount of baseband signals is $2\lambda r_n s_{k_n}$. Denoted by C the computation capacity of each UAV, and P_{c} the processing power when the UAV is processing the baseband signals. Note that all the computation capacity is used to process the baseband signals to minimize the processing delay, and thus the processing power of different functional split schemes is the same, while the processing delays are different. The baseband processing and baseband signals transmission should be completed within a delay constraint D. Assume that the BBU has enough computation resources, and thus the baseband processing delay at the BBU is ignored. In summary, the delay constraint can be expressed as $\frac{2\lambda r_n c_{k_n}}{C} + \frac{2\lambda r_n s_{k_n}}{R_{\text{f},n}} \leq D$.

III. ENERGY EFFICIENT UAV DEPLOYMENT

A. Problem Formulation

The total energy consumed in each subframe by UAV-n can be expressed as

$$E_n = P_{\text{c}}\frac{2\lambda r_n c_{k_n}}{C} + P_{\text{f},n}\frac{2\lambda r_n s_{k_n}}{R_{\text{f},n}} + E_0, \qquad (13)$$

where E_0 is the circuit energy consumption from down conversion, filter, and etc., which is assumed to be constant, $P_{\text{c}}\frac{2\lambda r_n c_{k_n}}{C}$ is the energy consumed by the baseband processing, and $P_{\text{f},n}\frac{2\lambda r_n s_{k_n}}{R_{\text{f},n}}$ is the energy consumed by the wireless fronthaul. We aim to minimize the total energy consumption of all UAVs, and the corresponding optimization problem is formulated as

$$\begin{aligned}
\textbf{P0} \quad & \min_{N,\boldsymbol{l},\boldsymbol{h},\boldsymbol{r},\boldsymbol{k}} \quad \sum_{n=1}^{N} E_n && (14)\\
& \text{s.t.} \quad P_{\text{u}}(d_{\text{u},n}, \theta_{\text{u},n}) \leq P_{\text{th}}, && (15)\\
& \qquad \frac{2\lambda r_n c_{k_n}}{C} + \frac{2\lambda r_n s_{k_n}}{R_{\text{f},n}} = D, && (16)\\
& \qquad l_{n+1} - l_n = r_n + r_{n+1}, && (17)\\
& \qquad l_1 - r_1 = -\frac{L}{2}, l_N + r_N = \frac{L}{2}, && (18)
\end{aligned}$$

where Eq. (15) is the constraint of the user transmission power, Eq. (16) is the delay constraint, Eq. (17) and Eq. (18) are the constraints to guarantee that there is no coverage hole and we assume that there is no coverage overlap. Note that the fronthaul rate $R_{\text{f},n}$ is not a variable to be optimized, because the minimum energy consumption is obtained when

$$\frac{2\lambda r_n c_{k_n}}{C} + \frac{2\lambda r_n s_{k_n}}{R_{\text{f},n}} = D, \qquad (19)$$

i.e., $R_{\text{f},n}$ is determined by the coverage radius r_n and functional split scheme k_n. The reason is that the energy consumed by wireless fronthaul, i.e., $P_{\text{f},n}\frac{2\lambda r_n s_{k_n}}{R_{\text{f},n}}$, increases with $R_{\text{f},n}$, and thus E_n increases with $R_{\text{f},n}$. The minimum value of E_n is achieved when $R_{\text{f},n}$ is minimized, we thus have $\frac{2\lambda r_n c_{k_n}}{C} + \frac{2\lambda r_n s_{k_n}}{R_{\text{f},n}} = D$.

The number of UAVs N is a variable to be optimized, and the dimension of optimization variables $\boldsymbol{l}, \boldsymbol{h}, \boldsymbol{r}, \boldsymbol{k}$ is $1 \times N$. To solve **P0**, we first fix the number of UAVs N, obtain the corresponding optimal energy consumption, and then get the optimal N by comparing the energy consumption of all possible N. We need to determine the lower bound of the optimal N to guarantee that the problem formulation has solutions, and the upper bound of the optimal N to reduce the feasible region, , i.e., the searching complexity of the problem.

B. Lower Bound of the Optimal Number of UAVs N

To satisfy the delay constraint, the baseband processing delay should be smaller than the delay bound D, and thus the coverage radius of UAV-n should satisfy $\frac{2\lambda r_n c_{k_n}}{C} < D$, i.e., $r_n < \frac{CD}{2\lambda c_{k_n}}$. On the other hand, given the coverage radius r_n, there should exist a vertical location h_n to satisfy the user transmission power constraint. The maximum r_n can be obtained by solving the following problem:

$$\begin{aligned}
\textbf{P1} \quad & \max_{r_n,h_n} \quad r_n \\
& \text{s.t.} \quad P_{\text{u}}(r_n, h_n) < P_{\text{th}}, && (20)\\
& \qquad 0 < r_n < \frac{CD}{2\lambda c_1}, && (21)
\end{aligned}$$

Denoted by r_{max} the maximum r_n obtained by solving **P1**, the *lower bound* of N, denoted by N_{min}, can be expressed as

$$N_{\text{min}} = \left\lceil \frac{L}{2r_{\text{max}}} \right\rceil, \qquad (22)$$

where $\lceil x \rceil$ is the minimum integer that no smaller than x.

C. Upper Bound of the Optimal Number of UAVs N

To obtain an upper bound of the optimal number of UAVs N, we first obtain an upper bound of the optimal energy consumption. If the horizontal location of a UAV is $\hat{l}$, we first explore the corresponding vertical location $\hat{h}$ and coverage radius $\hat{r}$ to minimize energy density $\rho(\hat{l})$, which is defined as

$$\rho(\hat{l}) = \frac{\hat{E}}{2\hat{r}}, \qquad (23)$$

where $\hat{E}$ is the energy consumption of the UAV given $\hat{l}$, $\hat{h}$, $\hat{r}$ and functional split scheme $\hat{k}$. Energy density $\rho(\hat{l})$ is the average energy consumed to serve the users in unit coverage length. The minimum $\rho(\hat{l})$ can be obtained by solving the following problem:

$$\textbf{P2} \quad \min_{\hat{r},\hat{h},\hat{k}} \quad \rho(\hat{l}) \tag{24}$$

$$\text{s.t.} \quad P_{\text{u}}(\hat{r},\hat{h}) < P_{\text{th}}, \tag{25}$$

$$0 < \hat{r} < \frac{CD}{2\lambda c_{\hat{k}}}. \tag{26}$$

Denoted by $\rho^*(\hat{l})$ the minimum energy density given $\hat{l}$. As the wireless fronthaul energy consumption increases with $|\hat{l}|$ given $\hat{h}$, $\hat{r}$ and $\hat{k}$, energy density $\rho(\hat{l})$ is an increasing function of $|\hat{l}|$, the optimal energy density $\rho^*(\hat{l})$ also increases with $|\hat{l}|$. For UAV-n, we have $\frac{E_n}{2r_n} \geq \rho^*(0)$, and we thus have

$$\sum_{n=1}^{N} E_n \geq \sum_{n=1}^{N} 2r_n\rho^*(0) = L\rho^*(0), \tag{27}$$

i.e., the total energy consumption of all the UAVs should be no less than $L\rho^*(0)$, and thus a lower bound of the optimal energy consumption is

$$E_{\text{lb}} = L\rho^*(0). \tag{28}$$

The maximum energy density is achieved when $|\hat{l}| = \frac{L}{2}$, which can be expressed as $\rho^*(\frac{L}{2})$.

Lemma 1. *An upper bound of the optimal energy consumption is* $E_{ub} = \rho^*(\frac{L}{2})L + E_0$.

Proof. When the horizontal location of the UAV is $\hat{l} = \frac{L}{2}$, we can obtain the corresponding vertical location $\hat{h}^*$, coverage radius $\hat{r}^*$ and functional split scheme $\hat{k}^*$ to minimize the energy density, $\rho^*(\frac{L}{2})$ can be obtained by solving **P2**. Let $N = \lceil \frac{L}{2\hat{r}^*} \rceil$. We design a deployment scheme where $l_n = -\frac{L}{2} + (2n-1)\hat{r}^*$, $r_n = \hat{r}^*$, $h_n = \hat{h}^*$, and $k_n = \hat{k}^*$ for $1 \leq n \leq N-1$. As $|l_n| < \frac{L}{2}$, the energy consumed by the wireless fronthaul is less than the scenario when the horizontal location of the UAV is $\frac{L}{2}$, and we thus have

$$E_n \leq 2\hat{r}^*\rho^*(\frac{L}{2}), \quad 1 \leq n \leq N-1. \tag{29}$$

For UAV-N, $l_N = (N-1)\hat{r}^*$, $r_N = \frac{L}{2} - (N-1)\hat{r}^*$, $h_N = \hat{h}^*$, and $k_N = \hat{k}^*$. As $l_N < \frac{L}{2}$ and $r_N \leq \hat{r}^*$, the average energy consumed by wireless fronthaul of each user is smaller than the scenario when $\hat{l} = \frac{L}{2}$ and the coverage radius is $\hat{r}^*$, i.e., the energy density introduced by the wireless fronthaul is smaller, while the energy density introduced by baseband processing is the same with the scenario when $\hat{l} = \frac{L}{2}$ and the coverage radius is $\hat{r}^*$. The baseband processing energy and wireless fronthaul energy should satisfy

$$P_{\text{c}}\frac{2\lambda r_N c_{k_N}}{C} + P_{\text{f},N}\frac{2\lambda r_N s_{k_N}}{R_{\text{f},N}} < 2\rho^*(\frac{L}{2})r_N, \tag{30}$$

i.e., the energy consumption of UAV-N satisfies

$$E_N < E_0 + 2\rho^*(\frac{L}{2})r_N. \tag{31}$$

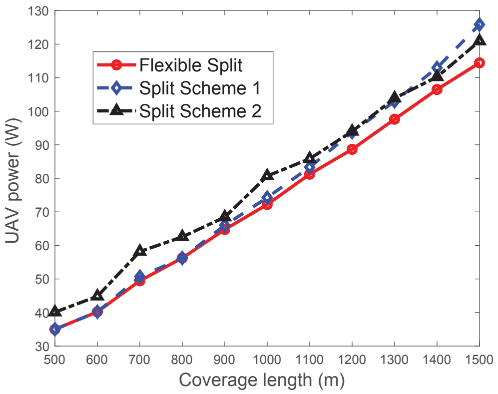

Fig. 2. The optimal power consumption of UAVs.

Further according to Eq. (29), we have

$$\sum_{n=1}^{N} E_n < \rho^*(\frac{L}{2})L + E_0, \tag{32}$$

which completes the proof. □

We are now able to obtain an upper bound of the optimal number of UAVs N with the upper bound of the optimal energy consumption in Lemma 1. As the minimum energy consumed by baseband processing of each user is determined by the functional split scheme, the minimum energy consumption introduced by baseband processing is $P_{\text{c}}\frac{\lambda L c_1}{C}$. Note that functional split scheme 1 has the least baseband functions at the UAV. When $N \geq \frac{\rho^*(\frac{L}{2})L + E_0 - P_{\text{c}}\lambda L c_1/C}{E_0}$, the sum of the constant energy consumption and the baseband processing energy is larger than the upper bound of the optimal energy consumption, which can be ignored when solving **P0**. We thus get an *upper bound* of N as

$$N < \frac{\rho^*(\frac{L}{2})L + E_0 - P_{\text{c}}\frac{\lambda L c_1}{C}}{E_0}. \tag{33}$$

The optimal solution of **P0** is in the region where $N < \frac{\rho^*(\frac{L}{2})L + E_0 - P_{\text{c}}\frac{\lambda L c_1}{C}}{E_0}$.

IV. NUMERICAL RESULTS

We set the user density as λ=0.1 m^{-1}. The carrier frequency of the air interface is 2.4GHz, the equivalent bandwidth of each user is 2MHz. Two candidate functional split schemes are considered [12], the average required fronthaul rate of each user in functional split scheme 1 is 80Mbps, and the baseband processing complexity of each user is 1.2GPoS. The average required fronthaul rate of each user in functional split scheme 2 is 24Mbps, and the baseband processing complexity of each user is 4GPoS. The bandwidth of wireless fronthaul is 100MHz, and the carrier frequency is 5GHz. The computation capacity of the UAV is 100GPoS, and the processing power of the UAV is 10W. The constant onboard circuit power is 10W. The baseband processing delay and fronthaul delay of each subframe should not exceed 2ms. The average transmission

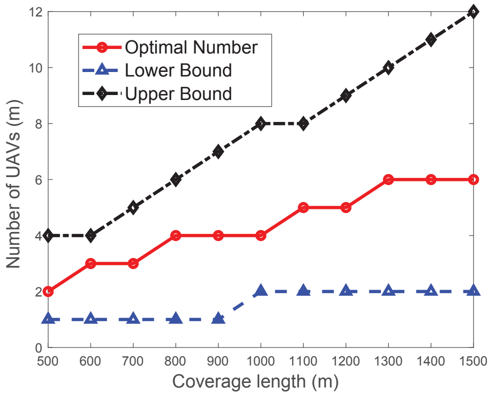

Fig. 3. The optimal number of UAVs.

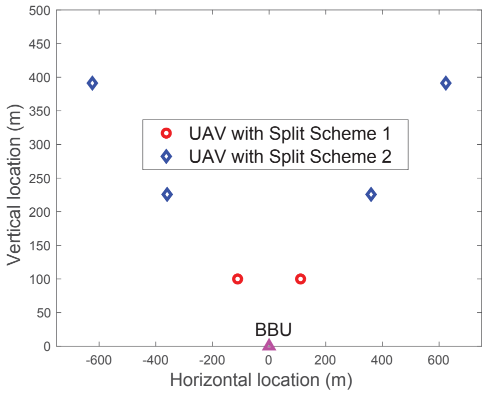

Fig. 4. The horizontal locations, vertical locations and selected functional split schemes of the UAVs when the coverage length is 1500m.

power constraint of each user is 10mW, and the required user data rate is 6Mbps. The noise power is $N_0 = -174$dBm/Hz.

The total power of UAVs with flexible functional split is presented in Fig. 2, compared with the schemes with one fixed functional split scheme. We can see that with flexible functional split, the power consumption of all the UAVs can be considerably reduced. Note that the curves are not smooth because the optimal number of UAVs changes with the coverage length, which is an integer, as illustrated in Fig. 3. The upper and lower bounds of the optimal number of UAVs are presented in Fig. 3, the gap between the upper bound and the lower bound is small, which makes it possible to traverse all possible values of the optimal number of UAVs.

In Fig. 4, the optimal horizontal locations, vertical locations and selected functional split schemes of UAVs are presented, when the coverage length is 1500m. The optimal number of UAVs is 6. Functional split scheme 1, which has less baseband functions at the UAV side, is selected by the 2 UAVs nearest to the BBU, and functional split scheme 2 is selected by the other 4 UAVs far from the BBU. With larger distance between the UAV and the BBU, the vertical location of the UAV becomes larger to reduce the probability of NLoS link.

V. CONCLUSIONS

In this paper, we consider the UAV deployment jointly with the functional split scheme selection of each UAV. We optimize the horizontal location, the vertical location, the coverage radius, the functional split scheme of each UAV, to minimize the energy consumption of all UAVs, under the constraints of the average user transmission power, and the total delay including baseband processing and fronthauling. To obtain the optimal energy consumption, we derive the upper and lower bounds of the optimal number of UAVs. Numerical results show that, by jointly considering the UAV deployment and flexible functional split, the energy consumption of UAVs can be reduced compared with fixed functional split scheme. We also find that when the distance between the UAV and the BBU is larger, more baseband functions should be placed at UAVs, and the UAV should fly higher.

ACKNOWLEDGMENT

This work is sponsored in part by the Nature Science Foundation of China (No. 91638204, No. 61571265, No. 61621091), and Hitachi Ltd.

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