QoX-Driven Hierarchical Networking Scheme for Multi-UAV Assisted IoT Networks

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***Abstract*—Applying unmanned aerial vehicles (UAVs) to assist Internet of Things (IoT) networks has recently attracted wide attention, thanks to their fast and flexible deployment. Despite the advantages, one key challenge is how to evaluate the service performance and thus provide service-demand-based coverage and form a robust UAV network with limited resources. In this paper, we consider a multi-UAV assisted IoT network with devices of varied service demands. A comprehensive quality of X (QoX) model is proposed to evaluate the service performance. Then, to serve the devices as per their QoX levels, we propose a hierarchical networking scheme. Specifically, based on the device hierarchical architecture built on the QoX order, UAVs are deployed layer by layer sequentially. Meanwhile, bandwidth is reserved for lower-layer devices to ensure their access. Separately in each layer of this hierarchy scheme, the optimization problem is formulated as minimizing the number of UAVs through joint optimization of UAV location, device association, and bandwidth allocation while forming a robust UAV network. To solve this problem, we first apply a problem transformation for variable decoupling and then propose an improved particle swarm optimization (PSO) algorithm. Simulation results show that the proposed scheme reduces the number of UAVs while satisfying the diverse service demands evaluated by our QoX model.**

***Index Terms*—unmanned aerial vehicle, Internet of Things, performance evaluation, quality of X.**

I. Introduction

The application of unmanned aerial vehicles (UAVs) to assist the Internet of Things (IoT) networks has become an inevitable trend in future 6G wireless communication [1]. To take full advantage of UAV on-demand service, accurate assessments of the performance requirements of the applications are required. Therefore, an appropriate performance evaluation approach is of vital significance for guiding UAVs to better serve the IoT networks. However, due to the complex communication scenarios and diversified service demands of the IoT systems, the existing single assessment measures are obviously no longer applicable. In this context, quality of X (QoX), as a comprehensive evaluation metric compromising the combination of quality of service (QoS), quality of experience (QoE), quality of data (QoD) and quality of information (QoI), emerges as a more promising evaluation indicator [2].

Current researches are still far from a general definition and quantification of QoX in IoT. On one hand, the future IoT paradigm establishes a completely different scenario, which, for instance, requires minimal or no human participation. Therefore, traditional user perspective-centric evaluation indicators are not applicable anymore, and instead an objective evaluation method is expected to be proposed [3]. On the other hand, as the IoT systems are evolving in the directions of differentiation and isomerization, the coexistence of differentiated or even opposite service demands makes the QoX evaluation factors become more complicated [4]. In summary, it is still a great challenge to devise a comprehensive QoX metric, as well as a UAV deployment and resource allocation scheme based on this QoX model.

Currently, a lot of related works have been carried out in terms of QoS [5], [6] and QoE [7], [8] driven UAV deployment and resource allocation. In [5], the authors investigate the optimal single-UAV location and bandwidth allocation scheme subject to each node's statiscal delay-bound QoS requirement. The authors in [6] further extend the research to the scenario with multiple UAVs. To go a step further, several QoE-driven schemes that take users' opinions into account have been investigated. The work in [7] proposes a QoE-driven cache-enabling UAV deployment, power, and bandwidth allocation scheme, where QoE is only related to latency. A similar problem is studied in [8], where QoE is modeled as a joint consideration of latency and throughput. However, QoE in these studies is only in connection with QoS factors. In particular, there is still a lack of researches considering QoD or QoI metrics, let alone the comprehensive consideration of the combination of QoS, QoE, QoD and QoI metrics.

In this paper, we consider a multi-UAV assisted heterogeneous IoT network, where the service demands of the devices are diversified. We propose a quantitative and comprehensive QoX model to better evaluate the service performance. Then, in order to serve the devices as per their QoX levels, a hierarchical networking scheme is proposed. To be specific, a QoX-oriented device hierarchical architecture is constructed via QoX layering. Then, based on this architecture, UAVs are deployed sequentially layer by layer. Simultaneously, a portion of the bandwidth is reserved for lower-layer devices. In each layer of the hierarchy scheme, the optimization problem is formulated as minimizing the number of UAVs by jointly optimizing their location, device association, and bandwidth allocation under the constraint of airborne network connectivity, respectively. To solve the problem, we first employ a problem transformation for problem decomposition and then solve it via an improved particle swarm optimization (PSO) algorithm. Simulations have been carried out to evaluate the performance of the proposed scheme.

II. System Model

A. System Description

As shown in Fig. 1, we consider a downlink communication system where multiple UAVs are utilized as aerial base stations to support ground heterogeneous IoT devices in an infrastructure-free area. Define $\mathcal{U} = \{1, 2, ...U\}$ as the set of U UAV-BSs and $\mathcal{L} = \{1, 2, ...L\}$ as the set of L IoT devices. Furthermore, according to the QoX values of the services provided (as described in the next subsection), the devices are classified into K levels, where $\mathcal{L}_k$ is the set of devices of level k. In this model, the levels are supposed to be opposite of k, that is, level $k = 1$ represents the highest QoX rank while level $k = K$ indicates the lowest level. Frequency division multiple access (FDMA) scheme is adopted for downlink communication. In addition, it is assumed that the locations of the devices can be obtained in advance by means of satellite links. Specifically, a three dimensional (3D) Cartesian coordinate system is constructed where the coordinates of device $l \in \mathcal{L}$ and UAV $u \in \mathcal{U}$ are denoted by $p_l = (x_l, y_l, 0)$ and $p_u = (x_u, y_u, h_u)$, respectively.

B. QoX Model

In this paper, QoX is introduced as a quantitative and comprehensive indicator to evaluate the performance of services provided by IoT devices. Considering the characteristics of urgency, completeness, dynamics, etc., of IoT scenarios, priority, transmission rate, completeness, and up-to-dateness are chosen as measurement metrics [2], [9].

1) Priority

Priority reflects the importance of the service and is calculated by

$$s_l^{priority} = \frac{w_l}{w_{max}}, \tag{1}$$

where w_l is the importance value of the service provided by device l, and w_{max} is the maximum value of importance.

2) Transmission rate

To eliminate the effects of data magnitude and magnitude, the Z-score normalization method is adopted to normalize the transmission rate, thereby limiting the value to (0,1) range. The normalized rate is

$$s_l^{rate} = \frac{R_l - E(R)}{\sqrt{D(R)}}, \tag{2}$$

where R_l is the original data rate of device l, $E(R)$ denotes the mean value of the rates, and $D(R)$ denotes the deviation.

3) Completeness

Data is an essential component of the IoT system, as all applications require data to be transmitted in some way. Therefore, completeness is adopted as one of the evaluation metrics of data quality, given by

$$s_l^{complete} = \frac{\sum_{j=0}^{m} w_j}{\sum_{i=0}^{n} w_i}, \tag{3}$$

where m is the number of messages provided by device l, n is the total number of available messages, w_j and w_i are the weights corresponding to messages j and i.

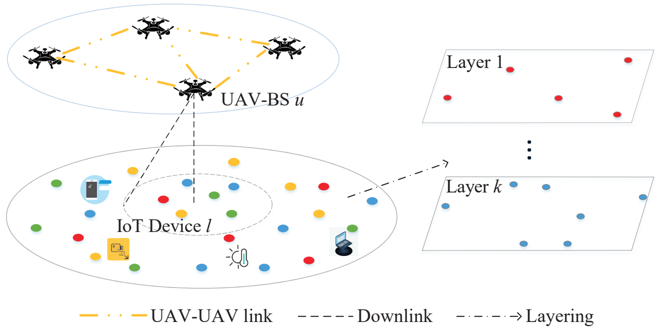

Fig. 1: Service QoX-based hierarchical deployment scheme for UAV-assisted heterogeneous IoT network.

4) Up-to-dateness

Up-to-dateness is another measurement index of data quality indicating the freshness of the information, expressed as

$$s_l^{date} = \begin{cases} 1 - \frac{t_{new} - t_{old}}{t_{max}}, & t_{new} - t_{old} < t_{max} \\ 0, & otherwise, \end{cases} \tag{4}$$

where t_{new}, t_{old} and t_{max} are the current, collection and maximum effective time of the information, respectively.

For calculating the QoX values, a weighted linear combination of the metrics is adopted as the comprehensive evaluation model, which is modeled as

$$s_l = \mu_p s_l^{priority} + \mu_r s_l^{rate} + \mu_c s_l^{complete} + \mu_d s_l^{date}, \tag{5}$$

where μ_p, μ_r, μ_c and μ_d are the corresponding weighting factors. Further, the continuous QoX value is discretized into k segments.

To eliminate the possible impact of improper weight calculation methods on QoX values, multiple methods are supposed to be adopted, and then the average of the weights are incorporated into the model.

C. Air-to-Ground Channel Model

Referring to [10], the air-to-ground (A2G) channel is modelled by jointly considering the LoS and non-line-of-sight (NLoS) components along with their occurrence probabilities. The probabilities of LoS and NLoS connections between device l located at an elevation angle $\theta_{l,u} = \frac{180}{\pi} arctan(\frac{h_u}{d_{l,u}})$ and UAV u are given respectively by

$$P_{l,u}^{LoS} = \frac{1}{1 + \alpha \exp(-\beta(\theta_{l,u} - \alpha))}, \tag{6}$$

$$P_{l,u}^{NLoS} = 1 - P_{l,u}^{LoS}, \tag{7}$$

where α and β are environment-dependent constant values, and $d_{l,u} = \sqrt{(x_u - x_l)^2 + (y_u - y_l)^2}$ represents the horizontal distance between the device and UAV.

Affected by free space path loss and shadowing fading, the pathloss of LoS link and NLoS link are respectively

$$LoS_{l,u} = 20 \log(\frac{4\pi f r_{l,u}}{c}) + \eta_{LoS}, \tag{8}$$

$$NLoS_{l,u} = 20 \log(\frac{4\pi f r_{l,u}}{c}) + \eta_{NLoS}, \tag{9}$$

where f is the carrier frequency of channel, c is the speed of light, $r_{l,u} = \sqrt{d_{l,u}^2 + h_u^2}$ is the 3D distance between device l and UAV u. Moreover, η_{LoS} and η_{NLoS} are the mean additive pathloss related to the environment of LoS and NLoS links.

Therefore, the average pathloss between device l and UAV u can be expressed in dB as

$$\begin{aligned} PL_{l,u} &= P_{l,u}^{LoS} \times LoS_{l,u} + P_{l,u}^{NLoS} \times NLoS_{l,u} \\ &= \frac{A}{1 + \alpha \exp(-\beta(\frac{180}{\pi} arctan(\frac{h_u}{d_{l,u}}) - \alpha))} \\ &+ 10 \log(d_{l,u}^2 + h_u^2) + B, \end{aligned} \tag{10}$$

where $A = \eta_{LoS} - \eta_{NLoS}$ and $B = 20 \log(\frac{4\pi f}{c}) + \eta_{NLoS}$.

Since the interference among UAVs is able to be mitigated by assigning different spectrum bands [11], the received signal-noise-ratio (SNR) of device l from UAV u is

$$SNR_{l,u} = \frac{P_u g_{l,u}}{\sigma^2}, \tag{11}$$

where P_u is the transmission power from UAV u to device l, $g_{l,u} = 10^{-\frac{PL_{l,u}}{10}}$ denotes the channel gain between them, and σ^2 represents the power of Gaussian white noise.

Assuming that if the received data rate of device l from UAV u exceeds a threshold, denoted by γ, the device is covered and its QoS requirement is satisfied. The data rate is calculated by

$$R_{l,u} = b_{l,u} B \log_2(1 + SNR_{l,u}) \geq \gamma, \tag{12}$$

where B is the total bandwidth, and $b_{l,u}$ is the proportion of bandwidth used by UAV u to communicate with device l.

III. Problem Formulation

In order to ensure that devices can be served as per their QoX levels, we propose a hierarchical networking scheme. In this section, the main idea of the proposed scheme is first introduced. Then, taking a layer of the hierarchy as an example, we give the formulation of the optimization problem.

A. Deployment and Reservation-based Bandwidth Allocation of the kth Layer UAVs

In the hierarchy scheme, a multi-layer device hierarchical architecture, as shown in Fig. 1, is obtained by layering the devices in order of QoX levels. Then, based on this QoX-oriented device hierarchical architecture, UAVs are deployed for each layer respectively, from highest to lowest.

In addition, we further adopt a dynamic bandwidth reservation mechanism to ensure that devices with lower QoX levels also have the possibility to access the upper layer UAVs. That is, when UAVs are deployed at this layer, part of their bandwidth resources are reserved for lower layer devices.

Given the bandwidth reservation ratio δ_{k-1} of the $(k-1)th$ layer UAVs and the bandwidth allocation ratio $b_{l_{k-1},u_{k-1}}$ of the $(k-1)th$ layer devices, we can calculate and dynamically adjust the proportion of the reserved bandwidth used by the kth layer devices, which is given by

$$\delta_k^{'} = 1 - \delta_{k-1} \sum_{l_{k-1} \in \mathcal{L}_{u_{k-1}}} b_{l_{k-1},u_{k-1}}, \tag{13}$$

With the locations of the deployed UAVs fixed, part of the kth layer devices $l_k^{'} \in \mathcal{L}_k$ can be served through the remaining bandwidth $\delta_k^{'} B$ (via Algorithm 1). Meanwhile, for devices $l_k \in \mathcal{L}_k$ outside the coverage of the $(k-1)th$ layer UAVs, additional UAVs $u_k \in \mathcal{U}_k$ can be introduced as supplementary aerial base stations. Similarly, the bandwidth reservation ratio of the supplementary UAVs is denoted as δ_k, which is

$$\delta_k \begin{cases} \in (0,1), & k \neq K \\ = 1, & k = K. \end{cases} \tag{14}$$

According to Eqs. (12) - (14), the achievable received data rate of device l_k from the supplementary UAV u_k can be transformed as

$$R_{l_k,u_k} = b_{l_k,u_k} \delta_k B \log_2(1 + SNR_{l_k,u_k}). \tag{15}$$

B. Problem Formulation

In the proposed hierarchy scheme, the optimization problem is molded in each layer separately. Define the binary variable a_{l_k,u_k} as an indicator that indicates the association between device l_k and UAV u_k, that is, $a_{l_k,u_k} = 1$ means device l_k is covered by UAV u_k while $a_{l_k,u_k} = 0$ means otherwise. Let $\boldsymbol{A} = a_{l_k,u_k}$, $\boldsymbol{B} = b_{l_k,u_k}$ and $\boldsymbol{P} = (x_{u_k}, y_{u_k}, h_{u_k})$. Then, our objective is to find the optimal UAV 3D location, device association and bandwidth allocation to minimize the number of UAVs required while meeting the connectivity constraints between them. Therefore, the optimization problem can be formulated as

$$\min_{\boldsymbol{A},\boldsymbol{B},\boldsymbol{P}} \; U_k, \tag{16}$$

$$\begin{aligned} \text{s.t.} \quad & C1: a_{l_k,u_k} = \{0,1\}, \forall l_k, \\ & C2: \sum_{u_k \in \mathcal{U}_k} a_{l_k,u_k} \leq 1, \forall l_k, \\ & C3: \sum_{u_k \in \mathcal{U}_k} \sum_{l_k \in \mathcal{L}_k} a_{l_k,u_k} \geq \\ & \qquad \xi_k L_k - \sum_{u_{k-1} \in \mathcal{U}_{k-1}} \sum_{l_k^{'} \in \mathcal{L}_k} a_{l_k^{'},u_{k-1}}, \\ & C4: R_{l_k,u_k} \geq a_{l_k,u_k} \gamma_k, \forall l_k, \\ & C5: b_{l_k,u_k} \geq 0, \forall l_k, u_k, \sum_{l_k \in \mathcal{L}_{u_k}} b_{l_k,u_k} \leq 1, \forall u_k, \\ & C6: \min_{u_k \neq u_m} r_{u_k,u_m} \leq R_c, \forall u_k, \\ & C7: \min r_{u_k,u_{k-1}} \leq R_c, \end{aligned}$$

where $C1$ is the Boolean constraint. $C2$ indicates that a device can only be served by no more than one UAV. $C3$ illustrates the minimum coverage requirement. $C4$ points out the QoS requirement of a device. $C5$ ensures that the bandwidth allocated to devices will not exceed the maximum available bandwidth, where $\mathcal{L}_{u_k}$ represents the set of devices served by UAV u_k, denoted as $\mathcal{L}_{u_k} \triangleq \{l_k | a_{l_k,u_k} = 1, l_k \in \mathcal{L}_k\}$. $C6$ and $C7$ jointly ensure a robust UAV network, where R_c is the communication range between UAVs.

In particular, for the optimization problem of the first layer, there is no such constraint $C7$, and the constraint $C3$ should be converted to

$$\sum_{u_k \in \mathcal{U}_k} \sum_{l_k \in \mathcal{L}_k} a_{l_k,u_k} \geq \xi_k L_k. \tag{17}$$

Obviously, problem (16) is a mixed integer non-convex optimization problem with both binary and continuous variables, and thus is challenging to solve. First, the binary optimization variable $\boldsymbol{A}$ makes constraints $C1 - C5$ include integer constraints. Second, even with a fixed device association $\boldsymbol{A}$, constraints $C4 - C7$ are still non-convex with respect to UAV bandwidth allocation $\boldsymbol{B}$ and location $\boldsymbol{P}$.

IV. Proposed Solution

In this section, we propose the solution to the optimization problem. First, a transformation of the problem is applied to decouple the optimization variables. Then, to tackle the transformed problem, we propose an improved PSO algorithm for joint UAV location-bandwidth allocation.

A. Problem Transformation

To decompose the highly coupled optimization variables in problem (16), that is, the minimum number of UAVs, their optimal 3D locations and bandwidth allocation, a joint optimization algorithm of UAV location and bandwidth allocation for a given number of UAVs is first designed [12].

Starting from U_k UAV, the joint UAV location and bandwidth allocation optimization algorithm is repeated by increasing the number of UAVs by one, until the number of covered devices meets the coverage requirement, that is, constraint $C3$. When this process is finished, the minimum number of UAVs, their optimal positions and bandwidth allocation are obtained.

Based on the analysis above, the optimization problem of minimizing the number of UAVs for a given device coverage can be transformed into the problem of maximizing the number of covered devices for a given number of UAVs, which can be expressed as

$$\max_{\boldsymbol{A},\boldsymbol{B},\boldsymbol{P}} \sum_{l_k \in \mathcal{L}_k} a_{l_k,u_k}, \tag{18}$$

$$\text{s.t.} \quad C1,\ C2,\ C4,\ C5,\ C6,\ and\ C7.$$

B. UAV Location and Bandwidth Allocation Optimization

In the proposed PSO-based joint UAV location-bandwidth allocation optimization algorithm, the bandwidth allocation optimization is performed for each particle position in each generation of the PSO algorithm, optimizing the bandwidth allocated to each device.

To deal with the problem of bandwidth allocation, that is, maximizing the number of served devices with minimum bandwidth, we first assume fixed UAV locations and propose a bandwidth allocation algorithm. A description of the proposed algorithm is given in Algorithm 1.

First, the received SNR of each device from each UAV is calculated (line 2). Then the device with the maximum SNR

Algorithm 1 Bandwidth Allocation Optimization

1: **repeat**
2: Calculate the SNR_{l_k,u_k} of device $l_k \in \mathcal{L}_k$ from UAV $u_k \in \mathcal{U}_k$.
3: **repeat**
4: Select device $l_k = argmax_{l_k \in \mathcal{L}_k}\{SNR_{l_k,u_k}\}$.
5: Calculate the bandwidth b_{l_k,u_k} using Eq. (19).
6: **if** $\sum_{l_m \in \mathcal{L}_k, l_m \neq l_k} a_{l_m,u_k} b_{l_m,u_k} + b_{l_k,u_k} \leq 1$ **then**
7: Set $a_{l_k,u_k} = 1$, and $\mathcal{L}_k = \mathcal{L}_k \setminus \{l_k\}$.
8: **end if**
9: **until** Bandwidth limit of any UAV is reached.
10: Set $\mathcal{U}_k = \mathcal{U}_k \setminus \{u_k\}$.
11: **until** Bandwidth limit of all UAVs is reached or each device is covered.

is selected (line 4). And the minimum bandwidth required to satisfy its QoS requirement, that is, the bandwidth that makes $C4$ equal, is allocated to the device, which is (line 5)

$$b_{l_k,u_k} = \frac{a_{l_k,u_k}\gamma_k}{\delta_k B \log_2(1 + SNR_{l_k,u_k})}. \tag{19}$$

Each UAV accepts its most suitable devices one by one until its bandwidth limit is reached (lines 6-9). Afterwards, it is removed from the UAV list (line 10). The algorithm stops when all UAVs have reached their bandwidth limit or each device has been covered (line 11).

C. UAV Number and Bandwidth Reservation Ratio Initialization

Obviously, $(U_k^* - U_k + 1)$ iterations of the improved PSO algorithm are required, where U_k and U_k^* are the initial and the minimum number of UAVs respectively. To reduce the computation complexity, a more accurate U_k is desired.

For a given UAV flight area, Fig. 2 shows the variation of channel gain $g_{l,u}$ with respect to UAV altitude h_u and horizontal distance $d_{l,u}$ between the UAV and the device. From this figure, the point at which the channel gain is maximum can be obtained. That is, h_u is equal to the minimum UAV safety flight height and $d_{l,u}$ is equal to zero. Then the maximum data rate that a UAV can provide is calculated as

$$R_u = B \log_2(1 + SNR_{l,u}). \tag{20}$$

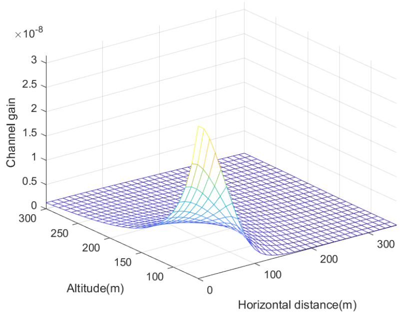

Fig. 2: Channel gain vs. UAV altitude and horizontal distance.

Algorithm 2 Hierarchical Networking Scheme

1: **Initialize**: $k = 1$, and $\boldsymbol{A_k} = \emptyset$
2: **while** $k \leq K$ **do**
3:   **if** $k \neq 1$ **then**
4:     Calculate $\delta_k = \delta_k^{'}$ using equation (13).
5:     Solve the bandwidth allocation problem using **Algorithm 1**, and denote the optimal solution as $\{\boldsymbol{A_k}, \boldsymbol{B_k}\}$.
6:   **end if**
7:   **if** not satisfy constraint $C3$ **then**
8:     Initialize U_k with Eq. (21) and δ_k with Eq. (22).
9:     Solve problem (18) using the **improved PSO algorithm**, and denote the optimal solution as $\{\boldsymbol{A_k}, \boldsymbol{B_k}, \boldsymbol{P_k}\}$
10:     **while** not satisfy constraint $C3$ **do**
11:       Update $U_k = U_k + 1$, and δ_k with Eq. (22).
12:       Repeat the operation in line (9).
13:     **end while**
14:   **end if**
15:   Update $k = k + 1$
16: **end while**

Given the device data rate requirement γ_k, device number L_k and minimum coverage requirement ξ_k, the number of UAVs required is given by

$$N_{UAV} = \lceil \frac{\xi_k L_k \gamma_k}{R_u} \rceil. \tag{21}$$

According to [13], the number of devices served by UAVs reaches a maximum if the traffic load of each UAV is nearly equal. Therefore, with a given number of UAVs, the bandwidth reservation ratio can be initialized approximately as

$$\delta_k \begin{cases} = \frac{\xi_k L_k \gamma_k}{R_u N_{UAV}}, & k \neq K \\ = 1, & k = K. \end{cases} \tag{22}$$

D. Overall Algorithm

Algorithm 2 summarizes the details of the proposed hierarchical networking scheme. In detail, starting from U_k UAV, the improved PSO algorithm is iteratively repeated by increasing the number of UAVs by one until the coverage requirement is satisfied. This process is repeated at each layer of the hierarchy scheme in order of QoX levels.

V. Simulation Results

In this section, simulations are executed to evaluate the performance of our proposed scheme. We consider a 250 m $\times$ 250 m square area in which IoT devices with different importance, data rates, message amount and collection time are distributed, following a homogeneous Poisson point process distribution with a density of $\rho = 0.6$.

For computing the weight coefficients, the balanced weight distribution method, the entropy weight method (EWM), and the criteria importance through intercriteria correlation (CRITIC) method are adopted. And the QoX values is discretized into three levels, with the number of devices of each level being 30, 50 and 70 respectively. Referring to [14], the urban environment parameters are set up as follows: $\alpha = 0.96$, $\beta = 0.16$, $\eta_{LoS} = 1$, $\eta_{NLoS} = 20$. Other simulation parameters are listed in Table I.

TABLE I: Simulation Parameters

Parameter	Description	Value
P_u	Transmit power of each UAV	50dBm
B	Bandwidth of each UAV	2MHz
f	Carrier frequency	2GHz
δ^2	Power of Gaussian white noise	174dBm
h_u	Flight Height of UAVs	[60,300]m
R_c	Communication range between UAVs	300m
ξ_1	Coverage rate for level 1 devices	0.90
ξ_2	Coverage rate for level 2 devices	0.80
ξ_3	Coverage rate for level 3 devices	0.70

For comparison, another three schemes are utilized as benchmark algorithms. Scheme 1: reservation-based bandwidth allocation optimization for uniformly distributed UAVs, Scheme 2: UAV location optimization for fixed bandwidth allocation, Scheme 3: PSO algorithm without QoX-based hierarchy method, Scheme 4: UAV location and bandwidth allocation optimization without reservation mechanism.

Fig. 3 shows the 3D locations of UAVs and the connection links between them obtained through the proposed scheme. Five UAVs are deployed to serve a total of 142 devices, including 30, 48 and 64 devices per level. As the figure shows, most of the UAVs approach high-QoX devices due to the hierarchy method.

Fig. 4 illustrates the relationship between the number of covered devices and the number of deployed UAVs. Obviously, our proposed scheme outperforms other benchmark schemes, since through joint optimization of UAV location and bandwidth allocation, as well as the hierarchy method, our

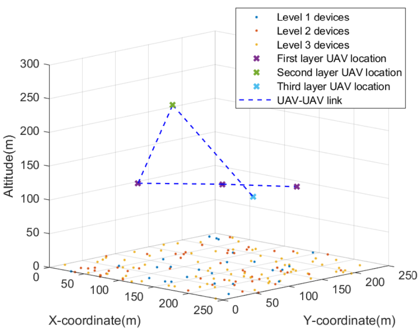

Fig. 3: UAV 3D location and network connectivity.

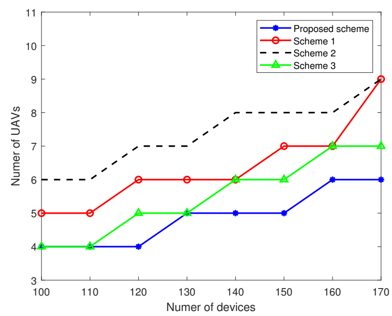

Fig. 4: Number of UAVs vs. Number of devices.

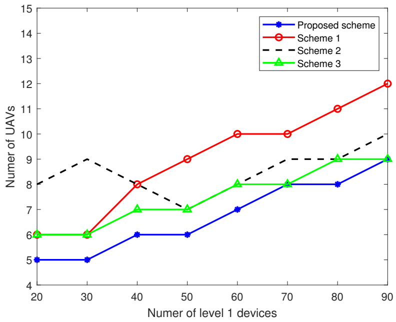

Fig. 5: Number of UAVs vs. Number of high-QoX devices.

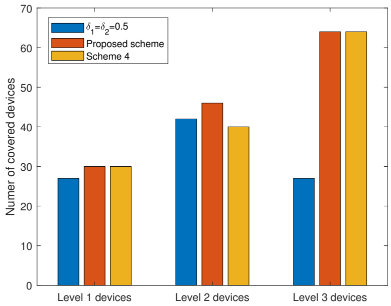

Fig. 6: Number of covered devices of each level vs. bandwidth reservation ratio.

proposed scheme reduces the bandwidth required for device communication, and thus the number of UAVs required.

Fig. 5 demonstrates the impact of the number of high-QoX levels devices on the number of UAVs, under a fixed total number of devices. As the figure shows, as the number of high-QoX devices increases, the primary influencing factor for the number of UAVs changes from bandwidth allocation to UAV location. In addition, the demands of high-QoX devices are the major determinants of UAV positions and bandwidth allocation because of the hierarchical scheme.

Fig. 6 indicates the number of covered devices of each level versus bandwidth reservation ratio, with five UAVs deployed in all these cases. It can been found that an appropriate bandwidth reservation ratio can increase the number of covered devices of lower QoX, while ensuring the services of high-QoX devices. And the most suitable bandwidth reservation ratio is that achieves load balance among UAVs. In contrast, an inappropriate bandwidth reservation ratio may result in too many UAVs being deployed in locations unsuitable for other level devices, resulting in higher path loss.

VI. Conclusion

In this paper, we investigate the diversified service demand-based deployment and bandwidth allocation problem of a multi-UAV assisted IoT network. A comprehensive QoX model is devised to evaluate the service performance. Then a hierarchical networking scheme is proposed. Specifically, we first construct a device hierarchical architecture by layering in order of QoX levels. Then, based on this architecture, UAVs are deployed sequentially, layer by layer, with bandwidth reserved for lower-layer devices. Respectively in each layer of the hierarchy scheme, UAV location, device association and bandwidth allocation are jointly optimized while meeting the connectivity constraints among UAVs. We first decouple the problem through the optimization problem transformation, and then solve it through an improved PSO algorithm. Numerical results demonstrate that our proposed scheme has better performance in case of the number of deployed UAVs compared with benchmark algorithms. For future study, the interference among UAVs would be considered to make the research scenario closer to the practical situation.

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