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Resource Allocation for Data Gathering in UAV-aided Wireless Sensor Networks

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Abstract: As the development of Unmanned Aerial Vehicle (UAV) communication in the residential and commercial areas, different from the traditional Wireless Sensor Networks (WSNs), in this paper we consider a two-layer wireless networks for data gathering, one is sensor nodes to UAVs layer, the other one is UAVs to the outside layer. The sensor nodes sense data and transmit to UAVs, and then UAVs send data to the outside. In this paper, we only focus on the first layer, and we suppose the capacity is sufficient for UAVs to transmit their gathered data in the second layer. The sensor nodes aim to maximize the total data transmitting rate. Because of the limited resources (i.e. limited bandwidth, limited energy of each node, and so on) in the system, thus how to allocate the limited resources to maximize the total data transmitting rate is challenging, and it is necessary to propose an efficient algorithm to allocate the resources. We formulate the problem that jointly considers bandwidth allocation and energy allocation to maximize the total transmitting rate while guarantees the rate in each time slot for each sensor node. Then an optimal algorithm based on dynamic programming named "DPBA" is proposed. Finally, we conduct the extensive simulation to compare our proposed algorithm and the benchmark algorithm (i.e. equal resource allocation algorithm, denoted by "ERAA"). Simulation results show that our proposed algorithm outperforms the benchmark algorithm.

1 Introduction

Generally, sensors in Wireless Sensor Network (WSN) sense data and transmit to sink nodes which are usually located at the edge of the sensing field through multiple hops. However, in many cases, there is no any condition to deploy sink nodes, and no any communication infrastructure to provide services to the end users. Therefore, we can use Unmanned Aerial Vehicle (UAV) to gather data and send to the outside server which can provide data service to the end users. Due to the rapid development of the UAV communications in the residential and commercial areas, it makes possible use UAV to establish a two-layer (sensors-UAVs, UAVs-outside) wireless structure to gather data in the disaster areas, mountain areas, desert areas, and so on. Satellite communication are largely used in the residential and commercial areas [1], we can use satellite as a server to collect data from UAVs. Y. Kawamoto *et al.* [2] use satellite to collect data for the global-scaled internet of things. UAV is an aircraft without pilots, was first used in military. Recently, UAVs are used in many applications, such as monitoring traffic [3], data ferrying [4], communication enhanced [5]–[11], and collecting data [12]–[15].

In [3], some applications using UAVs to monitor traffic were presented. Anthony J. Carfang *et al.* in [4] applied a UAV to ferry data between two nodes. In [5], the authors presented a survey on ad-hoc networks based on UAVs (FANETs), the survey shows that FANETs is a special ad-hoc network but different due to UAV’s characteristics (i.e. high mobility, longer distance). In [6], packet scheduling in ad-hoc based on UAVs was proposed. In [7]–[11], UAV is used as a relay to enhance communication. Y. Yan *et al.* in [12] used a robot (UAV) to visit some fixed points to collect data. In [13], a heuristic algorithm was proposed for optimizing the total energy consumed in data collection application with a UAV. Dac-Tu Ho *et al.* in [14] mainly dealt with selection of sensor network communication topology and UAV path planning. In [15], the authors presented a framework using a mobile UAV to move between sink nodes and sensor nodes to collect data in wireless linear sensor network, and studied some parameters such as UAV speed. Although, all of the above work uses UAV to collect data, however, they all don’t consider resource allocation problem (i.e. bandwidth allocation and energy management) to maximize the total amount of gathering data rate. To the best our knowledge, this is the first time to consider bandwidth allocation and energy management for data gathering in UAV-based wireless sensor networks. There is a lot of work to consider data gathering in wireless sensor networks without using UAV. In [16]–[18], the authors consider data gathering problem in rechargeable wireless sensor networks, they mainly consider energy management while data is sent to the sink node through multiple hops. Shaobo Mao *et al.* in [19] consider a joint energy allocation for sensing and transmission in rechargeable wireless sensor networks between single sensor node and a sink node, it considers the consumed energy for sensing data and transmission. In this paper, we also consider the energy for sensing and transmission.

In this paper, we consider resource allocation for data gathering in UAV-aided wireless sensor networks. Time is divided into slots. UAVs fly for a given number of time slots, the UAV decides how much bandwidth to allocate for each sensor node at each slot. Each node has its energy budget for these time slots. The sensor node needs to decide the amount of energy for sensing and transmission in each slot. Our objective is to maximize the total data transmitting rate while guarantees the data rate in each slot for each sensor node. The main contributions of our work are as follows:

A. We propose the framework for data gathering in UAV-aided two-layer wireless sensor networks. In the first layer, the sensor nodes sense data and then transmit to UAV. In the second layer, UAVs send the data gathered from sensor nodes to the outside. Our objective is to maximize the total data transmitting rate while guarantees the data rate in each slot for each sensor node.

B. In the first layer, we study and formulate bandwidth allocation and energy allocation for sensing and transmission problem for data gathering in UAV-aided wireless sensor networks. We propose a dynamic programming based algorithm to solve this problem. Our simulation results show that our proposed algorithm outperforms the benchmark algorithm (equal resource allocation algorithm).

The rest of the paper is organized as follows. We describe the system model and formulate the problem in Section 2. In Section 3, a dynamic programming based algorithm is proposed. In Section 4, we evaluate the performance of the proposed algorithm and compare it with the benchmark algorithm. Conclusions are given in Section 5.

2 System model and problem formulation

As shown in Figure 1, the system model we consider in this paper is a two-layer structure model, one is sensor-UAV layer, and the other one is UAV-outside layer (we use UAV-satellite as an example in Figure 1). The sensor nodes sense data and transmit to UAVs, then UAVs send to the outside. In this paper, we only consider the first layer, and the capacity of the second layer is sufficient to transmit data. The system is time-slotted, the duration of a slot is τ. N UAVs in the system, are denoted by $\{1,2,\ldots,N\}$. Also, there are N fields, denoted by $\{1,2,\ldots,N\}$. K_n sensor nodes, represented by $\{1,2,\ldots,K_n\}$, are deployed in field n. UAV n flies along its trajectory over field n to gather data from sensor nodes in this field. The number of slots for gathering is given, denoted as T. Next, we will introduce sensor model, UAV model, respectively.

Sensor model: Sensor model includes sensing model and transmission model. In this paper, we consider zero-delay of data transmission, it means that each sensor senses data at slot t and transmit it at slot t + 1. Before UAV flying, there is an initial slot (slot 0) to sense data for transmission at slot 1. For describing clearly, we call that sensing at slot t and transmission at slot t + 1 as a complete process t. For sensing model, let $x(e^s_{n,k,t})$ denote the data generating rate, $x(e^s_{n,k,t}) = e^s_{n,k,t}\gamma_{n,k}$ [19][20], $e^s_{n,k,t}$ is the energy for sensing at process t for sensor k in field n, $\gamma_{n,k}$ denotes the sensing efficiency parameter of sensor k in field n. For transmission model, data transmitting rate at process t for sensor k in field n is

$$R\big((e^r_{n,k,t}, b_{n,k,t})\big) = b_{n,k,t}\Delta \log_2(1 + {e^r_{n,k,t}}/{(\tau N_0 d^{\alpha}_{n,k,t})}) \quad (1)$$

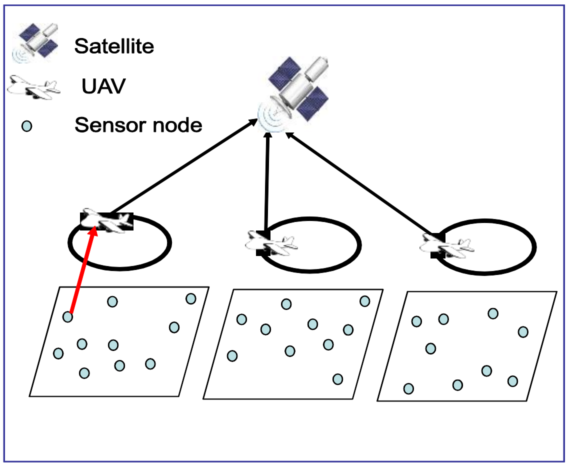

Figure 1 System Model

$e^r_{n,k,t}$ is the energy for transmission, $b_{n,k,t}$ is the number of bandwidth blocks allocated to sensor k in field n, Δ is the size of a block, N_0 is the noise power. $d_{n,k,t}$ is the average distance between sensor k and UAV n at transmission slot, α is the path loss exponent parameter. Each sensor has an energy budget for this data gathering task, denoted by $E_{n,k}$ for sensor k in field n.

UAV model: Each UAV flies over its corresponding field along its trajectory with a fixed speed and height. All of the sensor nodes on the field can communicate with the UAV. The total bandwidth can be allocated to sensors for a UAV is $B\times \Delta$, B denotes the number of bandwidth blocks, Δ denotes the size of a block. There is a data buffer for each sensor.

For complete process t, the transmitting data should be equal to the sensed data. Thus, the following constraint should be satisfied.

$$x\big(e^s_{n,k,t}\big) = \mathrm{R}\big(e^r_{n,k,t}, b_{n,k,t}\big)\ \forall n,k,t \quad (2)$$

The bandwidth for UAV to allocate to sensors is limited, thus the constraint of bandwidth at complete process t is

$$\sum_{k=1}^{K_n} b_{n,k,t} \le B, \forall n,t \quad (3)$$

We take into quality of service account here, we set a minimal required data rate as Q, and the data transmitting rate for each sensor at every complete process should be great or equal to this value. Then the following shows this constraint.

$$x\big(e^s_{n,k,t}\big) \ge Q, \forall n,k,t \quad (4)$$

We know that each sensor has an energy budget, and energy is allocated equally to all of the complete processes for each sensor, it means at complete process t the total energy for sensing and transmission for sensor k in field n is $E_{n,k}/T$. Therefore, the following constraint should be satisfied.

$$e^s_{n,k,t} + e^r_{n,k,t} = \frac{E_{n,k,}}{T}, \forall n, k, t \quad (5)$$

Our objective is to maximize the total data transmitting rate while guarantees the rate at each complete process. Therefore, at complete process *t* we can formulate the problem for UAV *n* as follows.

$$\textbf{(P1)} \quad \textbf{max.} \sum_{k=1}^{K_n} e^s_{n,k,t}\gamma_{n,k} \quad (6)$$

subject to (2), (3), (4), (5) and

$$e^s_{n,k,t} \geq 0, e^r_{n,k,t} \geq 0, b_{n,k,t} \in \{0,1,\dots,B\}, \forall k$$

where $e^s_{n,k,t}$, $e^r_{n,k,t}$, and $b_{n,k,t}$ are the parameters that we need to decide. In next section, we will discuss the solution for this problem.

3 The proposed algorithm

In order to lead to the algorithm successfully, we first introduce the following lemmas.

Lemma 1: If the bandwidth allocate to a sensor is fixed, then the energy for sensing and transmission can be achieved, thus we can calculate the data transmitting rate for this sensor.

Proof: From (5), we can get the energy for transmission as $e^r_{n,k,t} = E_{n,k}/T - e^s_{n,k,t}$, and we substitute it into (2), then we can get an equation, $e^s_{n,k,t}\gamma_{n,k} - b_{n,k,t}\Delta\log_2(1 + (E_{n,k}/T - e^s_{n,k,t})/(\tau N_0 d^\alpha_{n,k,t})) = 0$. As the number of blocks $b_{n,k,t}$ is given, thus function $e^s_{n,k,t}\gamma_{n,k} - b_{n,k,t}\Delta\log_2(1 + (E_{n,k}/T - e^s_{n,k,t})/(\tau N_0 d^\alpha_{n,k,t}))$ is on $e^s_{n,k,t}$ and we can easily prove it is an increasing function. Therefore, there exists a unique solution for the equation, in other words, we can achieve the energy for sensing. At last, the energy for sensing and transmission can be achieved, and in the course of nature we can get the data transmitting rate.

Lemma 2: For a sensor, the data transmitting rate at a complete process only relies on the bandwidth allocated to it. Allocating more bandwidth, more data rate can be achieved.

Proof: From lemma 1, we know that we can get the data transmitting rate with a given bandwidth. If increasing the bandwidth, in order to make constraint (2) holds, we need to increase the sensing energy (decrease the transmission energy as the total energy for sensing and transmission is fixed). Naturally the data transmitting rate increases.

From constraints (2) and (5), we conclude lemma 1 and lemma 2. Based on these two lemmas, we know that the total data transmitting rate depends on the bandwidth allocated for each sensor. Therefore, a dynamic programming based algorithm, denoted as "DPBA", is proposed in the following space. First we define a utility function $U_{n,t}(k1, k2, b_{12})$ which denotes the total data transmitting rate of sensors $\{k1, \dots, k2\}$ in field *n* at complete process *t* when the total number of bandwidth blocks allocated to $\{k1, \dots, k2\}$ is b_{12}. In order to satisfy constraint (4), we need to calculate the minimal required bandwidth blocks $B^{min}_{n,k,t}$ for each sensor at complete process *t*, and it can be calculated as

$$B^{min}_{n,k,t} = \left\lceil \frac{Q}{\log_2(1+\frac{E_{n,k}/T - Q/\gamma_{n,k}}{\tau N_0 d^\alpha_{n,k,t}})\Delta} \right\rceil \quad (7)$$

After satisfying the minimal required bandwidth of all of the sensors, thus we can get the left number of bandwidth blocks as follows.

$$B_{left} = B - \sum_{k=1}^{K_n} B^{min}_{n,k,t} \quad (8)$$

Because the total bandwidth is limited as shown in constraint (3), thus we need to achieve at last is $U_{n,t}(1, K_n, B)$. We can calculate $U_{n,t}(k1, k2, b_{12})$ using the following recurrence relationship.

I. Initial conditions:

$$U_{n,t}(k,k,b_k), \forall k, b_k = B^{min}_{n,k,t} + g, g \in \{0,1,\dots,B_{left}\}$$

II. Recurrence relationship:

$$U_{n,t}(k1, k2, b_{12}) = \max \left\{ \begin{array}{c} U_{n,t}(k1, k0, b'_{12}) + U_{n,t}(k0+1, k2, b_{12} - b'_{12}), \\ \forall k1 \leq k0 \leq k2 - 1, \\ \forall b'_{12} = \sum_{k=k1}^{k0} B^{min}_{n,k,t} + g', g' \in \{0,1,\dots,g\} \end{array} \right\},$$

$$\forall 1 \leq \text{k1} < \text{k2} \leq K_n, \forall b_{12} = \sum_{k=k1}^{k2} B^{min}_{n,k,t} + g, g \in \{0,1,\dots,B_{left}\}. \quad (9)$$

We can calculate the initial conditions as

$$U_{n,t}(k,k,b_k) = e^{s'}_{n,k,t}\gamma_{n,k}, \quad (10)$$

where $e^{s'}_{n,k,t}$ ca be got from $e^{s'}_{n,k,t}\gamma_{n,k} = \Delta b_k \log_2(1 + (E_{n,k}/T - e^{s'}_{n,k,t})/(\tau N_0 d^\alpha_{n,k,t}))$.

We summarize the algorithm as shown in Algorithm 1.

Algorithm 1: the Proposed Dynamic Programming Based Algorithm (DPBA)

1. Calculate the minimal required bandwidth blocks for each sensor according to (7),
2. Calculate the left number of bandwidth blocks according to (8),
3. Calculate the initial conditions according to (10),
4. Calculate $U_{n,t}(1, K_n, B)$ according to the recurrence relationship (9),
5. $U_{n,t}(1, K_n, B)$ is the final result of problem (P1),
6. Return $U_{n,t}(1, K_n, B)$.

For complete process *t*, we can get the final total data transmitting rate, $U_{n,t}(1, K_n, B)$ according to algorithm1 for UAV *n*. At last, the total transmitted data is $\sum_{n=1}^{N}\sum_{t=0}^{T-1} U_{n,t}(1, K_n, B)$ for *N* UAVs in *T* slots.

Theory 1: Our algorithm can get the optimal solution.

Proof: For problem (P1), $U_{n,t}(1, K_n, B)$ is the final result of our proposed algorithm. And next we prove this result is the optimal solution by using induction. Let $L = k2 - k1 + 1$, we assume $U_{n,t}(k1, k2, b_{12})$ is the optimal result for any $L \in \{1, 2 \dots, k\}$, $\forall b_{12}$. Then we calculate $U_{n,t}(k1, k2, b_{12})$ when $L = k + 1$ for any b_{12} according to $U_{n,t}(k1, k2, b_{12}) = \max\{U_{n,t}(k1, k0, b'_{12}) + U_{n,t}(k0+1, k2, b_{12} - b'_{12}), \forall k1 \leq k0 \leq k2 - 1, \forall b'_{12}\}$. $U_{n,t}(k1, k0, b'_{12})$ and $U_{n,t}(k0+1, k2, b_{12} - b'_{12})$ are the optimal solutions because of $k0 - k1 + 1 \leq k$, $k2 - k0 - 1 + 1 \leq k$. Thus, $U_{n,t}(k1, k2, b_{12})$ when *L*

= k+1

returns the optimal solution. When $L = 1$, we can calculate according to (10), obviously it is optimal for a single sensor. Followed by analogy, we can get the optimal results when $L = \{2,3,\dots,K_n\}$. Naturally, of course $U_{n,t}(1, K_n, B)$ is optimal.

4 Simulation result

In this simulation, we have 5 UAVs, and there are 16, 17, 12, 11, and 18 sensors deployed randomly in the fields, respectively. Each of the fields is a square whose size is $2000m \times 2000m$. UAV's trajectory is also a square whose size is $400m \times 400m$ located at the center of the field. The height and speed of UAV are $100m$ and $50km/h$, respectively. UAVs start to fly from the left-down point of the trajectory along the clockwise direction as shown in the following top view figure.

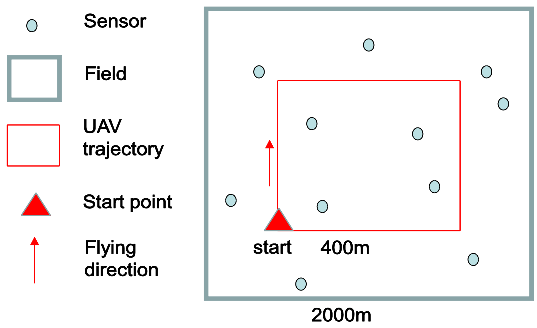

Figure 2 Simulation Model

Each sensor has its energy budget, thus in this simulation we set a base energy E_{base}, and the energy budget of each sensor generates randomly from E_{base} to $2E_{base}$. We consider the different sensing efficiency parameters for different sensors, also we set a base sensing efficiency γ_{base}, and the sensing efficiency of each sensor generates randomly from $0.5\gamma_{base}$ to γ_{base}. The other main parameters are shown in Table I.

Table I Main parameters

Parameter	Value	Parameter	Value
Duration τ	0.5s	T	40
Noise N_0	$10^{-10}W$	Pathloss α	3
Sensing γ_{base}	0.2Mbps/J	Energy E_{base}	20-120J
$B\times\Delta$	200×500HZ	Required Rate Q	0.020-0.035Mbps

In this simulation, we compare our results with a benchmark algorithm. The benchmark algorithm allocates the bandwidth to sensors equally (equal resource allocation algorithm, denoted as "ERAA"), and the energy for sensing can be calculated according to $e^s_{n,k,t}\gamma_{n,k} = \frac{B\Delta}{K_n}\log_2(1 + (\frac{E_{n,k}}{T} - e^s_{n,k,t})/(\tau N_0 d^{\alpha}_{n,k,t}))$.

First, we show the result of total transmitting data rate while changing the base energy budget and the minimal required rate is 0.02Mbps, as plotted in Figure 3. From Figure 3, we can see that our proposed algorithm "DPBA" outperforms the benchmark algorithm "ERAA" no matter the base energy is more or less. This is because that the benchmark algorithm doesn't consider the bandwidth allocation, just equally allocates the bandwidth. For different sensor nodes, the distances to the UAV are different, so are the energy budgets. Therefore, for some sensors, if we allocate more bandwidth to them, they can allocate more energy to sense data, in other words, the transmitting data rate of them can be larger. And each sensor want to get more bandwidth to achieve more data transmitting rate, however, the total bandwidth is limited. Therefore, allocating bandwidth is very important. Nevertheless, our proposed algorithm considers this bandwidth allocation problem based on the differences between sensor nodes to maximize the overall data transmitting rate. Based on the reasons outlined above, it is easy to see that our algorithm outperforms the benchmark algorithm.

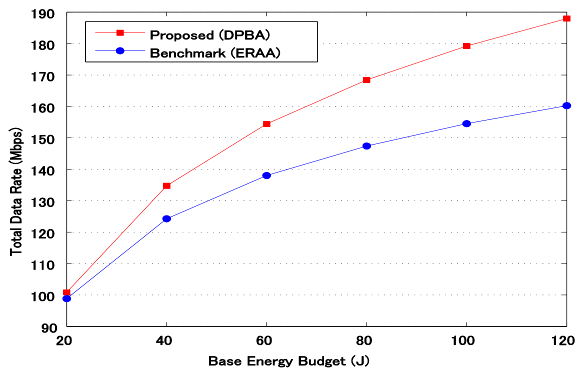

Figure 3 Total data rate vs. Base energy

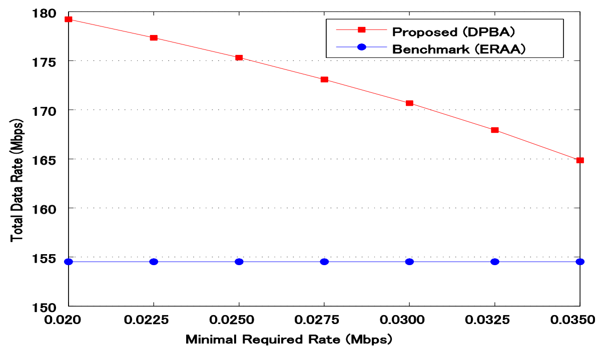

Figure 4 Total data rate vs. Minimal requirement rate

Next we show the result of total data transmitting rate while varying the minimal required rate, and we set the base energy budget is to be 100J. In Figure 4, we can see that the benchmark algorithm keeps the same value due to not considering the minimal required rate for each sensor. For our proposed algorithm, with the increasing of the minimal required rate, the total data rate decreases. This is because the more great minimal required rate, the more bandwidth required for each sensor, then the bandwidth for allocating dynamically gets less. At last, it results in the decreasing of the total rate.

As we known, we also consider the minimal required

rate
for each sensor at each slot while the benchmark algorithm cannot guarantee it due to equal bandwidth allocation (some sensors may not achieve the required rate). Thus we show the total rate of each sensor under a UAV when the minimal required rate is 0.035Mbps (the total required rate is 40*0.035 = 1.4Mbps for *T*=40 slots) and the base energy budget is 100J, as plotted in Figure 5, we just demonstrate the sensors under UAV 5 due to the limited space. In Figure 5, the numbers from 1 to 18 denote the number of sensors while the last number 19 denotes the average of all the sensors. It is obvious that our algorithm can guarantee 1.4Mbps of required rate for each sensor, the benchmark algorithm cannot guarantee it. But the average rate becomes a little less than the benchmark algorithm due to guaranteeing the minimal required rate for each sensor.

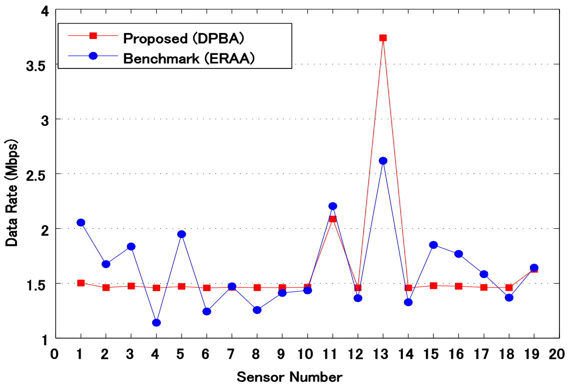

Figure 5 Data rate of each sensor

5 Conclusions

In this paper, we consider a bandwidth allocation for transmission, energy allocation for sensing and transmission problem for data gathering in a two-layer UAV-aided wireless sensor networks. Our objective is to maximize the total data transmitting rate while guarantees the data transmitting rate at each slot for every sensor. And an optimal dynamic programming based algorithm named ”DPBA” is proposed, and the simulation results show that our proposed algorithm outperforms the benchmark algorithm. In the future work, we will consider the interference problem when multiple UAVs gather data in the same field.

Acknowledgements

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