DPTM: A UAV Message Transmission Path Optimization Method Under Dynamic Programming

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Abstract. In the process of missions, how to transmit messages to the destination node quickly is a crucial issue for UAVs. Some existing methods show bad effects such as low delivery ratio, long delay, large average hop count, and high ping-pong effect ratio, thus this paper proposes a new algorithm. By considering the position of all UAVs at each moment, UAVs can obtain optimal message transmission, thus get the optimal path for the message to reach the destination node. After doing simulation experiments with the existing algorithms as DTNgeo, DTNclose and DTNload, the DPTM algorithm is superior to those in terms of delivery ratio, delay, hop count and ping-pong effect ratio.

Keywords: Dynamic programming · UAV · DTN · Ping-pong effect

1 Introduction

UAVs are the hotspot of a new round of scientific and technological revolution and industrial revolution in the world, and their industrial development is related to national interests. For many tasks that require drones, many UAVs are often required to work together to complete the task [1]. At this time, according to the characteristics of UAV networks, how to use routing strategies to quickly transmit messages to the ground station becomes an important technical problem [2].

UAVs establish high-throughput links through wireless transmission to form a temporary, multi-hop regional connection, which is a mobile ad hoc network [3]. However, due to the high-speed continuous movement of the drone, the network topology of drones changes frequently. When traditional MANET routing methods were used in UAVs, a series of problems occurred, such as low delivery rate and long delay, greatly affecting network performance [4].

Therefore, it is necessary to put forward higher requirements for UAV network routing strategy and conduct relevant researches in a targeted manner. At present, many scenes using UAVs are based on task-driven [5], and artificially plan the trajectory of

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the drone in advance. The drones can only move according to the planned trajectory [6]. Many existing methods [7, 8] only consider the current position status of UAVs, but not fully consider the current task-driven nature of UAVs, which makes it difficult to find the optimal transmission object.

In view of the above problems, this paper proposed a UAV message transmission path optimization method under dynamic programming (DPTM) based on the characteristics of task-driven. By globally considering positions of all UAVs at each moment, the method obtains the optimal object of message transmission at each moment, and then obtains the optimal path of messages to the destination node, reducing ping-pong effect ratio and delay. In addition, since the method avoids many unnecessary transmissions of messages, more messages can reach the ground station, thereby achieving the purpose of improving the delivery rate of the message transmission.

2 Related Work

In view of the frequent changes of network topology of UAVs, many researchers have studied it. The routing methods mainly include:

(1) *Traditional mobile ad-hoc network (MANET) routing algorithms.* The traditional routing protocol OLSR is applied in the network of two micro-aircrafts and ground stations in [9]. The results show that traditional routing protocols can't cope with rapidly changing topologies [10]. The main reason is that the UAV moves extremely fast, establishment and breakdown of the communication link is extremely frequent, which causes the network topology to change extremely fast [11]. The traditional mobile ad-hoc routing protocol does not have a certain time to converge, so the transmission efficiency is low [12].

(2) *DTN routing algorithms.* Since messages are allowed to be stored and carried, another methods are based on DTN network. DTN routing algorithms are suitable for intermittent connection [9]. Pure DTN routing methods such as Epidemic Routing [13] often use a multi-copy mechanism. Although the Spray and Wait [14] limits the number of copies, it still makes the nodes in the network carry many unnecessary information. This type of methods is generally applicable to limited flooding of mobile nodes and network in a long-term disconnected state, but can cause unnecessary loss for long-time connected networks such as the UAV network [15, 16].

(3) *Geographic routing algorithms.* Another idea is to transmit messages in a direction closer to the target node based on geographic routing [17]. In [18], DTNgeo is proposed, which is combined with geographic routing and DTN algorithm. DTNgeo forwards one message to a neighbor node that is closer to the destination in space. If there is no neighbor node closer to the ground station, the message will be carried. However, DTNgeo only considers the current position of drones, which is easy to cause messages to be transmitted back and forth and experiments show that the ping-pong effect ratio is very large. In addition, DTNclose and DTNload are proposed. These two algorithms predict the future time position after a short time according to the current motion state of UAVs [17], and forward messages

to the neighbor node that is closer to the destination node in the future, to achieve the purpose of reaching the ground station as soon as possible [19]. These two heuristic algorithms only consider position information of the next moment, but do not consider the position of the future time as much as possible. The path of one message from source to destination node may still not be the optimal transmission path. The experimental result shows that ping-pong effect ratio still large, and there is still room for optimization in delay.

3 Time Consumption Model for UAVs' Message Transmission

Based on characteristics of UAVs for message transmission, the mathematical model for the time consumption of UAVs' message transmission is as follows:

$$minT = (x, t) \tag{1}$$

Where x represents UAV's ID, and $x \in [1, N]$ (N is the number of UAVs performing the task), in particular, we define the ID of the ground station as 0; t represents a certain moment; F indicates the time at which the message carried on one drone numbered x reaches the ground station at current time t.

In particular, when the message arrives at the ground station, process of message transmission ends, whereby a special value of Eq. (1) can be obtained:

$$F(0, t) = t \tag{2}$$

In addition, during mission, even if some messages cannot be transmitted to the ground station in the form of multiple hops, UAVs will fly back to the ground station at the end of mission to bring messages back. So the moment that one message arrives at the ground station at the latest is the end of the mission, it can be deduced that:

$$F_{\max}(x, t) = Final \tag{3}$$

The choice of the next nod for transmission at time t only consider the chronological order of the message to reach the ground station, and selects the UAV with the earliest time to the ground at time t as the next object. From this we can get:

$$F(x, t) = min\left\{F(x, t + 1), \min_{y \in \{neighbours\}} F(y, t)\right\} \tag{4}$$

Where $\{neighbours\}$ is the set of neighbor nodes of the drone numbered x at time t, $\forall$y, if d(x, y) $< Range,\ put\ y\ into\ \{neighbours\}$, $F(x, t + 1)$ is the time of messages carried by the node x to reach the ground station at time t + 1, and $\min_{y \in \{neighbours\}} \{F(y, t)\}$ is the earliest time of messages carried by neighbor nodes to reach the ground station at time t. Then compare the value of the function F, and select the node with the smallest value as the transmission object at time t.

Therefore, the transmission object of drones at each moment can be obtained, and the transmission object selected according to this algorithm can effectively avoid ping-pong effect, so that messages can reach the ground station as soon as possible, thereby obtaining a short delay.

4 DPTM

Based on the time consumption model of UAVs' message transmission in Sect. 3, this section introduces a UAV message transmission path optimization method under dynamic programming—DPTM. We firstly introduce several variables their meanings used in DPTM, as shown in Table 1:

Table 1. Meaning table of variables

Variable	Value
t	Current moment
f	A short time interval
T	All moments divided by f for time interval
N	The number of UAVs performing the task
i	One UAV numbered i $(i \in [1, N])$
Final	End moment of mission
{neighbours}	Set of neighbor nodes of UAV numbered x at current time t
F(N,T)	Recording all moments when all UAVs carry message at the moment to the ground station. ∃x∈N, F(x,t) indicates the time when UAV numbered x carries the message at time t to the ground station earliest
location(N,T)	Position of all UAVs at each moment, ∃x∈N, location(x,t) indicates the position of UAV numbered x at time t
next(N,T)	Recording transfer objects of all UAVs at each moment,∃x∈N, next(x,t) indicates the transfer object of UAV numbered x at time t
d(N,N)	Recording all distances between all UAVs

For calculating message transmission object $next(i, T)$ at any moment of any UAV, the specific steps of DPTM are as follows:

Step 1: Define a state function, obtain and the state transition equation the boundary conditions of the state transition equation.

From the time consumption model of UAVs' message transmission in the previous section, the state function of UAV numbered i at the time t can be obtained as F(i, t); from the formula (4), the state transition equation of UAV numbered i can be obtained as follows:

$$F(i,t) = min\{F(i,t+1),\ \min_{j\in\xi i} F(j,t)\} \tag{5}$$

Where ξ_i is the set of neighbor nodes of UAV numbered i at time t.

In addition, according to formula (2) (3), the boundary conditions of the state transition equation of UAV numbered i can be obtained as follows:

$$F(0,t) = t \tag{6}$$

$$F_{max}(i,t) = Final \tag{7}$$

Step 2: Collect the position of all UAVs at each moment.

Since trajectories of UAVs are planned by the ground station, the ground station can get all position of all drones at each moment and get the location(N, T).

Step 3: Calculate distance between UAV numbered i and any other UAV, and obtain the neighbor nodes that can communicate with i at time t.

Calculate the distance $d(i, j)$ between UAV numbered i and any other UAV numbered j at time t, and record the distance to $d(N, N)$. if $d(i, j) \leq Range$, then put j into ξ_i, where ξ_i is the set of neighbor nodes of i at time t.

Step 4: According to the state transition Eq. (5), the next hop at current moment is obtained until all the moments update, and the optimal message transmission object of one drone at each moment is obtained.

According to the formula (5) (6) (7), firstly compare the value of function F at the current moment t and the next moment $t + 1$, if $\mathrm{F(i, t+1)} < F(i, t)$, then $\mathrm{F(i, t) = F(i, t+1)}$, $\mathrm{next(i, t+1) = next(i, t)}$. Then compare the value of function F of i with its neighbor nodes, and send messages to the neighbor node with the smallest value of function F. $\forall \mathrm{j} \in \zeta_i$, if $F(j, t) < F(i, t)$, then $\mathrm{F(i, t) = F(j, t)}$and $\mathrm{next(i, t) = j}$.

After updating F(N, T) and next(N, T), let $\mathrm{t = t + 1}$ and judge if it has reached Final time. If $\mathrm{t <}$ Final, then repeat steps 3 and 4, otherwise end the operation.

Over time, DPTM finally converges to get message transmission object of all UAVs at each moment next(N, T). When one UAV need to transmit messages to the next hop obtained by DPTM, it need to judge if they can communicate with each other. If it cannot at current moment, it will carry until it can communicate with it (Table 2).

Table 2. DPTM algorithm

DPTM Algorithm

```
Input: location(N,T)
Output: next(N,T)
Inital:
t=0;          //current moment
Next（N,T)= -1;
F（N,T）=Final;
Procedure DPTM:
F(0,t)=t
Repeat
   t=t+1
   If  F(x,t)>F(x,t+1) then
      F(x,t)=F(x,t+1)
      Next(x,t)=next(x,t+1)
   For j∈{neighbours} do
      If F(x,t)>F(j,t) then
         F(x,t)=F(j,t)
         Next(x,t)=j
Until t=Final
```

5 Simulation Results

5.1 Simulation Setup

This article uses ONE to implement DTNgeo, DTNclose, DTNload and DPTM. The simulation scenario is a typical task-driven scenario– search and rescue. In order to find the target person and rescue him as soon as possible, the ground station pre-plans the trajectory of each drone. UAV collects message such as pictures and videos and quickly transmits them back to the ground station. The simulation experiment borrows the most cases of the number of drones in [18], as shown in Fig. 1.

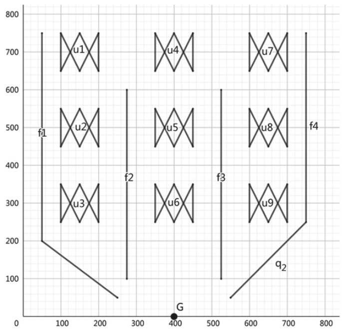

Fig. 1. Simulation experiment scene graph

Where G is the ground station; u1-9 are searching UAVs and are responsible to search and collect information, and can also serve as relays for transmission; f1-4 are ferry UAVs and act only as relays to help the search UAVs transmit. The search trajectory is shown in the figure. UAVs cooperate with each other to transmit information to the ground station G as soon as possible. Then ground station puts together the topography of entire search in area and finds location of the target person.

Table 3. The table of experimental parameters

Parameter	Value
Test area	800 * 800 m
The number of grounds	1
The number of UAVs (searching/ferry)	13 (9/4)
Mission time	8 min
Speed	4.5 m/s
Range	200 m
Size of each message	1.4 kb
The number of messages per second	5
f	0.1/0.2/0.5/1/2/4

In addition, the specific parameter settings during the experiment are shown in Table 3.

5.2 Discussion of Results

Experiments were carried out for different time intervals F. According to the data of ONE simulation experiments, we set the delivery rate, delay, hop count and ping-pong effect ratio as evaluation indexes to compare DPTM with DTNgeo, DTNclose and DTNload.

(1) **Comparison of delivery rate of different algorithms in different interval experiments**
The results in Fig. 2 show that the delivery rate of these four algorithms are all very high during the experimental time. Compared with other algorithms, DPTM slightly increases the delivery rate to about 90%. Since DPTM can obtain the optimal transmission path of messages, many unnecessary transmissions in other algorithm are avoided, so that more messages can reach the ground station.

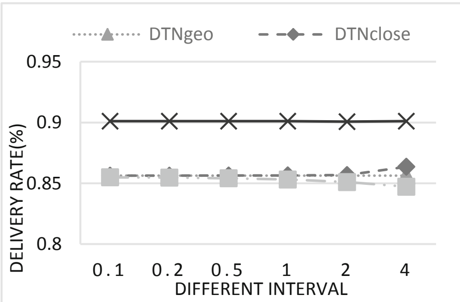

Fig. 2. Comparison of delivery rate between DPTM and DTNgeo, DTNclose, DTNload

(2) **Comparison of delay of different algorithms in different interval experiments**
The results in Fig. 3 show that DPTM reduces delay to about 40 s at different interval compared to other three algorithms. The reason is that DPTM obtains the optimal path of messages to the ground station according to the position information of all the drones at each moment. DTNgeo only considers the location information at current time. DTNclose and DTNload only consider the location of the next moment. So message transmission object of these three algorithms is optimal for current network topology, but not for the changing UAV network. The optimal object at a certain moment is likely to be not optimal for the whole process, so DTNgeo, DTNclose and DTNload cause long delay.

(3) **Comparison of hop count of different algorithms in different interval experiments**
The results in Fig. 4 show that DPTM reduces hop count to less than 4.8 at different interval compared to other three algorithms. The reason is that DPTM plans the optimal transmission path in advance according to the position information of all drones at each moment, so that drones can remember the transmission object at

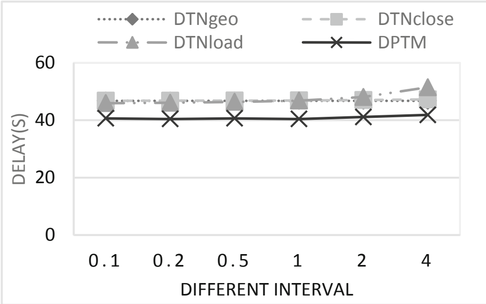

Fig. 3. Comparison of delay between DPTM and DTNgeo, DTNclose, DTNload

each moment. If the communication link between current node and the next hop can be established, messages will be transmitted, otherwise messages will be carried. The unnecessary round-trip transmission of messages is reduced, resulting in smaller hop count. DTNgeo only considers the location information of current time. DTNclose and DTNload only consider the location of the next moment. Messages are transmitted to the neighbor node closet to the destination, so many messages are likely to be re-transmitted at some point in the future, which leads to unnecessary ping-pong transmission and result in increased hop count.

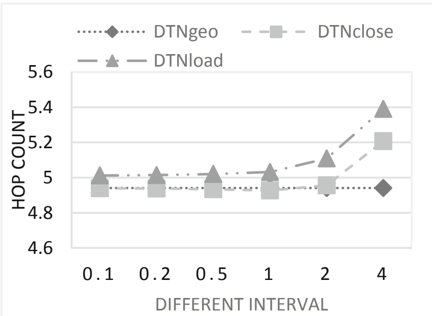

Fig. 4. Comparison of hop count between DPTM and DTNgeo, DTNclose, DTNload

(4) **Comparison of ping-pong effect ratio of different algorithms in different interval experiments**
The results in Fig. 5 show that DPTM can significantly reduce the ping-pong effect ratio to less than 5%. According to theoretical analysis of DPTM, the algorithm can find the optimal transmission path and completely eliminate the ping-pong effect ratio. However, in the actual execution of the mission, speed of messages transmission is fast, but it also spends time. Therefore, for some situations where the connection time is extremely short and the load is too heavy, some drones may not be able to transmit all messages to the planned next hop as a whole. It causes

some messages to miss the optimal object, thus result in a small proportion of ping-pong effect. Even so, DPTM significantly reduces the ping-pong effect ratio and reduces the time delay.

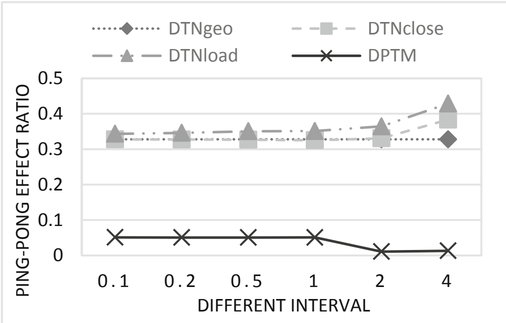

Fig. 5. Comparison of ping-pong ratio between DPTM and DTNgeo, DTNclose, DTNload.

6 Conclusion

This paper proposed a UAV message transmission path optimization method under dynamic programming named DPTM. By globally considering positions of all UAVs at each moment, DPTM obtains the optimal object of message transmission at each moment, and then obtains the optimal path of messages to the destination node, to reduce ping-pong effect ratio and delay. Comparing DPTM with DTNgeo, DTNclose and DTNload through simulation experiments, the results show that DPTM slightly improves the message delivery ratio. In terms of delay, DPTM has a reduction of nearly 6%. In terms of hop count, DPTM reduces it to 4.8 or less, and the result can reduce the waste of energy used by drones for messages' transmission. In terms of ping-pong effect ratio, DPTM significantly reduce it down to 5%, so that drones will waste less energy for useless transmission and use as much energy as possible to perform tasks.

Since many applications of UAVs, such as the scenario search and rescue mentioned in this paper at present are planned in advance, the UAVs only need to move according to the pre-planned trajectory of the ground station, so DPTM is of great significance in the current unmanned unit communication.

References

1. Canis, B.: Unmanned Aircraft Systems (UAS): commercial outlook for a new industry. In: Congressional Research Service Reports. Library of Congress. Congressional Research Service (2015)
2. Zhou, Y., Cheng, N., Lu, N., et al.: Multi-UAV-aided networks: aerial-ground cooperative vehicular networking architecture. IEEE Veh. Technol. Mag. **10**(4), 36–44 (2015)
3. Guvenc, I., Saad, W., Bennis, M., et al.: Wireless communications, networking, and positioning with unmanned aerial vehicles [Guest Editorial]. IEEE Commun. Mag. **54**(5), 24–25 (2016)

4. Grodi, R., Rawat, D.B., Bajracharya, C., et al.: Performance evaluation of Unmanned Aerial Vehicle ad hoc networks. Southeastcon, pp. 1–4 (2015)
5. Anantapalli, M.K., Li, W.: Multipath multihop routing analysis in mobile ad hoc networks. Wirel. Netw. **16**(1), 79–94 (2010)
6. Wu, Q., Zeng, Y., Zhang, R., et al.: Joint trajectory and communication design for multi-UAV enabled wireless networks. IEEE Trans. Wirel. Commun. **17**(3), 2109–2121 (2018)
7. Hausman, K., Preiss, J.A., Sukhatme, G.S., et al.: Observability-aware trajectory optimization for self-calibration with application to UAVs. IEEE Robot. Autom. **2**(3), 1770–1777 (2017)
8. Harounabadi, M., Puschmann, A., Artemenko, O., Mitschele-Thiel, A.: TAG: trajectory aware geographical routing in cognitive radio ad hoc networks with UAV nodes. In: Mitton, N., Kantarci, M.E., Gallais, A., Papavassiliou, S. (eds.) ADHOCNETS 2015. LNICST, vol. 155, pp. 111–122. Springer, Cham (2015). https://doi.org/10.1007/978-3-319-25067-0_9
9. Badis, H., Agha, K.A.: QOLSR, QoS routing for ad hoc wireless networks using OLSR. Eur. Trans. Telecommun. **16**(5), 427–442 (2010)
10. Asadpour, M., Egli, S., Hummel, K.A., Giustiniano, D.: Routing in a fleet of micro aerial vehicles: first experimental insights. In: Proceedings of 3rd ACM MobiHoc Workshop Airborne Networks and Communication, pp. 9–10 (2014)
11. Bekmezci, I., Sahingoz, O.K., Temel, Ş., et al.: Flying ad-hoc networks (FANETs). Ad Hoc Netw. **11**(3), 1254–1270 (2013)
12. Cetinkaya, E.K., Rohrer, J.P., Jabbar, A., et al.: Protocols for highly-dynamic airborne networks. In: ACM/IEEE International Conference on Mobile Computing and Networking, pp. 411–414 (2012)
13. Vahdat, A., Becker, D.: Epidemic Routing for Partially-Connected Ad Hoc Networks. Master Thesis (2000)
14. Li, J., Guan, J., Xu, C., et al.: Adaptive multiple spray and wait routing algorithm. J. Chin. Comput. Syst. **36**(10), 2275–2278 (2015)
15. Lu, F., Li, J., Song, Y., et al.: Location position and message delivery ratio based controlled epidemic routing for DTNs. J. Chin. Comput. Syst. **39**(5), 918–923 (2018)
16. Caini, C., Cruickshank, H.S., Farrell, S., et al.: Delay- and disruption-tolerant networking (DTN): an alternative solution for future satellite networking applications. Proc. IEEE **99**(11), 1980–1997 (2011)
17. Shirani, R., St-Hilaire, M., Kunz, T., et al.: Quadratic estimation of success probability of greedy geographic forwarding in unmanned aeronautical ad-hoc networks. In: Vehicular Technology Conference, pp. 1–5. IEEE (2012)
18. Asadpour, M., Hummel, K.A., Giustiniano, D., et al.: Route or carry: motion-driven packet forwarding in micro aerial vehicle networks. IEEE Trans. Mobile Comput. **16**(3), 843–856 (2017)
19. Muzaffar, R., Yanmaz, E.: Trajectory-aware Ad hoc routing protocol for micro aerial vehicle networks. In: IMAV 2014: International Micro Air Vehicle Conference and Competition 2014, Delft, The Netherlands, 12–15 August 2014. Delft University of Technology, pp. 301–315 (2014)