A Congestion-Free Mechanism for Geographic Routing Protocols in Aerial Sensor Networks

Xinquan Huang
College of Communications Engineering
Army Engineering University
Nanjing, China
e-mail: huangxinquan1993@sina.com

Aijun Liu*
College of Communications Engineering
Army Engineering University
Nanjing, China
e-mail: liuaj.cn@163.com

Xiaohu Liang
College of Communications Engineering
Army Engineering University
Nanjing, China
e-mail: liangxiaohu688@163.com

2020 IEEE 6th International Conference on Computer and Communications (ICCC) | 978-1-7281-8635-1/20/$31.00 ©2020 IEEE | DOI: 10.1109/ICCC51575.2020.9345267

***Abstract*—In aerial sensor networks, the limited queue lengths of sensor UAVs will make existing geographic routing protocols witness congestions on a series of intermediate sensor UAVs. As a result, packets will be dropped once the queues of intermediate receivers are full. To solve this problem, in this paper a Cooperative Motion based Random Destination (CMRD) mechanism is proposed. First, this mechanism employs flocking algorithm to help number-limited relay UAVs and the ground station form a stable and connected relay network. Then each packet generated by corresponding sensor UAV, randomly selects a node from the relay network as its destination, and decides next-hop node based on the geographic information of both neighboring sensor UAVs and neighboring relay UAVs. Simulation results shown that, the CMRD mechanism will help geographic routing handle the congestion problem, so as to achieve reliable and efficient packet delivery.**

Keywords-Geographic routing protocols; aerial sensor networks; distributed control algorithms; relay UAVs.

I. Introduction

Aerial sensor networks (ASNs) are a field of ad-hoc networks which are formed by a lot of sensor unmanned aerial vehicles (UAVs) [1]. As the radio range of each sensor UAV is limited, multi-hop routing is important to provide a reliable and efficient packet delivery towards the ground station. Recently, geographic routing protocols [2]–[8] emerge in the area of wireless ad-hoc networks. Employing geographic routing protocols, each node selecting next hop node only depends on the geographic position of neighbors. The scalability of geographic routing protocols makes them suitable for ASNs [9].

In ASNs, only one destination (ground station) can be seen as an advantage, it can also be a disadvantage since all data traffics travelling to the destination will cause congestions on a series of intermediate UAVs. Moreover, the limited queue lengths of UAVs in ASNs make the congestion problem particularly relevant and serious. As a result, a lot of packets will be dropped once the queues of intermediate receivers are full. However, existing geographic routing protocols do not design mechanisms to handle the congestion problem. This has led to the improvement of geographic protocols which are the main work of this paper.

In this paper, we propose a mechanism called Cooperative Motion based Random Destination (CMRD) for geographic routing protocols. The CMRD mechanism makes limited relay UAVs to automatically create a connected relay network with the ground station using a flocking algorithm. Then these relay UAVs and ground station together are treated as potential destinations, and are called 'target node set'. Their positions are periodically broadcast by the ground station through beacons, such that the positions of potential destinations can be acknowledged by all sensor UAVs. Then the CMRD randomly selects a node from 'target node set' as the destination of each packet. Moreover, during the forwarding process, the next-hop node is selected based on both the positions of neighboring UAVs and positions of neighboring relay UAVs.

The remainder of this paper is organized as follows. In Section II, the communication model is described and the main problem is formulated. Moreover, in Section III, the detail steps of the CMRD mechanism are illustrated. The evaluation of proposed mechanism is provided in Section IV. Finally, a brief conclusion is given in Section V.

II. System model

We consider a ASN which consists of N sensor UAVs and a ground station. Moreover in the ASN, we introduce $M(N > M)$ relay UAVs which are critical in the design of the proposed CMRD mechanism. The relay UAVs do not perform the sensing task, however only relay data packets to the ground station. The number of relay UAVs should be as small as possible to reduce the cost. In this paper, we specify that $M \leq N/10$.

In the ASN, not all sensor UAVs and relay UAVs have the ability to directly communicate with the ground station, they construct a multi-hop ad-hoc network. However, sensor UAVs can transmit the collected data to sensor UAVs, relay UAVs or ground stations, while relay UAVs can only transmit the received data to the relay UAVs or ground station.

The radio range of each sensor UAV equals to r, while the radio range of each relay UAV is $2r$. Note that for any relay UAV, the sensor UAVs in the neighborhood should be the sensor UAVs within the distance r. This is because the

Authorized licensed use limited to: National Taiwan Univ of Science and Technology. Downloaded on September 23,2023 at 14:44:22 UTC from IEEE Xplore. Restrictions apply.

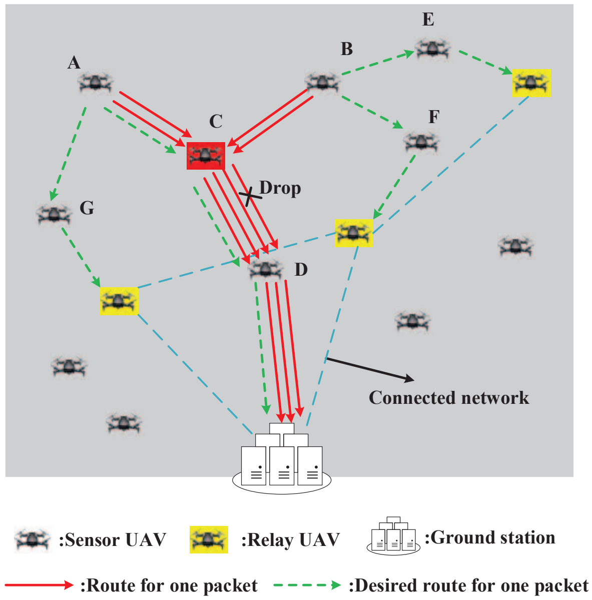

Fig. 1. The basic idea of CMRD mechanism.

asymmetry of communication radius between relay UAVs and sensor UAVs, so that relay UAVs can only receive the data packets sent by the sensor UAV within range r. Since the ground station is equipped with adequate energy unit, the radio range of the ground station is assumed far enough to cover all UAVs (sensor UAVs and relay UAVs). Our network model relies on the following assumptions:

- *Availability of location information*: The availability of a positioning sensing technology is assumed such as provided by global positioning system (GPS) and inertial measurement units (IMUs).
- *Dense node deployment*: in this scenario, we assume the sensor UAVs are densely deployed for maintaining connectivity of ASN.
- *Single ground station*: in this paper, only one ground station is considered, which is assumed stationary or only moderately moving.

III. The Proposed CMRD Mechanism

Typically, when all data traffics move towards the ground station through solely the multi-hop links among sensor UAVs, congestions will happen on a series of sensor UAVs since the limited queue lengths. This can be illustrated by red arrows in Fig. 1, with each arrow representing a packet. It can be seen that the packets generated by sensor UAV A and B all choose C as intermediate nodes, which could be witnessed under geographic routing protocols when A and B are very close geographically. Moreover, all the following packets of A and B will travel the same route if the ASN is considered static. As a result, the packets will spend extra time waiting in the queue of C and D, and some will be discarded once their queues is full. To make the geographic routing protocols be able to handle congestion problems, the CMRD is proposed and the details of it is described in this section.

A. Basic idea

An important idea involved in CMRD is to make packets sent from the same source always take different target nodes as destinations. If the relay UAVs form a stable and connected relay network with the ground station as shown by the blue dotted line in Fig. 1, packets received by the relay network will always be able to travel to the ground station. Then each sensor UAV could choose any node in the relay network as a destination. Note that the two packets of A choose a relay UAV and ground station as destinations respectively, and the two packets of B select different relay UAVs as destinations. As a result, the traffics will be scattered in different directions as the green dashed arrows in Fig. 1, so as to reduce the congestion happened on sensor UAV C.

B. Deployment of relay UAVs

To fulfill the CMRD mechanism, the deployment of relay UAVs should satisfy following requirements:

- Given the number of relay UAVs, automatically deploy them in unknown environment to cover as many sensor UAVs as possible, while avoiding collisions between relay UAVs and with obstacles.
- Given the number of relay UAVs, automatically deploy them to form a stable and connected network with ground station in the unknown environment.

The two requirements can be modelled as a optimization problem. Define following sets and constants:

- Let $S = \{1, ..., N\}$ denotes the set of sensor UAVs;
- Let $R = \{1, ..., M\}$ denotes the set of relay UAVs;
- Let G denotes the ground station;
- Let $\forall i \in S$, $\forall j \in S$

$$S_{ij} = \begin{cases} 1 & \text{if } i \text{ is within the range of } j \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

- Let $\forall i \in R$, $\forall j \in R$

$$R_{ij} = \begin{cases} 1 & \text{if } i \text{ is within the range of } j \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

- Let $\forall i \in R$, $\forall j \in S$

$$O_{ij} = \begin{cases} 1 & \text{if } i \text{ is within the range of } j \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

- Let $\forall i \in S$

$$S_{iG} = \begin{cases} 1 & \text{if } G \text{ is within the range of } i \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

- Let $\forall i \in R$

$$R_{iG} = \begin{cases} 1 & \text{if } G \text{ is within the range of } i \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

Authorized licensed use limited to: National Taiwan Univ of Science and Technology. Downloaded on September 23,2023 at 14:44:22 UTC from IEEE Xplore. Restrictions apply.

Then, the two requirements can be modelled by following optimization problem:

$$\max \quad \sum_{i=1}^{M}\sum_{j=1}^{N} O_{ij} \tag{6}$$

$$\text{s.t.} \quad \sum_{j=1}^{N} S_{ij} \geq 1, \quad \forall i \in S \tag{7}$$

$$\sum_{j=1}^{M} R_{ij} \geq 1, \quad \forall i \in R \tag{8}$$

$$\sum_{i=1}^{N} S_{iG} \geq 1, \quad \forall i \in S \tag{9}$$

$$\sum_{i=1}^{M} R_{iG} \geq 1, \quad \forall i \in R \tag{10}$$

The constraints (7) and (8) guarantee the connectivity between sensor UAVs and relay UAVs themselves respectively. The constraint (9) guarantees the connectivity between sensor UAVs and ground station. The constraint (10) guarantees the connectivity between relay UAVs and ground station.

Since the use scenarios of ASNs are generally unknown environments and the ASNs could be of great dynamics, it is impractical to solve equation (6) in advance. In this paper, we employ a distributed motion control algorithm called flocking algorithm to solve (6) and a flocking algorithm in [10] is chosen in this paper. When each relay uses the flocking algorithm to maneuver itself, it only treats the relay UAVs or the ground station as neighbors, while the latter is treated as a neighbor with speed equalling to zero.

The flocking algorithm maneuvers each relay UAV according to four rules, that is, aggregation, separation, obstacle avoidance and virtual leader following. We refer the details of the four rules into [10]. Note that the aggregation rule aims at preventing the topology between relay UAVs and ground station from being disconnected which corresponds to (8) and (10). As for separation rule and virtual leader following rule, they aim to expand the coverage of relay UAVs on the sensor UAVs. The purpose of separation rule is to make all relay UAVs spread out from the ground control station as much as possible, such that the relay UAVs could cover more sensor UAVs. The two rules correspond to the optimization object in (6).

C. forwarding strategy

By using flocking algorithm [10] to control movements for a certain periods, all relay UAVs will form a stable and connected network with ground station, while maximum the coverage to sensor UAVs. Each relay UAV periodic reports its position to the ground station through single-hop or multi-hop mode. Moreover, the ground station announces positions of itself and all relay UAVs to the whole sensor UAVs periodically. Since a stable topology is formed, and the relay UAV network is of small scale, each relay UAV could use topology-based routing algorithm to relay packet to ground station. We call relay UAVs together with the ground station 'target node set'. This set can ensure all packets in it finally travel to the ground station.

Based on the knowledge of 'target node set', following forwarding strategy is designed in the CMRD mechanism. When a sensor UAV wants to send a data packet to the ground station, the UAV randomly selects a node from the 'target node set' as the destination of its data packet. Then both the ID of the sender and the ID of the selected destination is encapsulated in the header of the data packet. During the forwarding process, if any intermediate sensor UAV finds that the ground station is located within the communication range, the intermediate UAV select the ground station as the next-hop node. Otherwise if the intermediate sensor UAV finds one or more relay UAVs are located within its communication range, the intermediate UAV select the nearest relay UAV as next-hop node, even if the relay UAV is not the destination of the packet. If above-mentioned two cases do not happen, the intermediate sensor UAV selects next-hop node employing typical geographic routing protocols. When the data packet is received by a relay UAVs, it only travels among relay UAVs to the ground station. Moreover, when a data packet is received by the relay UAV, the destination ID in the packet header is changed by the ID of ground station. The pseudocode of the CMRD mechanism based routing protocol is described as in Table. 1.

Algorithm 1 CMRD mechanism

Input: A packet waiting to be forwarded by sensor UAV i.
Output: Next hop node.

```
if The destination zone in the packet header is empty. then
    if the ground station is within communication range of i then
        Select ground station as next hop node.
    else
        Randomly select a node in the 'destination zone' as the destination of the packet
    end if
else
    if the ground station is within communication range of itself then
        Select ground station as next hop node.
    else
        if one or more relay UAVs are within communication range of i then
            Select the nearst relay UAV as the next hop node, and change the destination ID in the packet header by the ID of the selected relay UAV.
        else
            Select the next hop node using geographic protocol.
        end if
    end if
end if
```


Authorized licensed use limited to: National Taiwan Univ of Science and Technology. Downloaded on September 23,2023 at 14:44:22 UTC from IEEE Xplore. Restrictions apply.

TABLE I
SIMULATION PARAMETERS

Parameters of the ASN	
Simulation area	$800m \times 800m$
Communication radius of each Sensor UAV	200m
Communication radius of each relay UAV	400m
Central coordinate of obstacle	(400m,400m)
Obstacle radius	200m
Packet size	512Byte
Maximum hops of a packet	20
queue length of sensor UAV	64 packets
queue length of relay UAV	128 packets
Packet generation rate of each sensor UAV	(1,5,10,20,40) packets/s
Number of sensor UAVs	50,60,70,80,90
Number of relay UAVs	5
Parameters of flocking algorithm	
Parameters	Values
Weighting coefficient c_1^{nei}	0.1
Weighting coefficient c_2^{nei}	$2\sqrt{c_1^{nei}}$
Weighting coefficient c_1^{obs}	20
Weighting coefficient c_2^{obs}	$2\sqrt{c_1^{obs}}$
Weighting coefficient c_1^{leader}	0.2
Weighting coefficient c_2^{leader}	$2\sqrt{c_1^{leader}}$
Desired inter-UAV distance d (m)	400/1.2
Position of virtual leader	(400m,400m)
Speed of virtual leader	(400m,400m)
Constant value b	5
Constant value ε	0.1
Constant value h	0.2
Constant value a	5

IV. SIMULATIONS

In this section, we simulate the proposed CMRD mechanism. We integrate the CMRD mechanism into the coordinate-assisted geographic routing (CAGR) protocol [7] and call the new protocol ECAGR protocol. The performances on packet delivery ratio and average packet hop of the ECAGR and the CAGR protocol are compared. The parameters used in the simulation are shown in the Table I, where we refer the definitions on parameters of the flocking algorithm involved in the CMRD mechanism to [10]. In our simulation, all sensor UAVs are randomly distributed in an area of $800m \times 800m$, and keep hovering during the whole simulation process. Initially, all relay UAVs are located in the ground station, whose coordinate is ($400m$, $0m$). One obstacle is located in the simulation area, whose boundary is circular, with the coordinate of the center being (400,400) and radius being 200m. In the simulation, we consider the data traffic arrival of each sensor UAV to be constant bit rate (CBR), while the relay UAVs do not generate data packets instead they only relay them. We make each sensor UAV generate a total of 1500 packets for each simulation run.

A. Verification of flocking algorithm

In Fig.2, the snap shot of UAVs (50 sensor UAVs and 5 relay UAVs) when the relay UAVs reach a stable structure are shown. Each black star represents one sensor UAV, while each black circle represents one relay UAV and the black diamond represents the ground station. One red solid is plotted between two relay UAVs or between one relay UAV and the ground station, if their distance is within 400m which is the radio range of each relay UAV. Moreover, one green dashdot line is plotted between one sensor UAV or one relay UAV if their distance is within 200m which is the radio range of each sensor UAV. It can be shown in Fig.2, the flocking algorithm indeed help relay UAVs form a connected network with the ground station, meanwhile avoiding collisions with the obstacle.

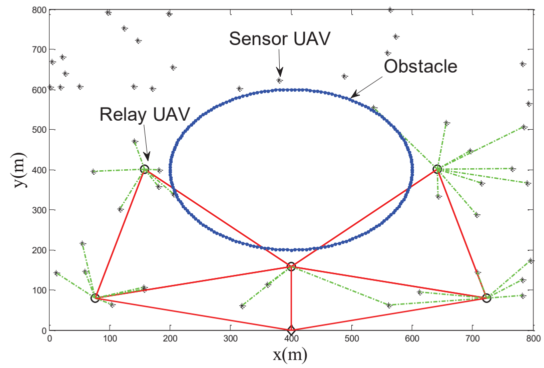

Fig. 2. The spots of UAVs.

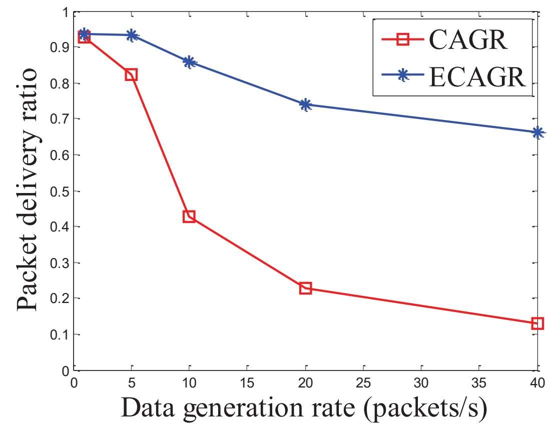

Fig. 3. Packet delivery ratio versus packet generation rate.

B. Performances regarding different traffic loads

To generate different traffic loads, we change the data generation rate of each sensor UAV. Fig.3 and Fig.4 show the performances of the two considered protocols under different packet generation rates. In the simulations, the number of sensor UAVs is 50, and the number of relay UAVs is 5. The data generate rates vary among 1,5,10,20, and 40. As can be seen from Fig.3, as the packet generation rate increases, the packet delivery rates of both protocols decrease. However, the ECAGR protocol decreases much more slowly. Moreover the ECAGR protocol also achieves less average hops than the CAGR algorithm.

Obviously, ECAGR achieves better performances in terms of packet delivery ratio and average hops. As for CAGR protocol, it does not have a strategy in the routing layer

Authorized licensed use limited to: National Taiwan Univ of Science and Technology. Downloaded on September 23,2023 at 14:44:22 UTC from IEEE Xplore. Restrictions apply.

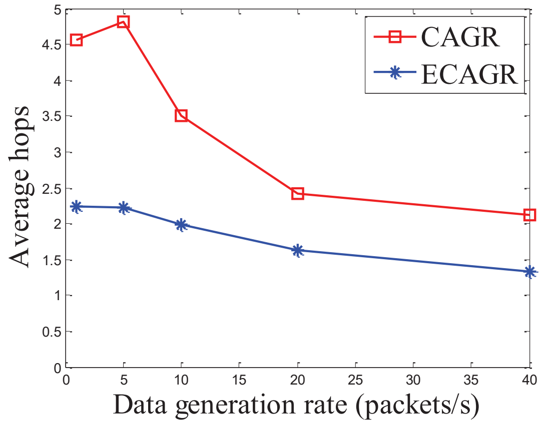

Fig. 4. Average hops versus packet generation rate.

to handle congestion problem. Therefore as data traffic load increases, the congestion problem in the ASN becomes more serious. Consequently, the frequency a UAV's queue is full increases, which makes more packets be discarded. However, since the CMRD mechanism effectively balances the loads in the network by making packets sent from the same source always take different destinations, the congestion problem are appropriately relieved. Therefore the discarded packets under ECAGR protocol are greatly reduced. Moreover, as most packets will eventually be forwarded by the relay UAV and the communication radius of each relay UAV is larger than that of each sensor UAV, the number of hops under ECAGR protocol is less than that under CAGR protocol. In addition, the CMRD mechanism allows a UAV forward packet to any relay UAV located in the proximity even it is not the initial destination. This makes the hops under ECAGR protocol be further reduced.

V. Conclusion

In this paper, a Cooperative Motion based Random Destination (CMRD) has been proposed to help geographic routing protocols handle congestion problem in ASNs. By using flocking algorithm, a small number of relay UAVs can maintain stable and connected relay network with the ground station in a complex environment. Based on the relay network, the CMRD mechanism makes packets sent from the same source always take different destinations, and decides next-hop node based on the geographic information of both neighboring sensor UAVs and neighboring relay UAVs. We find that compared with typical geographic routing protocols, the modified protocols which introduce CMRD mechanism, can achieve a higher packet success rate when the network load increases. This is because the CMRD mechanism can greatly handle the congestion problem in the ASNs, such that the packets discarded when the queues are full are reduced. In the future, the route decision to each selected destination can be further optimized regarding network congestion.

Acknowledgment

This work is supported in part by the National Natural Science Foundation of China (No. 61671476), Natural Science Foundation of Jiangsu Province of China (No. BK20180578), China Postdoctoral Science Foundation (2019M651648), National Natural Science Foundation of China (No. 61901516).

References

[1] M. Asadpour, K. A. Hummel, D. Giustiniano, and S. Draskovic, "Route or carry: Motion-driven packet forwarding in micro aerial vehicle networks," *IEEE Transactions on Mobile Computing*, vol. 16, no. 3, pp. 843–856, 2017.

[2] B. Karp and H.-T. Kung, "Gpsr: Greedy perimeter stateless routing for wireless networks," in *Proceedings of the 6th annual international conference on Mobile computing and networking*. ACM, 2000, pp. 243–254.

[3] J.-D. M. M. Biomo, T. Kunz, and M. St-Hilaire, "Routing in unmanned aerial ad hoc networks: A recovery strategy for greedy geographic forwarding failure," in *2014 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE, 2014, pp. 2236–2241.

[4] H. Huang, H. Yin, G. Min, J. Zhang, Y. Wu, and X. Zhang, "Energy-aware dual-path geographic routing to bypass routing holes in wireless sensor networks," *IEEE Transactions on Mobile Computing*, vol. 17, no. 6, pp. 1339–1352, 2017.

[5] J. Na, D. Soroker, and C.-k. Kim, "Greedy geographic routing using dynamic potential field for wireless ad hoc networks," *IEEE Communications Letters*, vol. 11, no. 3, pp. 243–245, 2007.

[6] A. Mostefaoui, M. Melkemi, and A. Boukerche, "Localized routing approach to bypass holes in wireless sensor networks," *IEEE transactions on computers*, vol. 63, no. 12, pp. 3053–3065, 2013.

[7] H. Huang, H. Yin, G. Min, X. Zhang, W. Zhu, and Y. Wu, "Coordinate-assisted routing approach to bypass routing holes in wireless sensor networks," *IEEE Communications Magazine*, vol. 55, no. 7, pp. 180–185, 2017.

[8] Q. Chen, S. S. Kanhere, and M. Hassan, "Adaptive position update for geographic routing in mobile ad hoc networks," *IEEE Transactions on Mobile Computing*, vol. 12, no. 3, pp. 489–501, 2012.

[9] J. Jiang and G. Han, "Routing protocols for unmanned aerial vehicles," *IEEE Communications Magazine*, vol. 56, no. 1, pp. 58–63, 2018.

[10] R. Olfati-Saber, "Flocking for multi-agent dynamic systems: Algorithms and theory," *IEEE Trans. Autom. Control*, vol. 51, no. 3, pp. 401–420, Mar. 2006.

Authorized licensed use limited to: National Taiwan Univ of Science and Technology. Downloaded on September 23,2023 at 14:44:22 UTC from IEEE Xplore. Restrictions apply.