Adaptive Data Sharing Algorithm for Aerial Swarm Coordination in Heterogeneous Network Environments (Short Paper)

Yanqi Zhang[1], Bo Zhang[2(✉)], and Xiaodong Yi[2]

[1] State Key Laboratory of High Performance Computing (HPCL), National University of Defense Technology (NUDT), Changsha, China
zhangyanqi15@nudt.edu.cn

[2] Artificial Intelligence Research Center (AIRC), National Innovation Institute of Defense Technology (NIIDT), Beijing, China
bo.zhang.airc@outlook.com, yixiaodong@nudt.edu.cn

Abstract. With the development of unmanned aerial vehicle (UAV) systems, multi-UAV cooperation has attracted noticeable attention. In response to the communication constraints faced in UAV swarm coordination, both the lazy and the eager strategies were proposed to enable swarm-wide reliable information exchange to further behavior coordination for UAV swarms. However, these two algorithms are only evaluated in a fixed and homogeneous network scenario. Hence, how to choose the proper information exchange strategy for a UAV swarm in realistic dynamic and heterogeneous network environments remains an open while interesting problem. Therefore, in this paper, we first evaluate the convergence and payload cost of both strategies for robotic swarms in realistic network scenarios. Then we propose a novel online adaptive information exchange strategy by adopting single relay selection schemes to ensure low payload and fast convergence in various network environments. Numerical results reveal our novel strategy performs well across different network scenarios in terms of convergence and payload cost, showing its robustness, adaptive capability and potential applications in UAV swarms.

Keywords: Multi-UAV · Single relay selection · Heterogeneous network environments

1 Introduction

With the rapid development of unmanned aerial vehicle (UAV) technology, multi-UAV cooperation has stronger operability, but there are still many

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challenges to overcome. The restricted communication environments [3,7] can significantly affect the performance of UAV swarm coordination.

Many multi-UAV coordination problems require shared swarm-wide situational awareness. Both the lazy and the eager consensus algorithms were proposed for reliable information exchange to share situational awareness across swarms to converge to an agreed-upon solution for coordination problems depending on distributed UAV-state information [5]. However, these two algorithms are only evaluated in fixed and homogeneous network scenarios. So we first evaluate the performance of both algorithms in realistic network scenarios. According to the performance evaluation of two algorithms in the homogeneous network environments, both algorithms only perform well in simple network environment. However, in reality, the network environments faced by UAV swarms are very complex.

The information exchange strategies in the lazy and the eager algorithms takes two extremes, so we propose an adaptive algorithm that autonomously choose the optimal strategies based on the current network conditions, and we use the single relay selection schemes to optimize the eager strategy.

The remainder of the paper is organized as follows. Section 2 describes the system model, including network model and underlying assumptions, along with the lazy and the eager algorithms. Section 3 details our adaptive data sharing algorithm. The comparative analysis of the performance of three algorithms in different dynamic network environments is presented in Sect. 4. Finally, conclusions are provided in Sect. 5.

2 System Model

2.1 Network Model and Assumptions

It is common to model information exchange between individual UAVs in swarm by directed graph or undirected graph. For a swarm of n UAVs, the network topology is represented by a directed graph with the weighted adjacent matrix $A = [a_{ij}] \in R^{n\times n}$ [12]. a_{ij} denotes the probability of a successful communication between UAV i and j. Although a time-invariant communication model can significantly simplify the consensus problems [9], in reality, the quality of communication links between UAVs in an ad hoc network varies with movements of UAVs. So the network model is described as a time-varying model: $A(t) = [a_{ij(t)}]$. In order to simplify the problem, we abstract the communication model into a synchronous and discretized model. The whole communication process is seen as a series of separate communication rounds.

2.2 Lazy and Eager Consensus Data Sharing Algorithms

In a swarm of n UAVs, each UAV has its own data. To share data across the swarm, request messages and data messages are transmitted until all data are available on each UAV.

The only difference between the information exchange strategy of the lazy and eager algorithm lies in the response to request messages. In the lazy algorithm, an UAV broadcasts a data message only when its own data is requested, so a data message only contains its own data. In the eager algorithm, an UAV broadcasts a data message as long as it has the requested data, regardless of whether the requested data is from itself or through information exchange, so a data message contains all requested data the UAV can provide.

We can regard these two information strategies as schemes of relaying. The "decoding set" here represents a collection of UAVs which contain requested data, including the source UAV. In the lazy algorithm, we choose only one UAV in the "decoding set", namely the source UAV, to transmit data as a relay in a new communication round. In contrast, in the eager algorithm, all UAVs in the "decoding set" serve as relays to forward data. Obviously, the eager algorithm improves the probability that a data message is successfully received in each communication circle, thus accelerating the algorithm convergence. In theory, the eager algorithm can achieve the fastest convergence, while the lazy algorithm requires the lowest message payloads per round. The extreme nature of both strategies limits their applicability to the environment. Experimental results in the fixed and homogeneous network scenarios also prove this point. Both algorithms were tested in MATLAB and SITL [6] simulations with communication packet loss rates of 0.25, 0.50, 0.75 and 0.90 in [5]. The experimental results show: in low-loss communications environments (i.e., 0.25 and 0.50), the eager algorithm converges slightly faster than the lazy algorithm, but the total message payload bytes required by the eager algorithm far exceeds that of the lazy algorithm compared to the difference in convergence; in high-loss communications environments (i.e., 0.75 and 0.90), the eager algorithm is superior to the lazy algorithm in terms of both convergence and total message payload.

In order to adapt to the actual complex communications environments, we design an adaptive algorithm that selects one of these two strategies based on the current instantaneous network conditions in each communication round, and we adopt single relay selection schemes to optimize the eager strategy for reducing payload per round.

3 Adaptive Data Sharing Algorithm

A variety of relay selection schemes are proposed for wireless relay networks. We refer to these selection schemes [8] and choose single relay selection schemes for our adaptive algorithm. Among the existing single relay selection schemes, the nearest neighbor selection scheme [10,11] is adopted by selecting "the nearest relay" with the strongest channel to the source or destination.

Here, we choose a UAV with the strongest channel to the destination for relay forwarding. A method of distributed timers is proposed for distributed relay selection [4]. Each relay listens for pilot signals transmitted from the destination (Clear-to-Send or CTS). Upon receiving CTS, each relay starts a timer, the duration of a timer is inversely proportional to the channel gain. The timer of

Algorithm 1. The adaptive data sharing algorithm

```
swarm ← swarm_uav_ids
data_avail ← {own_data}
repeat
   if ∃uav ∈ swarm ⋀ uav ∉ data_avail then
      new_data ← NET_RECV_DATA
      data_avail = data_avail ∪ new_data
      own_request ← swarm \ data_avail
      NET_SEND_REQUEST(own_request)
   end if
   requests ←NET_RECV_REQUESTS
   requests ← requests ∩ data_avail
   for request ∈ requests do
      if  request is for own_data ⋀ PER < PER_th then
         data_to_send ← {own_data}
      else
         single relay selection
         update data_to_send
      end if
   end for
   NET_SEND_DATA(data_to_send)
until terminated
```

the "best" relay expires first and then the relay sends a flag packet. Other relays will stop their timers once they have received the flag packet.

The information exchange strategy in the adaptive data sharing algorithm is as follows. In each communication round, for the source and the destination UAVs in low-loss communications environments, we use the lazy strategy that the response to a request message is sent by the source UAV; for two UAVs in high-loss communications environments, we use the optimized eager strategy that the response is sent by the chosen relay UAV. The adaptive algorithm expects to approach the eager algorithm in terms of convergence, and approach the lazy algorithm in terms of payloads in a communication round.

The low-loss and high-loss communications environments are determined by the packet loss rate between the source UAV and the destination UAV and the threshold of packet loss rate for the partition is determined by the experimental results at fixed and homogeneous network scenarios.

Two initialization variables are required. The variable *swarm* is a set of UAV identifiers for which data is required. The variable *data_avail* is a set of identifier/data tuples for which the data are obtained. At initialization, the *swarm* set contains all swarm UAV identifiers, the *data_avail* set contains the only identifier/data tuple belonging to the executing UAV.

Two types of messages are transmitted between swarm UAVs: a request message and a data message. A request message contains all UAV identifiers (2-byte unsigned integers) for which the data are required. A data message contains a set of identifier/data (4-byte floating point) tuples. The total per-round message payload bytes required for this implementation is described by Eq. 1:

$$PB = \sum_{i=1}^{n} 2r_i + \sum_{i=1}^{n} 8d_i \tag{1}$$

where n is the number of swarm UAVs, r_i is the number of UAVs requested by UAV i, an UAV identifier is two bytes, d_i is the number of identifier/data tuples to be sent, and an identifier/data tuple is eight bytes.

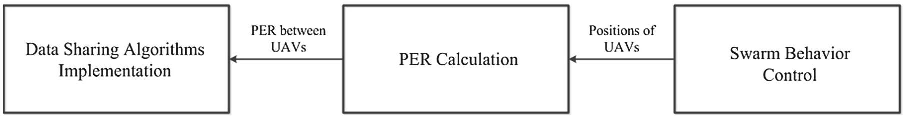

Fig. 1. The three components of the experimental architecture and their relationships. The swarm behavior control module implements different swarm behaviors in Gazebo simulator and sends UAVs' location information to the PER calculation module. The PER calculation module sends the PER information between UAVs to the algorithm implementation module. The algorithm implementation module implements different data sharing algorithms and utilizes the PER information to simulate packet loss in communications.

The algorithm starts with the initialization on the first UAV and ends with the termination on the last UAV in the swarm. At the beginning of each communication round, if the executing UAV does not have identifier/data tuples from all other swarm UAVs, *data_avail* set is updated according to all received data messages since last round. Then a request message is transmitted if there are tuples still missing from the *data_avail* set. In the middle of each communication round, all received request messages are processed. For a request to the executing UAV's own data, if the PER between the executing UAV and the requesting UAV is lower than the PER threshold, then the own data will be send by the executing UAV; if the PER between two UAVs is higher than the threshold, then whether the own data is sent by executing UAV will be determined by the relay selection. For a request to other data obtained through transmission, whether these data are sent by the executing UAV also determined by the relay selection.

The relay selection process is as follows. For each request, the executing UAV starts a corresponding timer. Then wait for timers to stop or interrupt. In the process of waiting, if the executing UAV receives the corresponding flag packet before the timer expires, then interrupt the timer. If no flag packet is received until the timer stops, then broadcast a flag packet to stop timers on other UAVs, thus the corresponding requested data will be sent by the executing UAV. Finally, all UAV tuples selected from the *data_avail* set are sent after all timers have been processed.

4 Experiments

4.1 Experimental Environment

In order to simulate realistic UAV swarm behavior, we choose Robot Operating System (ROS) software framework [2] for development. The swarm-robot communication analysis (SRCA) tool provides the ability to simulate communication channels and packet loss in ROS platform [13], so we use it to simulate lossy communications environments.

The SRCA tool contains three modules: swarm behavior control module, PER (packet error rate) calculation module and packet loss simulation module. The data sharing algorithms are implemented in the packet loss simulation module that simulates packet loss in communications. Swarm behaviors implemented in the swarm behavior control module are used to provide various communications environments. And the PER calculation module simulates communication channels and calculate the PER between any two UAVs. The experimental architecture is shown in the Fig. 1.

In experiments, the threshold of the packet loss rate is set to 0.7, which may be affected by the experimental environment. We choose quadrotor as the UAV model in Gazebo simulator [1]. The communication between UAVs remains synchronized, and after the completion of one communication round, the next round starts.

4.2 Experimental Results and Analysis

We set up experiments in three typical dynamic communications environments to compare and analyze the convergence and total message payload bytes of the three algorithms.

Dynamic Low-Loss Communication Environment. Eight quadrotors are placed equidistantly on the circumference, and the packet loss rate between any two quadrotors is less than 0.7. All quadrotors move radially to the center of the circle, namely that any two quadrotors are in a low-loss communication environment during motion. Figure 2a shows the initial position of the swarm in Gazebo. The triangles on the graph indicate the positions of quadrotors, inside the circle is the range of motion, and the arrows point to the movement directions. Table 1 shows the average number of communication rounds and average total message payload bytes of per UAV required for three algorithms convergence in different realistic communication environment.

The eager algorithm converges slightly faster than the lazy and adaptive algorithms, but the required total message payload bytes exceed that of the lazy and adaptive algorithms. Convergence and required total message payload bytes of the adaptive algorithm is almost the same as that of the lazy algorithm. The performance of the lazy and the eager algorithm in a dynamic low-loss communication environment is consistent with that in a fixed and homogeneous communication environment. The lazy algorithm and the adaptive algorithm behave

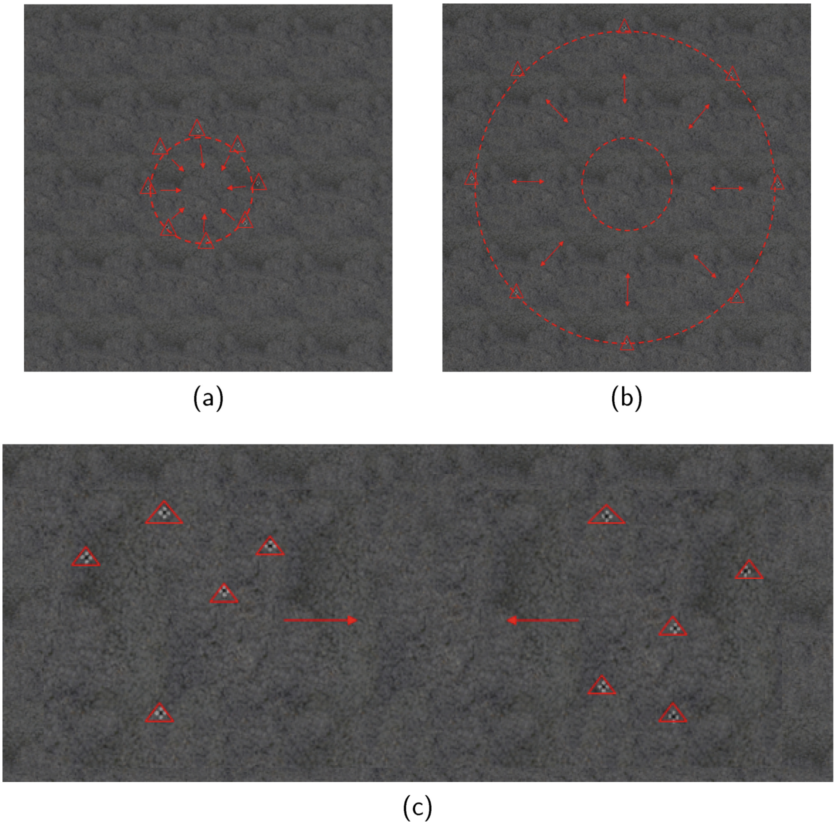

Fig. 2. The initial position of the swarm in Gazebo in (a) low-loss communication environment, (b) high-loss communication environment, (c) mixed communication environment. The triangles indicate quadrotors' positions, the dashed circles show the range of motion, and the arrows point to the movement directions.

Table 1. Experimental results in different realistic communications environments

Environment	Algorithm	Avg convergence rounds	Avg total payload bytes
Low-loss	Lazy	2.23	14.10
	Eager	2.15	74.30
	Adaptive	**2.35**	**15.70**
High-loss	Lazy	1784.28	15967.30
	Eager	96.98	1067.95
	Adaptive	**109.68**	**413.70**
Mixed	Lazy	1129.94	8645.92
	Eager	158.90	1715.00
	Adaptive	**175.10**	**1640.56**

similarly both in convergence and payload bytes because the adaptive algorithm degenerates into the lazy algorithm in this low-loss network environment.

Dynamic High-Loss Communication Environment. Eight quadrotors are placed equidistantly on the circumference, with the packet loss rate of about 0.9 between any two adjacent quadrotors initially. All quadrotors move along the radius until the packet loss rate between two quadrotors on the diameter approaches 0.7 and then moves in the opposite direction. The portion between the two dashed circles in Fig. 2b is the range of motion.

The eager algorithm converges much faster than the lazy algorithm, and the total payload bytes it requires is much lower than the lazy algorithm, which align with the results in the fix and homogeneous network environments. The adaptive algorithm converges a litter slower than the eager algorithm, but it requires lower payload bytes, which proves the effectiveness of the single relay selection method in reducing load.

Dynamic Mixed Communication Environment. Ten quadrotors are divided into two sub-swarms, each with five quadrotors. Two sub-swarms move towards each other until they form a large swarm. The packet loss rate between quadrotors in a sub-swarm is less than 0.7, and the packet loss rate between quadrotors in two different sub-swarms is greater than 0.7. Quadrotors in a sub-swarm are in a low-loss environment, and quadrotors between two sub-swarms are in a high-loss environment. This hybrid communication environment is used to verify the adaptability and effectiveness of the adaptive algorithm. Two arrows in Fig. 2c point to the different movement directions of the two sub-swarms.

The eager algorithm converges fastest, but the adaptive algorithm converges only a little slower, and the lazy algorithm converges the slowest. And the total message payload bytes required for adaptive algorithm convergence is lowest, that of the eager algorithm is next, and that of the lazy algorithm is the highest. The adaptive algorithm proves its effectiveness with the lowest total payloads and the fast convergence that approaches that of the eager algorithm.

5 Conclusion

In this paper, we first evaluate the performance of the lazy and the eager algorithms in dynamic communication scenarios. Then we propose an adaptive algorithm by adopting single relay selection schemes and do simulation experiments in different realistic network environments to compare the performance of these algorithms. Experimental results show the adaptive algorithm converges very close to the eager algorithm and it requires the lower total message payloads in various environments, which reflects its robustness, adaptive capability and potential applications in UAV swarms.

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