



Design of Optimal Routing for Cooperative Microsatellite Swarm Network

Zhi Yang^(✉), Dandan Wang, and Yan Zhang

DFH Satellite Co. Ltd., Beijing 100094, People's Republic of China
young_zhi@163.com

Abstract. The cooperative microsatellite swarm network has the advantages of low construction cost, short development cycle, flexible working mode and strong anti-destruction ability. In the network, micro-satellite nodes need to complete network control functions such as link maintenance, state monitoring and routing calculation. The valuable on-board payload and inter-satellite link resources are consumed. In order to reduce the energy consumption of satellite communication transmission, this paper focus on the routing issue in swarm network. A specific routing protocol is proposed, which defines the uniform format of swarm network packets suiting for path addressing based multi-hop transfer and the header deletion technique based packet routing scheme. An algorithm for optimal routing in swarm networks is devised, in which the transmission power consumption and the transfer time delay are chosen as the primarily concerned factors. The routing problem is mathematically formulated as a constrained optimization problem, with the total transmission power consumption of satellites as the optimization objective and with the transfer time delay as the constraint respectively. Then the graph theory approach is utilized as the tool to solve the problem. Examples are used to demonstrate the performance and efficiency of the proposed routing protocol and algorithm.

Keywords: Swarm network · Routing protocol · Routing algorithm · Constrained optimization problem · Graph theory

1 Introduction

With the in-depth development of space exploration, networking and data communication between satellites and other spacecraft have gradually become an important challenge [1]. However, there are some problems in the traditional design methods of satellite constellation network, such as relying on fixed configuration, vulnerable to be attacked, poor network reliability and high construction cost. The swarm network organized by micro-satellites has the advantages of low construction cost, short development cycle, flexible working mode and strong anti-destruction ability. It can complete some tasks such as information collection and observation that can not be completed by large satellites [2]. It has been paid more and more attention by research institutions.

The study of satellite clusters is in its infancy. There are many problems in simulation verification and evaluation technology, network protocol design and optimization technology, multi-satellite cooperative control technology, adaptive task decision technology and so on. The topology of satellite cluster network is different from that of satellite constellation. Its network service requirements are very different from those of satellite constellations. The research on related technologies of swarm network is mainly focused on network topology control algorithm, network capacity research, task resource scheduling and so on [3–5]. More research is focused on the top-level architecture and bottom layer (physical layer and link layer) protocols, but there is no literature research on satellite cluster network routing protocols.

One of the most important functions of network layer quality-of-service (QoS) metrics is to provide guaranteed quality of data exchanging among satellites in an effective manner, which raises the problem of optimal routing in swarm networks. Space network routing techniques have been a research focus for years along with the rapid development of cooperative microsatellite swarm network. A large number of efforts have been made to explore the efficient routing strategies for space networks, and various routing protocols and algorithms have been proposed [6]. But these studies mostly focus on the application scenarios of conventional distributed space systems, such as low earth orbit (LEO) or medium earth orbit (MEO) communication or navigation satellite constellations, which are not directly applicable to swarm networks. For example, the mobility of network nodes (satellites or satellites) constitutes a major difference. The topology of a satellite constellation network is usually deterministic and can be predicted quite accurately, and the complete topology dynamic is periodic [6]. For ad hoc space networks, Shen et al. proposed a flexible routing architecture [7]. However, the proposed routing architecture is mainly oriented to inter planetary missions, in which the spacecraft is deployed in diverse orbits and has sparse and intermittent communication connectivity. So, it does not suit for the cooperative microsatellite swarm network. In a word, efficient routing strategies must consider the specific mission scenarios and optimization objectives of swarm network. Wu et al. proposed an optimization algorithm for signal routing in satellite sensor networks [8]. Although the sensor network mission scenarios in [8] are quite different from the microsatellite swarm network, the optimization objectives discussed in [8] are similar to that discussed in this paper. In [8] the authors transform the sensor network routing optimization problem into a single-objective optimization problem and a tabu search algorithm is used to solve the problem, while in this paper we formulate the swarm network routing optimization problem as a constrained optimization problem and utilize the graph theory based approach to solve the problem. In addition, a specific routing protocol is proposed for the microsatellite swarm network in this paper.

The rest of this paper is organized as follows. Section 2 concerns on routing protocol of swarm networks, in which format and routing scheme of network packets are presented. In Sect. 3, an on-board implementable routing algorithm is devised. In Sect. 4, some examples are studied. Finally, Sect. 5 concludes the paper.

2 Swarm Network Routing Protocol

2.1 Network Packet Format

Network packets are the basic data units being transferred in the swarm network, so all the application data must be encapsulated in network packets for transfer. As we have discussed in the previous sub-section, one of the major functions of network packets is to support the multi-hop transfer of application data in the swarm network. For this purpose, a specific swarm network packet format is defined below, as illustrated in Fig. 1.

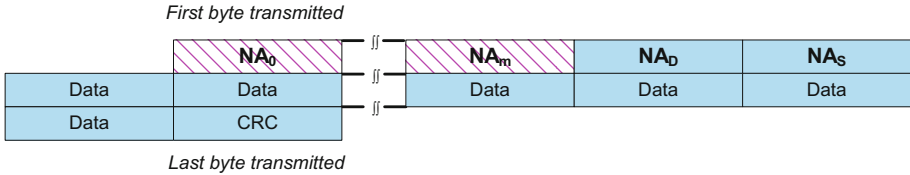


Fig. 1. Format of a network packet

In the packet, NA_0 to NA_m are the path address sequence, which define the route to be taken by the packet for transferring across the swarm network. The path address sequence is composed of the network addresses of routers used to guide the packet across the swarm network from the source node to the destination node. Note that, the path address sequence is generated by the router which locates in the same subnet with the source node by using route generation algorithm. NA_D is the destination address, which is specified as the network address of the destination node. NA_S is the source address, which is specified as the network address of the source node. Packet cargo comprises the application data that is encapsulated in the packet for transfer. CRC is an 8-bit cyclic redundancy check code used for packet error detection.

2.2 Packet Routing Scheme

Swarm network is a packet routing network. The routers provide a means of routing packets from the source node to the destination node. As discussed previously, path addressing is used for packet routing. With path addressing, the path address sequence is specified as a list of network addresses of routers that the packet will traverse.

Header deletion is a simple but effective technique designed in this paper to manage the transfer of packets across a swarm network. An intuitional illustration of the header deletion approach is illustrated in Fig. 2. As illustrated, when a packet is received at a router, its leading byte is firstly checked for validity verification. If the leading byte of the packet is not consistent with the NA of the router, it means that the packet should not be handled by this router. Then, the router should terminate the routing process and report the error to higher layers. Else, the router will check the second byte of the packet to determine the next hop to forward this packet to. Two cases are possible for this

situation: 1) If the four most significant bits of the second byte is not consistent with the SN of the router, it means that the packet should be forwarded to some other router in the swarm network whose NA is consistent with the second byte. In this case, the leading byte (i.e. header) of the packet should be deleted, and the packet will pass through the router without this leading byte. Then, the routing process has to continue by repeating the above process, and the second byte of the packet which is now the new leading byte will be used for the subsequent routing. 2) If the four most significant bits of the second byte is consistent with the SN of the router, it means that the packet should be sent to a certain node in the current subnet whose CN is consistent with the four least significant bits of the second byte. This node is just the destination node, and till now the packet routing is accomplished.

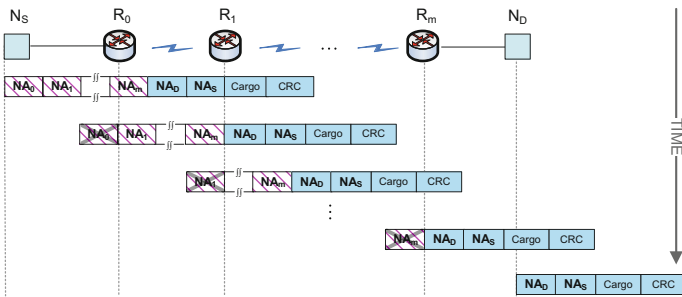


Fig. 2. Header deletion across multiple routers

3 Swarm Network Routing Algorithm

3.1 Routing Problem Formulation

As we known, power resources in cooperative microsatellite swarm network are very precious. Hence, power consumption is the first priority to be optimized in our design. An efficient routing algorithm is required to provide optimal routes in terms of both power consumption and transfer time delay.

Considering the m -hops data transfer process illustrated in Fig. 2, the overall power consumption for transferring the packet across the swarm network is formulated as

$$PC = \sum_{i=0}^{m-1} PC_{i,i+1} \tag{1}$$

where $PC_{i,i+1}$ is the power consumption of router R_i for transferring the packet to the next router R_{i+1} .

Let E_t be the transmitted energy per bit, according to the free space propagation model of signal, the received energy per bit E_r at the receiving end with distance d is

$$E_r = \frac{E_t}{d^\alpha} \quad (2)$$

where α is the signal attenuation factor, whose value is generally 2 for space communication. Assume that the minimum received energy per bit to maintain the required signal-to-noise ratio at the receiving end is E_b . Then, the minimum transmitted energy per bit E_m is

$$E_m = E_b \times d^\alpha \quad (3)$$

Let N be the total number of transmitted bits by router R_0 at the first hop, because of header deletion technique used for package routing, the total number of transmitted bits by router R_i at the $(i + 1)$ -th hop should be $N - 8 \times i$. Then, the minimum power consumption of router R_i should be

$$PC_{i,i+1} = (N - 8 \times i) \times E_b \times d_{i,i+1}^\alpha \quad (4)$$

where $d_{i,i+1}$ is the length of wireless link between router R_i and router R_{i+1} , or equivalently the relative distance between satellites that carry routers R_i and R_{i+1} .

According to (1) and (4), we have

$$PC = \sum_{i=0}^{m-1} (N - 8 \times i) \times E_b \times d_{i,i+1}^\alpha \quad (5)$$

Because N is generally much larger than $8 \times i$, (5) can be approximately written as

$$PC = N \times E_b \times \sum_{i=0}^{m-1} d_{i,i+1}^\alpha \quad (6)$$

For the example illustrated in Fig. 1, transfer time delay of the packet from the source node to the destination node is formulated as

$$TD = TD_{S,0} + \sum_{i=0}^{m-1} TD_{i,i+1} + TD_{m,D} \quad (7)$$

where $TD_{S,0}$ and $TD_{m,D}$ is the intra-satellite transfer time delay, and $TD_{i,i+1}$ is the inter-satellite transfer time delay for forwarding the packet from router R_i to router R_{i+1} . Assuming that the upper bound of inter-satellite transfer time delay is τ , we have

$$TD_{\max} = TD_{S,0} + m \times \tau + TD_{m,D} \quad (8)$$

From (6), it is not difficult to find that transferring a packet in a multi-hop manner may remarkably decrease the overall power consumption compared with transferring the packet directly in some cases. For example, assume that the satellites that carry routers $R_0 \sim R_m$ (denoted as $M_0 \sim M_m$) are in a formation of ‘string-of-pearls’, where M_0 and M_m locate at two ends of the string, and the rest satellites distribute equidistantly between M_0 and M_m . Then, the overall power consumption for transferring a packet successively passing through $M_1 \sim M_{m-1}$ from R_0 to R_m with m -hops is $m^{(1-\alpha)}$ times of that for transferring the packet directly. Although it is effective for power saving, the penalty is that multi-hop transfer will take much more time.

From the designers’ point of view, the power consumption is expected to be as low as possible. Meanwhile, the transfer time delay has to meet the strict real-time constraint. Let power consumption be the optimization objective and transfer time delay be the constraint, then the swarm network routing problem can be modeled as a constrained optimization problem, which is formally formulated as:

$$\begin{cases} \text{Given } N_S, N_D \\ \text{Find } \{R_0, R_1, \dots, R_m\} \\ \text{Min } PC = N \times E_b \times \sum_{i=0}^{m-1} d_{i,i+1}^\alpha \\ \text{s.t. } TD_{S,0} + m \times \tau + TD_{m,D} \leq TD_C \end{cases} \quad (9)$$

where TD_C is the end-to-end time delay constraint pre-defined according to the task requirement. For N and E_b are constants, (9) is equivalent to

$$\begin{cases} \text{Given } N_S, N_D \\ \text{Find } \{R_0, R_1, \dots, R_m\} \\ \text{Min } \sum_{i=0}^{m-1} d_{i,i+1}^\alpha \\ \text{s.t. } m \leq \left\lfloor \frac{TD_C - TD_{S,0} - TD_{m,D}}{\tau} \right\rfloor \end{cases} \quad (10)$$

3.2 Routing Algorithm Implementation

The main purpose of this section is to illustrate the implementation of the algorithm. Main procedure of the algorithm is presented in Algorithm 1 using pseudo code. Giving the graph model $G = \langle V, E, W(t) \rangle$ of a swarm network, a pre-specified source node v_s , and a hop limitation L_{hop} as inputs, Algorithm 1 is used to compute the optimized routing paths from v_s to each $v_i \in V$ with hop limitation L_{hop} . Here we say that a path is optimized if the path is a minimum weight path between two specific nodes in G with bounded length L_{hop} (Table 1).

Table 1. Routing optimization algorithm.

Algorithm 1. Routing Optimization Algorithm

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1: input: graph model of a swarm network  $G=<V, E, W(t)>$ ; source node  $v_s$ ;
   hop limitation  $L_{hop}$ .
2: output: optimized routing paths from  $v_s$  to each  $v_i \in V$  with hop limitation
    $L_{hop}$ , i.e.  $P_{route} = \{p_{si} \in P_{min}(v_s, v_i, L_{hop}) \mid v_i \in V\}$ .
3: begin
4: /* initialization*/
5: for  $i=1$  to  $|V|$ 
6:    $p_{si} = v_s \rightarrow v_i$ ;
7:    $p'_{si} = p_{si}$ ;
8:    $improved = 0$ ;
9: end for
10: /* main loop*/
11: for  $hop=1$  to  $L_{hop}-1$  do
12:   foreach  $p_{si}$  whose length is equal to hop do
13:     foreach  $v_j \in V$  do
14:       if  $w(p_{si}, t) + w(e_{ij}, t) < w(p'_{sj}, t)$  then
15:          $p'_{sj} = p_{si} \rightarrow v_i \rightarrow v_j$ ;
16:       end if
17:     end foreach
18:   end foreach
19:   for  $i=1$  to  $|V|$ 
20:     if  $w(p'_{si}, t) < w(p_{si}, t)$  then
21:        $p_{si} = p'_{si}$ ;
22:        $improved = 1$ ;
23:     end if
24:   end for
25:   if  $improved==0$  then
26:     break;
27:   end if
28: end for
29: end

```

4 Examples and Discussions

4.1 Experiment Scenarios and Items

In this section, some examples will be presented to test and evaluate the routing protocol and algorithm we proposed. Assume that the swarm is composed of eight satellites, in which the satellites are required to stay within a bounded range $D_{max} = 10$ km.

The osculating orbital elements of each satellite at the initial time are listed below in Table 2. Data used in the experiments can be calculated from the initial conditions.

Table 2. Osculating orbital elements of satellites at initial time

Satellite no	a (km)	e	i (rad)	Ω (rad)	ω (rad)	M (rad)
1	7044.7770	0.0017655062	1.7135689	0.41960884	0.71080177	5.8878418
2	7044.7959	0.0019333002	1.7141038	0.41978852	0.61962430	5.9790881
3	7044.7543	0.0017789350	1.7136303	0.41962750	0.70051393	5.8983631
4	7044.7585	0.0018306072	1.7137249	0.41966203	0.71456895	5.8840353
5	7044.8015	0.0018911526	1.7138806	0.42000115	0.82386247	5.7748226
6	7044.7924	0.0017659261	1.7135688	0.41970884	0.71606259	5.8830248
7	7044.7999	0.0017710582	1.7135765	0.41961160	0.71162926	5.8867685
8	7044.8003	0.0019047291	1.7138145	0.41967736	0.70718406	5.8914562

As we have stated, the main objective of our network routing algorithm is to minimize the total transmission power consumption of the satellites with the transfer time delay, or equivalently the hop limitation, as constraint. So, the performance for power saving of the algorithm is the first priority to be tested. Normalized power consumption index, denoted as PC_{norm} , is used as the criterion for evaluation, which is defined as

$$PC_{\text{norm}} = \frac{PC_{\text{route}}}{PC_{\text{direct}}} \quad (11)$$

where PC_{route} and PC_{direct} are respectively the total transmission power consumption of satellites in the swarm for transferring the packets with and without multi-hop routing in a specified time interval.

4.2 Results of Centralized Organization

For centralized organization, we assume that all the satellites in the swarm could be selected as the leader. So, there are 8 cases. In each case, the network communication traffic is assumed to be as follows: every second, the leader polls all the followers in the swarm by sending polling packets to them one by one; once a follower is polled by the leader, it replies an acknowledgement packet to the leader immediately. Each packet is transferred from the source to the destination with multi-hops, where the hop limitation could be 2 to 7 according to different real-time demands, and all the packets are assumed to be of the same size in order to simplify the discussion.

The results of PC_{norm} at each second for the 8 different cases are illustrated in Fig. 3. For each case, several curves are plotted according to the experimental data of different hop limitations L_{hop} . On each curve, there are about 3000 samples, which correspond to the results of PC_{norm} at second i ($i = 0, 1, \dots, 3000$). From Fig. 3 we can see that, for all the 8 cases (i.e. no matter which satellite is designated as the leader), with hop

limitation $L_{hop} \geq 2$, the value of PC_{norm} at each second is less than 1, exactly it is between about 0.4 to 0.8. This means that, using our algorithm can considerably reduce (about 20% to 60% for different situations) the total transmission power consumption of the satellites at each second, with the real-time requirement being considered. For the 8 cases, the optimization degrees of power consumption are different, because their dataflow relations are various. Focusing on a specific one of the 8 cases (i.e. a specific sub-figure in Fig. 3) we can see that, the looser the hop limitation is the better the effect of power saving will be. Besides, for each curve in the sub-figure, its value varies with time because topology of the swarm changes from second to second.

Results in Fig. 3 shows that, the routing optimization algorithm we proposed is well suitable for power saving in the swarm network with centralized organization.

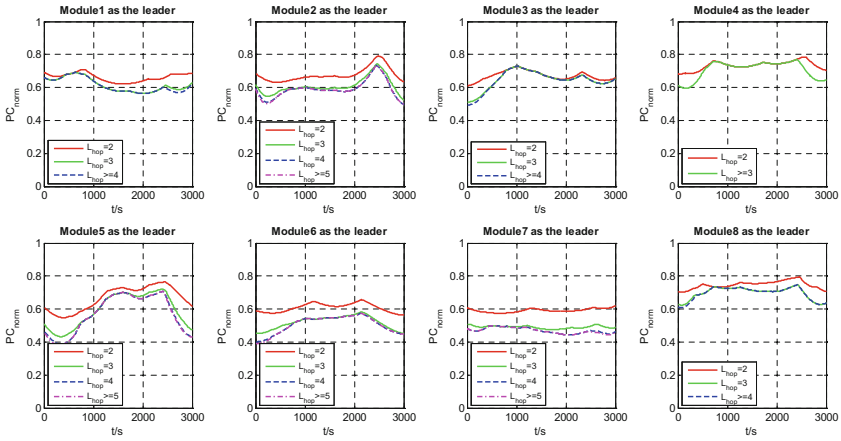


Fig. 3. Results of PC_{norm} at each second for different cases in centralized organization

4.3 Results of Distributed Organization

In a distributed organized swarm, all the satellites are of the same probability to transfer data to the other satellites. So we assume that, in each second there is a mutual communication (i.e. packet transfer) between each pair of satellites, and all the packets are of the same size.

For the network communication specified above, the results of PC_{norm} at each second for different hop limitations are illustrated in Fig. 4, which show that our algorithm performs well in each second for power saving, and the looser the hop limitation is the better the performance will be.

Results in Fig. 4 shows that, the routing optimization algorithm we proposed is well suitable for power saving in the swarm network with distributed organization.

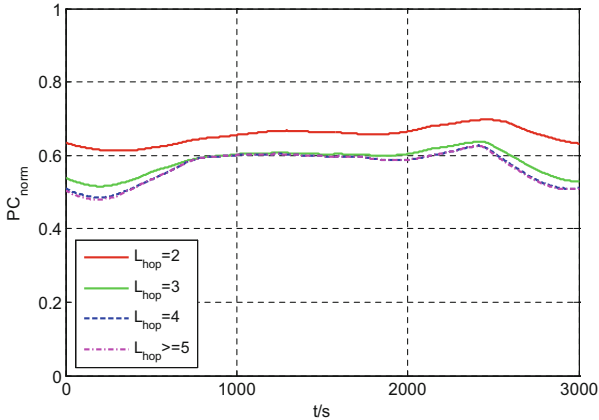


Fig. 4. Results of PC_{norm} at each second in distributed organization

5 Conclusions

The protocol and algorithm for optimal routing in swarm networks of cooperative microsatellite swarm network were studied in this paper. The path addressing based packet format and the header deletion technique based packet routing scheme were proposed. The transfer time delay constrained and transmission power consumption optimized routing algorithm was devised. Examples with different experiment scenarios were provided to demonstrate the efficiency of the proposed routing algorithm. The experimental results shown that, our algorithm is very effective in transmission power saving for both centralized-organized and distributed-organized swarm networks.

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