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A multi-path routing algorithm of LEO satellite networks based on an improved ant colony system①

Wang Houtian (王厚天)②* **, Zhang Qi* **, Xin Xiangjun* **, Tao Ying***, Chen Dong***, Liu Naijin***
(* School of Electronic Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, P. R. China)
(** State Key Lab of Information Photonics and Optical Communication, Beijing 100876, P. R. China)
(*** China Academy of Space Technology (CAST), Beijing 100094, P. R. China)

Abstract

Geography rectangle is used to reduce signaling overhead of the LEO satellite networks. Moreover, a multi-path routing algorithm based on an improved ant colony system (MPRA-AC) is proposed. Matrix indicating the importance of the link between satellites is introduced into MPRA-AC in order to find the optimal path more quickly. Simulation results show that MPRA-AC reduces the number of iterations to achieve a satisfactory solution. At the same time, the packet delivery ratio of LEO satellite networks when running MPRA-AC and DSR-LSN (dynamic source routing algorithm for LEO satellite networks) is compared. The packet delivery ratio is about 7.9% lower when running DSR-LSN. Moreover, because of the mechanism of active load balancing of MPRA-AC, simulation results show that MPRA-AC outperforms DSR-LSN in link utilization when data packets are transmitted in the networks.

Key words: ant colony algorithm, low earth orbit (LEO), packet delivery ratio, routing, satellite networks

0 Introduction

The current trend toward the migration to all IP-based services opens new opportunities to low earth orbit (LEO) satellite systems. LEO satellite networks have a feature of covering a wide range of area. And it can meet the requirements of high bandwidth and low end-to-end delay. So transmitting data via satellite links has attracted world-wide attention. How to design an efficient, reliable and flexible routing algorithm is a big challenge to the satellite networks.

Routing mechanism of satellite networks is divided into two categories, namely static routing mechanism and dynamic routing mechanism. The static routing algorithm[1] makes use of the periodicity and predictability of the LEO satellite networks and packets are sent according to the routing table pre-calculated, so this algorithm can keep complexity and signaling overhead to a low level. But sometimes the optimal path cannot be found because the static routing algorithm is not able to adapt the diversification of the inter-satellite links and network load. The dynamic routing algorithm[2-8] can adaptively update its path when network traffic or link delay changes, thus it can ensure the efficiency of packet forwarding.

On-demand routing is a reactive dynamic routing mechanism[9-13]. In recent years, how to implement the on-demand routing protocol in the satellite networks is one of the hotspots in the fields of satellite communication. A location-assisted on-demand routing (LOAR) protocol for LEO satellite networks that employs inter-satellite link (ISL) has been proposed[9]. LOAR can be viewed as a variant of the ad-hoc on-demand distance vector (AODV) routing algorithm.

Dynamic source routing algorithm in LEO satellite networks (DSR-LSN) is also proposed[11]. This algorithm adopts the strategy of constructing virtual nodes and uses the concept of restricted route request area to minimize the related overhead. But when the satellite networks are congested, the performance of this algorithm descends.

Ant colony algorithm is a new kind of optimization algorithm, first proposed by an Italian scholar Dorigo in

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② To whom correspondence should be addressed. E-mail: wanghoutian32@sina.com
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1991[14]. It has the characteristics of parallelism and robustness and has been successful in solving the traveling salesman problem (TSP) and some other assembled optimization problems. The principle of the ant colony algorithm is that it chooses the route by probability. It makes use of forward ants and backward ants to discover routes. In this paper, we take advantage of the ant colony algorithm and try to use this algorithm in the routing computing of satellite networks. In order to let the algorithm converge rapidly, the original ant colony algorithm is improved. The rest of the paper is structured as follows. The system model and QoS goal are presented in Section 1. The principle of algorithm is illustrated in Section 2. In Section 3 simulation results are presented and discussed, while concluding remarks are drawn in Section 4.

1 System model and QoS goal

1.1 System model

The system model is shown in Fig. 1. In this paper, an Iridium-like satellite constellation is considered for our study. There are two intra-plane ISLs (namely, links to the adjacent satellites in the same orbital plane) and two inter-plane ISLs (that is, links to the neighboring satellites in the right-hand and left-hand orbital planes). While intra-plane ISLs are maintained for the whole satellite period, inter-plane ISLs are broken as satellites come close to the poles due to adverse pointing and tracking conditions, when satellites move to lower latitudes, inter-plane ISLs are reestablished. Moreover, cross-seam ISLs, namely links between satellites in counter-rotating orbits, are not used.

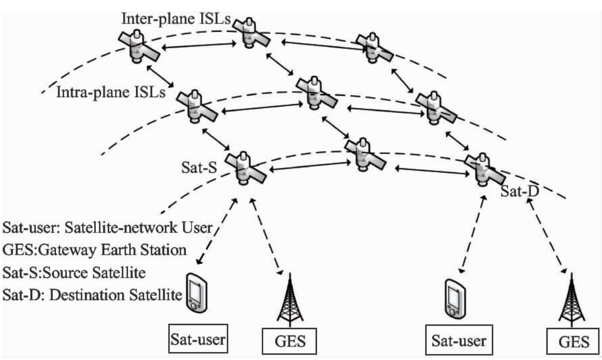


Fig. 1 The LEO satellite networks

According to the geographical location (longitude and latitude) of every satellite, the distance between satellites can be figured out. Fig. 2 shows the spherical coordinates system. Its center is geocentric, and Z axis is agreed with rotating axis of the earth. $(R, \theta, \Phi) = (6378\text{Km}, \pi/4, 0)$ is corresponding to 0°longitude of the earth equator.

The calculation formulas for the three-dimensional coordinate of satellite nodes are as follows:

$$x = R \times \sin(\theta) \times \cos(\phi) \quad (1)$$

$$y = R \times \sin(\theta) \times \sin(\phi) \quad (2)$$

$$z = R \times \cos(\phi) \quad (3)$$

Supposing the coordinates of two satellites are (x_1, y_1, z_1), (x_2, y_2, z_2), then the distance between them is

$$dis = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \quad (4)$$

The spread delay equals to the distance divided by the speed of light. That is

$$delay_{tra} = dis/(3 \times 10^8) \quad (5)$$

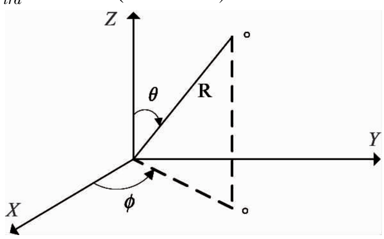


Fig. 2 Satellite coordinate diagram

1.2 QoS goal

In this paper, residual bandwidth and delay metrics of the ISL are used for QoS routing of an application. Thus, path $P(Src, Des)$ should satisfy the following constraints for an application to begin and progress, where Src refers to the source satellite, Des refers to the destination satellite and l_{same} refers to the similarity coefficient between the main path and the alternate path. This paper makes use of the method in Ref. [15] to calculate the similarity coefficient, and chooses the main path and the alternate path from the path set P that satisfies the constraints in Eq. (6). The length of the main path is the shortest and the alternate path has the minimum similarity coefficient with the main path, which is shown in Eq. (6).

$$\begin{aligned} &\min l_{same} \\ &\sum_{(u,v) \in P(src,des)}^{des} delay(u,v) \leqslant De \\ &\min_{(u,v) \in P(src,des)} bw(u,v) \geqslant B \end{aligned} \quad (6)$$

where De refers to the maximum delay the LEO satellite networks can tolerate and B refers to the minimum bandwidth constraints of the LEO satellite networks.

1.3 Routing table structure

The structure of the routing table is shown in Table 1. The routing table consists of three entries named destination, route and delay. The destination entry indicates the destination satellite node. For each destination, we have two paths, namely the main path and the alternate path. A route entry is a list of satellite IDs along the route. The delay entry shows the end-to-end delay along the route.

Table 1 Satellite routing table

Destination	Route	Delay (ms)
205	102 103 104 105 205	70
	102 202 203 204 205	80
…	…	…

The routing table updates itself at a specified time interval. Moreover, the routing table in each satellite is not the same. The source satellite only saves routes to destination satellites that communicate with it in the update cycle.

2 The multi-path routing algorithm based on ant colony systems

2.1 The principle of geography rectangle

As is shown in Fig. 3, LEO satellite networks can be modeled as a graph $G(V, E)$, where V is the set of satellite nodes and E is the set of ISLs. It is clear that the size of V is $|V| = N \times M$, where M is the number of the orbital planes and N is the number of satellites per plane. In this graph, each satellite is uniquely defined by the pair of virtual coordinates (x, y), where x and y denote the orbital plane and the position of the satellite in this plane respectively. Clearly, $x \in [0, M)$, $y \in [0, N)$. Assume that a ground terminal served by the jth satellite in the ith orbital plane (hereafter referred to as the source satellite with virtual coordinates $x_{src} = i$ and $y_{src} = j$) communicates with a ground terminal that is covered by the lth satellite in the kth orbital plane (hereafter referred to as the destination satellite with virtual coordinates $x_{dst} = k$ and $y_{dst} = l$). S_x and S_y

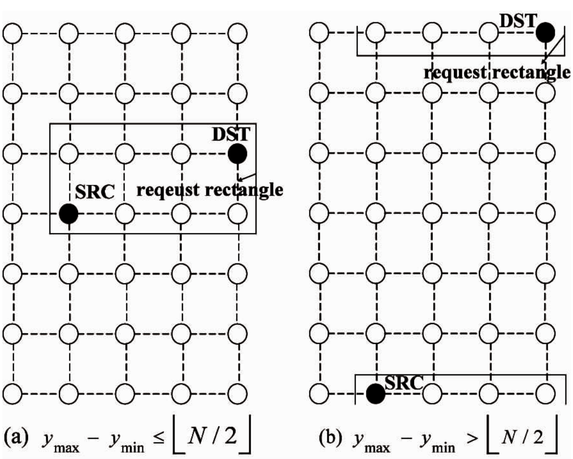


Fig. 3 Request area formation

are used to represent the sets of acceptable values for virtual coordinates of satellites in the request area. It is clear that $S_x = [x_{min}, x_{max}]$ with $x_{min} = \min[x_{src}, x_{dst}]$ and $x_{max} = \max[x_{src}, x_{dst}]$. As far as S_y is concerned, there are two alternatives for defining the rectangle area containing the source and destination satellites, that is

$$S_y = \begin{cases} [y_{min} - width, y_{max} + width], y_{max} - y_{min} \leqslant \lfloor \frac{N}{2} \rfloor \\ [0, y_{min} + width] \cup [y_{max} - width, M - 1], \\ \quad y_{max} - y_{min} > \lfloor \frac{N}{2} \rfloor \end{cases} \tag{7}$$

2.2 The rules of ant colony algorithm used in the routing strategy for LEO satellite networks

The improved ant colony algorithm proposed in this paper defines four kinds of matrix. These matrixes are described as follows:

$$\text{Distance matrix } \boldsymbol{D} = \begin{bmatrix} d_{00} & d_{01} & \cdots & d_{0n} \\ d_{10} & d_{11} & \cdots & d_{1n} \\ \cdots & \cdots & \cdots & \cdots \\ d_{n0} & d_{n1} & \cdots & d_{nn} \end{bmatrix}$$

$$\text{where } d_{ij} = \begin{cases} \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}, \\ \quad \text{sat } i \text{ is the neighbour of sat } j \\ 0 \quad ,\text{else} \end{cases}$$

$$\text{Pheromone matrix } \boldsymbol{\tau} = \begin{bmatrix} \tau_{00} & \tau_{01} & \cdots & \tau_{0n} \\ \tau_{01} & \tau_{11} & \cdots & \tau_{1n} \\ \cdots & \cdots & \cdots & \cdots \\ \tau_{n0} & \tau_{n1} & \cdots & \tau_{nn} \end{bmatrix}$$

Pheromone incremental matrix

$$\boldsymbol{\Delta\tau} = \begin{bmatrix} \Delta\tau_{00} & \Delta\tau_{01} & \cdots & \Delta\tau_{0n} \\ \Delta\tau_{01} & \Delta\tau_{11} & \cdots & \Delta\tau_{1n} \\ \cdots & \cdots & \cdots & \cdots \\ \Delta\tau_{n0} & \Delta\tau_{n1} & \cdots & \Delta\tau_{nn} \end{bmatrix}$$

Link importance matrix

$$\boldsymbol{Z} = \begin{bmatrix} z_{00} & z_{01} & \cdots & z_{0n} \\ z_{01} & z_{11} & \cdots & z_{1n} \\ \cdots & \cdots & \cdots & \cdots \\ z_{n0} & z_{n1} & \cdots & z_{nn} \end{bmatrix}$$

The key points of the proposed algorithm based on ant colony system are as follows:

(1) Define two kinds of ants, the forward ant and the backward ant. The forward ant is responsible for finding route from the source node s to the destination node d. When arriving at the destination node, the forward ant will change to backward ant and return along the original route.

(2) In this paper, the pseudo-random proportional selection rule[16] is used, which adopts the strategy of deterministic rules combined with random selection.

Ant k which is located at node i would choose the next node l through the following formula.

$$l = \begin{cases} \arg \max\limits_{u \in table_k} [\tau_{iu}(t)]^{\alpha}[\eta_{iu}]^{\beta} & \text{if} \quad q \leqslant q_0 \\ l & \text{if} \quad q > q_0 \end{cases} \tag{8}$$

here q is a random number which is even distribution in $(0, 1)$, and q_0 is a parameter $(0 < q_0 < 1)$, whose size reflects the relative importance of using priori knowledge and exploring of the new path. In the original ant colony algorithm, random variable l is chosen according to

$$p_{ij}^{k}(t) = \begin{cases} \dfrac{[\tau_{ij}(t)]^{\alpha}[\eta_{ij}]^{\beta}}{\sum\limits_{l \in table_k} [\tau_{il}(t)]^{\alpha}[\eta_{il}]^{\beta}} & l \in table_k \\ 0 & \text{else} \end{cases} \tag{9}$$

where $p_{ij}^{k}(t)$ is the probability of ant k going from node i to node j, in which $table_k$ represents the set of the next node which ant k can choose. $\tau_{ij}(t)$ is the information of path (i, j) at time t. $\eta_{ij}(t)$ is the reciprocal of distance of link (i, j), $\eta_{ij}(t) = 1/d_{ij}$. The relative importance of pheromone and distance can be controlled through setting the value of α and β.

The satellite network topology has particularity. That is, each satellite only has links with four adjacent neighbors. Assume that 102 is the source satellite and 407 is the destination satellite, the network topology is shown in Fig. 4.

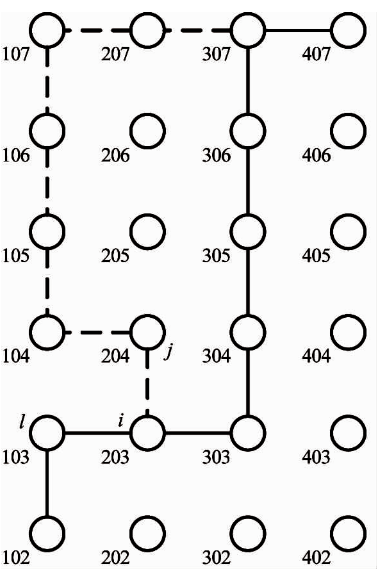


Fig. 4 The network topology

As is shown in Fig. 4, the paths calculated by the ant colony algorithm may be path1: 102-103-203-204-104-105-106-107-207-307-407 or path2: 102-103-203-303-304-305-306-307-407. It is clear that path2 has better performance than path1. In order to find the optimal path more quickly, link importance matrix Z is introduced in this paper. That is, link (i, j) is more important than link (i, l) if j is in the right side of i or j is above i but l is in the left side of i or l is below i. Assume that satellite j is the next hop of satellite i. The definitions used in this paper are shown as follows:

The matrix Z is defined according to Eq. (10).

$$z_{ij} = \begin{cases} 1 & (d_{ij} \neq 0 \&\& \mid d\_x - j\_x \mid > \mid d\_x - i\_x \mid) \\ 1 & (d_{ij} \neq 0 \&\& \mid d\_y - j\_y \mid > \mid d\_y - i\_y \mid \\ & \&\& y_{\max} - y_{\min} \leqslant \lfloor M/2 \rfloor) \\ 1 & (d_{ij} \neq 0 \&\& \mid 11 - (d\_y - j\_y) \mid > \\ & \mid 11 - (d\_y - i\_y) \mid \&\& y_{\max} - y_{\min} > \lfloor M/2 \rfloor) \\ 2 & (d_{ij} \neq 0 \&\& else) \\ 0 & (d_{ij} = 0) \end{cases} \tag{10}$$

The random variable l is chosen according to

$$p_{ij}^{k}(t) = \begin{cases} \dfrac{[\tau_{ij}(t)]^{\alpha}[\eta_{ij}]^{\beta}[z_{ij}]^{r}}{\sum\limits_{l \in table_k} [\tau_{il}(t)]^{\alpha}[\eta_{il}]^{\beta}[z_{il}]^{r}} & l \in table_k \\ 0 & \text{else} \end{cases} \tag{11}$$

where $\alpha + \beta + r = 1$. The relative importance of matrices $\boldsymbol{\tau}$, $\boldsymbol{D}$ and $\boldsymbol{Z}$ can be controlled through setting the value of α, β and r.

(3) When ant k goes through link (i, j), the pheromone should be updated according to

$$\tau(i, j, k) = (1 - \rho)\tau(i, j, k) + \Delta\tau_{ij} \tag{12}$$

(4) The definition of pheromone increments in the original ant colony algorithm is shown as

$$\Delta\tau_{ij} = \frac{Q}{d_{ij}} \tag{13}$$

where $\boldsymbol{Q}$ is a constant and d_{ij} is the distance between satellite i and satellite j. In order to reduce the number of iterations to achieve a satisfactory solution, we revise the method to calculate the pheromone increments. In this paper,

$$\Delta\tau_{ij} = \frac{Q \times z_{ij}}{d_{ij}} \tag{14}$$

It can be learned from Eq. (14) that the pheromone increment of link (i, j) is in direct ratio to the importance of this link.

2.3 Multi-path routing algorithm based on an improved ant colony system (MPRA-AC)

The multi-path routing algorithm based on an improved ant colony system (MPRA-AC) for LEO satellite networks is shown in Fig. 5. The routing algorithm proposed in this paper learns from on-demand driven protocols. That is, the nodes do not need to maintain the information of the whole network, the source node runs MPRA-AC only when the nodes need to communicate but do not have route passing to the destination node. The routing algorithm is described as follows:

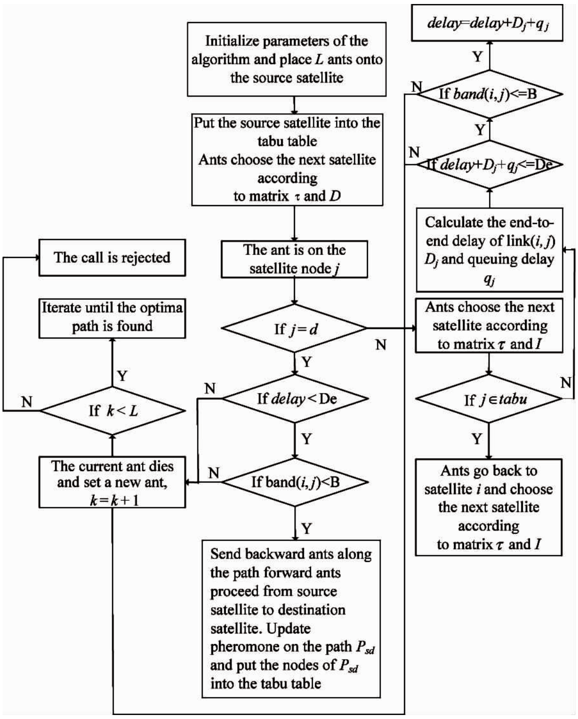


Fig. 5 The improved ant colony algorithm

(1) When the source node wishes to send data to the destination node, it should be found that whether routing table s has routing information to the destination d firstly, data packets will be sent directly when the routing table s exists routing information, otherwise, going to (2).

(2) Place L forward ants onto the source satellite node. Let them find route at the same time, then select a satellite node from $table_k$ as the next hop. The format of forward ant packet is as follows:

< *source _ addr*, *dest _ addr*, *route _ path*, *delay*, *tabu _ list* >

The *source _ addr* field indicates the ID of the source satellite, the *dest _ addr* field indicates the ID of the destination satellite, the *route _ path* field indicates one path from the source satellite to the destination satellite, the *delay* field indicates the sum of the delays along the path and the *tabu _ list* field indicates the satellites this forward ant has passed. The *tabu _ list* field is used to prevent routing loops.

(3) When the intermediate satellite node j receives forward ant k from node i: (a) To check whether the current node address is included in the tabu list of ant k, if so, go back to satellite node i and select a node from $table_k$ as the next hop again. (b) To check whether the value of the *delay* field in the forward ant packet is larger than De in Eq. (6), if so, make the forward ant die to reduce flood. To compute the delay of the path, the accumulating strategy is adopted. When the forward ant is forwarded by the nodes in the network, each node appends its link delay to the *delay* field. Let D_j be the propagation delay of the forward link from the source satellite to the destination satellite passing j and q_j be the queuing delay of this link, then the value of the delay is updated according to

$$delay = delay + D_j + q_j \tag{15}$$

(c) To check whether the residual bandwidth (*band*) of the forward link from the source satellite to the destination satellite passing j is smaller than B in Eq. (6), if so, make the forward ant die to reduce flood. Suppose that BW_j is the bandwidth of the forward link and Q_j is the mean queue length of this link. The residual bandwidth is calculated according to

$$band = BW_j - Q_j \tag{16}$$

If none of the above is satisfied, transfer to (4).

(4) **Step 1**: Calculate the transmission time of link (j, l) according to the distance between satellite j and satellite l.

Step 2: Calculate p_{jl} between current node and downstream node l according to d_{jl}, τ_{jl} and z_{jl} in Eq. (8) and Eq. (11).

Step 3: Update pheromone τ_{jl} according to Eq. (14).

When the first forward ant reaches the destination node, the destination node delays time T_{delay} to obtain the information of other routing. When all the ants arrive at the destination node or are declared to die, the destination satellite node selects the paths according to the *route _ path* field. The path that has the minimum delay is taken as the main path. In this paper, alternate path is select according to not only the entire route path but also similarity between the current path and the main path. In order to judge whether a path is similar to the main path or not, similarity coefficient is used to describe the degree of how they are similar. The path having the smallest similarity coefficient with the main path is chosen as the alternate path.

3 Simulation results

In this section, the performance of MPRA-AC is studied. All the simulations are performed with the simulation tool OPNET 14.5 on core I3 processor (3.3GHz clock). The OPNET simulator has three logical levels: network level (a LEO satellite system has been considered, together with satellite terminals), node level (consisting of all the algorithms of the protocol stack), and process level (finite state machine (FSM) developed in C that implements the proposed algorithms and the associated protocols). Table 2 gives the simulation parameters.

Table 2 Parameters for simulation

Parameters	Value
ISL queue length	1250 packets
ISL bandwidth	10Mb/s
Bandwidth required (B)	200kb/s
Delay bounds (De)	300ms

Table 3 tabulates the parameters of traffic bursts. According to Table 3, the chosen bitrates produce average (over both On and Off periods) bitrate values that are about 60 ~ 160Kb/s per earth station, which can be considered reasonable for a real-life scenario.

Table 3 Traffic generator's parameters

Packet size	1000 bytes
"On" period	0.2s
"Off" period	0.8s
Bit rate during "On" period	60 ~ 160kb/s

Iridium system, shown in Fig. 6, can realize global coverage, so the location of the source user terminal and the destination user terminal is arbitrary. In this subsection, three sets of simulations are conducted. In each scene, the location of the source user terminal and the destination user terminal is iconic and both user terminals are distributed according to the hot spot scenario described in Ref. [17]. In order to illustrate the performance of the improved ant colony algorithm, performance comparisons are carried out between the original algorithm and the improved algorithm. The parameters of ant colony algorithm are as follows: $\alpha = 0.4$, $\beta = 0.3$, $r = 0.3$, $Q = 10^5$, $q_0 = 0.5$, $\rho = 0.5$.

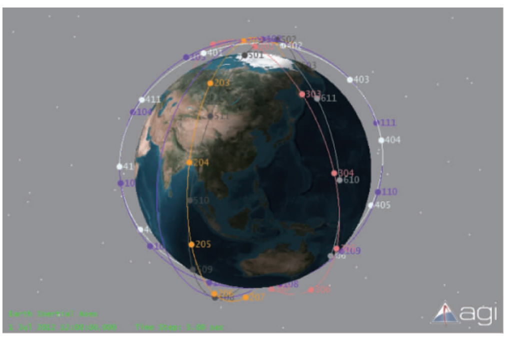
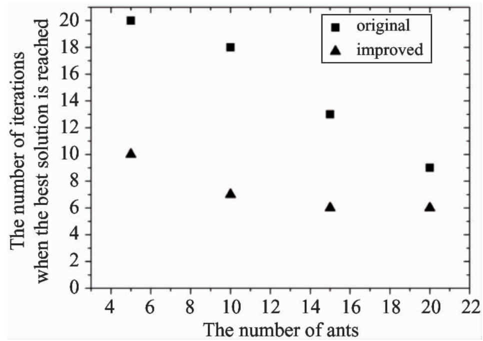
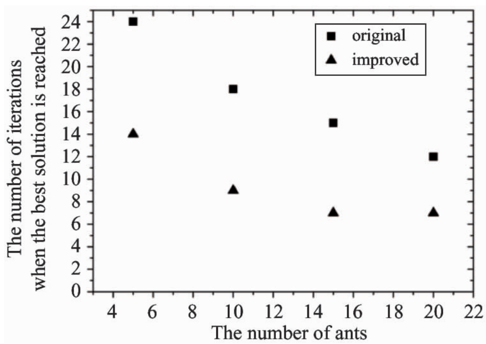


Fig. 6 The Iridium system

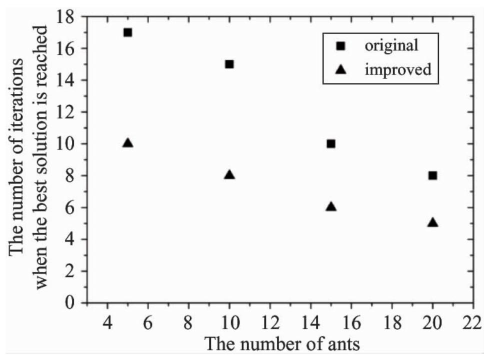
It has been shown in Fig. 7 that when the best solution is reached, the average number of iteration is 8 on the condition that the improved ant colony algorithm is made use of. But when the original ant colony algorithm is used, the average number of iteration is about 14. So it can be concluded from Fig. 7 that the proposed ant colony algorithm in this paper reduces the number of iterations to achieve a satisfactory solution.



(a) $N40°$, $E120°$ ~ $N45°$, $E15°$



(b) $N40°$, $W100°$ ~ $N40°$, $E120°$



(c) $N45°$, $E15°$ ~ $S15°$, $W50°$

Fig. 7 Comparison of the original algorithm and the improved algorithm

In this subsection, the performance of MPRA-AC and DSR-LSN is also compared when a satellite in the main path congests. The reason we choose DSR-LSN is that DSR-LSN consists of such main mechanisms as path discovery process and path reply process, which is similar to ant's looking for paths in the ant colony algorithm and it is also designed for LEO satellite network. Fig. 8 shows the throughput of the ground terminal that receives data packets.

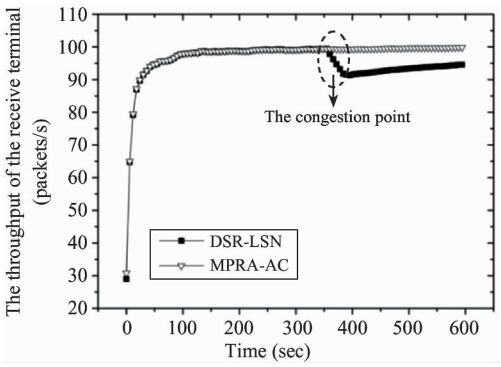


Fig. 8 The throughput of the ground terminal that receives data

It can be seen from Fig. 8 that before the satellite networks become congested, the throughput of the ground terminal that receives data packets is the same when we run MPRA-AC and DSR-LSN. After the network congests, the packet drop rate is lower when running MPRA-AC. As time goes by, the packet delivery ratio tends to be the same for both algorithms. The reason is that the shortest path from SRC to DST is not fixed due to the instability of the satellite networks.

Fig. 9 reveals the positive characteristic of MPRA-AC. When the satellite network becomes congested, MPRA-AC appears to be immune to such a decrease. Furthermore, it can be concluded from Table 4 that the packet delivery ratio is about 7.9% higher when running MPRA-AC.

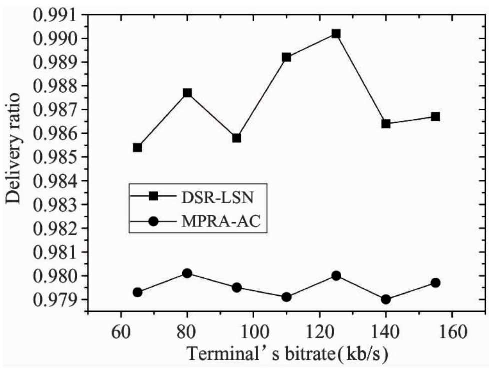


Fig. 9 Delivery ratio versus terminal's bitrate

Table 4 The delivery ratio for MPRA-AC and DSR-LSN

	MPRA-AC	DSR-LSN
65(kb/s)	0.9854	0.9793
80(kb/s)	0.9877	0.9801
95(kb/s)	0.9858	0.9795
110(kb/s)	0.9892	0.9791
125(kb/s)	0.9902	0.9800
140(kb/s)	0.9864	0.9790
155(kb/s)	0.9867	0.9797

In this section, the average utilization of all ISLs over the whole constellation is compared between MPRA-AC and DSR-LSN. According to Ref. [1], LEO satellite networks are modeled as a Finite State Automation (FSA) based on the observation that the orbit movement in LEO satellite networks is periodic. Since satellite networks run regularly in space, the running cycle is divided into S time intervals. Indicator random variable is used to indicate whether link $i \rightarrow j$ is utilized or not, shown in Eq. (17).

$$I_{i\rightarrow j} = \begin{cases} 1 & \text{link } i \rightarrow j \text{ is utilized} \\ 0 & \text{link } i \rightarrow j \text{ is notutilized} \end{cases} \tag{17}$$

So the average utilization of link $i \rightarrow j$ can be calculated according to

$$U = \frac{\sum_{k=1}^{S} (I_{i\rightarrow j})_k}{S} \tag{18}$$

Fig. 10 shows the link utilization between MPRA-AC and DSR-LSN.

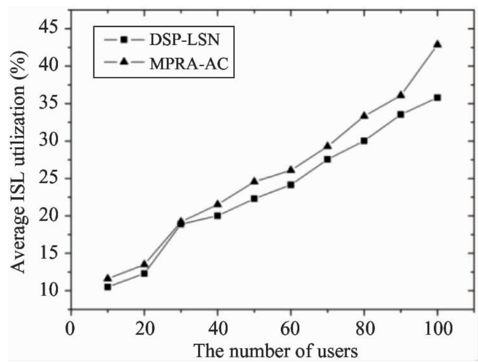


Fig. 10 ISL utilization

As is shown in Fig. 10, MPRA-AC outperforms DSR-LSN. This is because of the mechanism of active load balancing of MPRA-AC. DSR-LSN always tends to select the shortest path, which increases the burden of the shortest path. MPRA-AC can inherently offer multi-paths. That means the shortest path will not be greedily selected when data packets are transmitted from source satellite to destination satellite.

4 Conclusions

In this work, the performance of an improved ant colony algorithm and its application in multi-path routing in LEO satellite networks are evaluated. In order to diminish the signaling overhead introduced in the system, the routing algorithm in this paper utilizes a geography rectangle area. Furthermore, MPRA-AC improves the method to calculate pheromone increments and the probability of one ant to choose the next satellite node in the original ant colony algorithm. Thirdly, MPRA-AC designs a method to store the information on alternate paths in satellite networks. MPRA-AC is compared with DSR-LSN. The simulation tool OPNET has been adopted in this paper, simulation results show that MPRA-AC reduces the number of iterations to achieve a satisfactory solution. Compared with DSR-LSN, the packet delivery ratio is about 7.9% higher when running MPRA-AC. Moreover, MPRA-AC outperforms DSR-LSN in link utilization because of the mechanism of active load balancing of MPRA-AC. MPRA-AC improves the robustness of the LEO satellite networks.

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Wang Houtian, received the BE degree in communication engineering from Xi'an University of Posts and Telecommunications, P. R. China, in 2009. He is currently working toward his Ph. D degree in Beijing University of Posts and Telecommunications (BUPT). His research interests are in the field of designing routing algorithm and radio resource management in satellite networks.