Link Assignment and Information Transmission Route Planning for BDS Inter-satellite Link Network

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Abstract. Satellites of the third generation BeiDou Navigation Satellite System (BDS) will be equipped with Ka-band antennas and communicate through point-to-point Inter-Satellite Links (ISLs). Link assignment and routing algorithms of other Global Navigation Satellite Systems (GNSSs) are not suitable for BDS ISL due to its unique communication system. This article mainly focuses on inter-satellite link assignment and routing problem in BDS ISL network which is a new challenge and has no mature algorithm proposed specially for it before. Firstly, time slot matrix assigning algorithm is put forward to solve link assignment problem based on characteristic of BDS ISL. Performance of this algorithm is simulated and ISL network topology designed by this algorithm is proved to be good in aspects of average number of links, average position dilution of precision (PDOP) and other important indicators. Secondly, on the basis of determined network topology, this paper provides a heuristic route planning strategy for information transmission in BDS ISL network. Path Combinational Optimization algorithm based on Simulated Annealing (PCO-SA) is proposed and elaborated in this paper. By combining PCO-SA and adjusted Contact Graph Routing (CGR) algorithm, a common solution for routing problem of navigation related data can be achieved. Simulation results compared with other route planning methods show that PCO-SA can not only significantly increase success ratio of route planning, but also optimize average time delay and hop of planned path.

Keywords: BDS · Inter-satellite link · Link assignment · Route planning · Simulated annealing

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1 Introduction

BeiDou Navigation Satellite System is a global satellite navigation system independently constructed by China. It aims to provide high accurate positioning, navigation and timing services. In accordance with the construction plan, satellite constellation of the third generation BDS will be composed with three Geostationary Earth Orbit (GEO) satellites, three Inclined Geosynchronous Satellite Orbit (IGSO) satellites and 24 Medium Earth Orbit (MEO) satellites [1] (In the rest of this article, BDS refers to the third generation BDS if not specifically declared). It is impossible for domestic monitoring stations in China to track and communicate with all satellites all day long. Therefore, inter satellite links (i.e., wireless links for communication and ranging between satellites) can be used to improve the service performance of the navigation satellite system [2].

ISLs were first implemented in the GPS Block IIR satellites [3]. GPS ISLs work in the ultrahigh frequency band. Every satellite transmits a ranging signal in its own scheduled slot, and all its visible navigation satellites can receive the signal. With the technique development, the wide beam ISL system will be gradually upgraded to narrow beam with time division to reach better pointing flexibility and higher communication efficiency [4, 5]. The GPS will upgrade its ISL to the Ka or V band in the next stage to enhance the ISL performance [6]. Exploratory studies carried for other GNSSs such as GLONASS and Galileo also demonstrate the narrow beam ISL system [7, 8]. In a word, other GNSSs are planning on developing narrow-beam ISL systems, but there is no mature implementation until now.

As for BDS, Ka-band phased-array antennas will be equipped on satellites of the third generation BDS to achieve precise orbit determination and autonomous navigation [9]. Satellites communicate with each other for inter-satellite ranging and data transmission via Ka-band point beam inter-satellite links. In this communication system, one satellite can only communicate with one other satellite through bidirectional ISL simultaneously. To achieve higher ranging accuracy, satellites are demanded to connect with other satellites within short time period. In addition, satellites create telemetry data constantly in its life cycle and receive commands from ground facilities intermittently. Data are downlinked and uplinked between space segment and ground segment. These demands bring two problems. The first one is link assignment problem, that is, how to arrange the ISL antennas to build link with other satellites ensuring both ranging observations' quantity and information transmission quality. The second one is how to plan routes for all information to be transmitted based on the ISL network determined in the first problem.

Link assignment for communication between satellites has been discussed in many literatures [10–14]. Efficient algorithms for broadband low earth orbit (LEO) satellite systems were put forward to avoid dynamics and enhance communication performance of inter satellite links. But these algorithms are not suitable for link assignment in BDS for the reason that point-to-point communication is used in BDS ISL which is completely different with the mature broadcast communication in GPS or other fully researched broadband communication. In addition, ranging channel and data channel are synchronous in BDS ISL. So when planning ISL network topology, ranging needs and data transmission needs should both be taken into consideration. Focusing on narrow beam link between navigation satellites, Yang et al. proposes a timeslot scheduling method to achieve more observation and faster transmission of telemetry data [15]. But BDS is consist of space segment and ground segment, so BDS ISL network is a generalized network including satellite nodes and ground station nodes, which is different from Yang's work. Besides, there are several types of information to be transmitted instead of only telemetry data.

When it comes to routing problem, BDS ISL network can be considered as a special kind of delay-tolerant network. Routing algorithms in delay tolerant network are usually reactive without full knowledge of information in advance [16, 17]. But in BDS ISL network, transmission tasks of various navigation information within a time period are usually known a prior. This is the first difference with other routing problems. In addition, routing plan in BDS ISL network has low failure tolerance due to limited connectivity. For these reasons, route planning can be transformed into combinational optimization problem, which is quite different from fully-researched reactive routing protocol. The path set can be programmed in advance by ground station facilities who have sufficient computing capability. Then satellites just connect with each other according to the plan, and communication tasks just go as expected.

In conclusion, the topology design and routing plan problem for BDS ISL network have quite unique characteristics and are lack of targeted research. Based on the characteristics of BDS ISL, this paper provides solution to solve the whole problem. Firstly, link assigning algorithm is put forward. The ISL link assignment problem is converted into solving time slot assignment matrix. The solution can not only satisfy the ranging needs, but also provide a good topology structure for data transmission. Then, the paper proposes the path combination optimization algorithm based on simulated annealing (PCO-SA). By combining PCO-SA and adjusted contact graph routing algorithm for path searching, route planning problem for variable navigation messages can be solved effectively.

The structure of this paper is as follows: Sect. 2 introduces the principle and processing method of link assignment for MEO ISL network of BDS. Link assigning algorithm with large average inter-satellite link number, small ranging PDOP, and high connectivity between ground and space segment is proposed. Section 3 provides a route planning scheme for BeiDou navigation data transmission based on the determined link topology. In Sect. 3, contact graph routing is adjusted and applied in path searching. And PCO-SA is proposed. In Sect. 4, the link assigning method and PCO-SA are simulated respectively. Performances of algorithms are demonstrated. Section 5 summarizes the work of this paper and looks forward to the future work in BDS ISL.

2 Inter-satellite Link Assignment in BDS

2.1 Link Assigning Principles in BDS ISL Network

Under the new challenge, ISL network including the whole constellation is too complicated with three various types of satellites. So it has to be noted that in this paper, we are concerned about and will focus on MEO satellites since they are main satellites to carry out navigation mission. In addition, ISL network in this article refers to generalized ISL network composed of satellite nodes and ground station nodes.

Due to the constraints of satellite platform and the signal system, inter-satellite link antennas equipped in each satellite are very limited. The "Point to Point" communication between satellites is realized by these limited Ka-band phased array antennas. The goal of the ISL communication is inter-satellite ranging and data transmission, and signal of these two tasks are modulated on the same carriers. So, the two tasks share the same ISL network topology simultaneously. Since inter-satellite ranging is the primary task, network topology should firstly meet its requirements and try to increase ranging accuracy. Meantime, satellites receive commands and transmit telemetry track and control (TT&C) data, navigation data and other data via links between satellites and the ground stations. It also brings requirements to ISL network topology.

In this paper, we assume that the one MEO satellite is equipped with only one Ka-band antenna. Considering the commands of inter-satellite ranging and data transmission in BDS ISL, we conclude the principles of link assignment and network topology design as follows:

- Satellites should establish links with as many other satellites as possible within link assigning time period. The links number and geometry configuration of linked satellites should ensure high ranging accuracy.
- To satisfy the communication tasks between the space segment and the ground segment, ground stations are supposed to establish satellite-ground links with their visible satellites as long as they can.

Refer to the finite state automaton framework proposed in [14], we take T as the minimum link assignment period. In every time period T, the visibility and the relative position among all nodes in the ISL network are assumed to be fixed.

T is equally divided into K segments and each segment is called time slot. The topological structure doesn't change with each slot. Switching of links and changes of topological structure occur at the instant when the slot starts and ends. Under this link processing mechanism, for each minimum assignment period T with S nodes in the network, the inter-satellite connection relationship can be represented by an S*K matrix, i.e., time slot assignment matrix.

2.2 Link Assigning Method for BDS ISL Network

In this section, according to the principles mentioned above, the method for inter-satellite link assignment problem is proposed. Time slot link assignment matrix generated by this method can provide good topology for both inter-satellite ranging and data transmission. The flow chart is shown in Fig. 1 below.

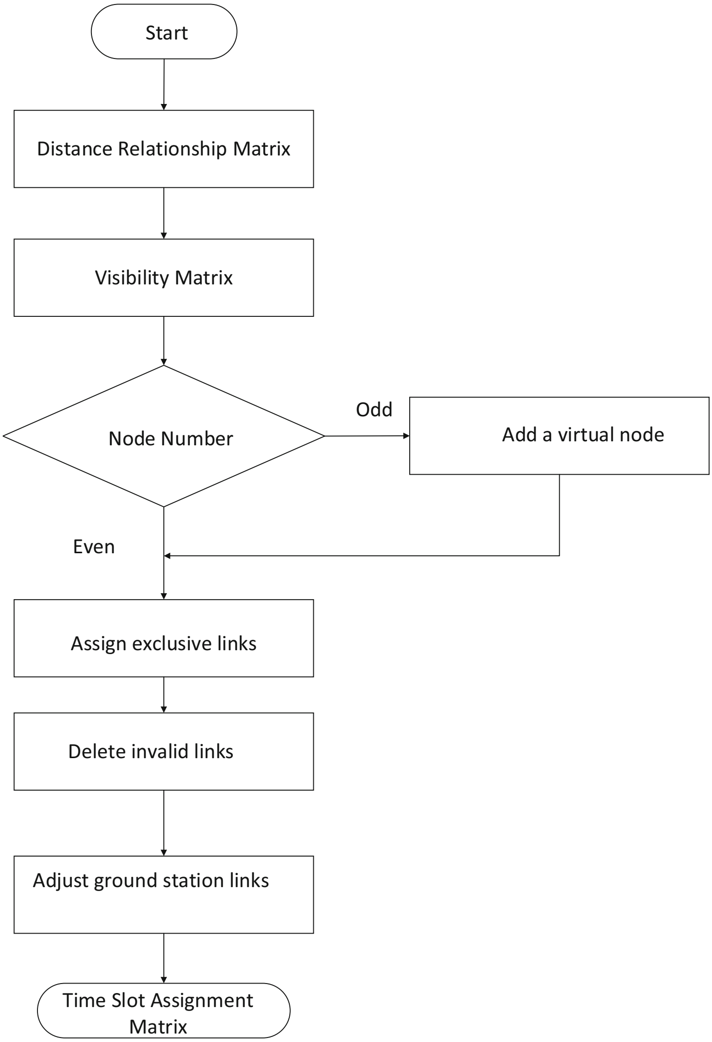

Fig. 1. Flow chart of the time slot matrix assignment algorithm

1. Firstly, we create the distance matrix, $D = \left[d_{i,j}\right] \in R^{N\times(N-1)}$, to represent the distance sequence between pairs of nodes. N denotes the total number of nodes in the ISL network. $D(i,:)$ is sorted from near to far by distance from other nodes to node i;
2. Then, we create the visibility matrix V. $V = \left[v_{i,j}\right] \in R^{N\times N}$ denotes the visible relationship among all pairs of nodes within T. $\mathrm{v_{i,j}} = 0$ means that node i and node j are invisible within T. Conversely, $\mathrm{v_{i,j}} = 1$ means this pair of nodes has the opportunity to contact with each other;
3. Preprocess when nodes number is odd: when the number of network nodes is odd, a pseudo node will be added and the total number O equals to N + 1. If N is even,

preprocessing is omitted, and O = N. The pseudo node is a virtual blank node with no position information. But we enforce it to be the farthest from any real node;

4. Assign exclusive links: we create the matrix $L = \left[l_{i,j}\right] \in R^{O\times(O-1)}$, where $l_{i,j}$ is the linking node with node i in the j-th link combination case. There are four rules in generating matrix L:
   a. Matrix L is generated by column. In each column, nodes take turn to choose their connecting node. Ground stations go first, and satellites ranks according to their average distance with ground stations.
   b. When choosing linking nodes, nodes pair with the smallest distance takes the first priority for the sake of communication quality. Every node will choose the nearest node in its available nodes set according to distance matrix D. Available nodes set is updated for every node in case some of its available nodes are chosen and linked by other nodes and cannot build link once more in this slot. This step can be implemented by calling recursive function.
   c. For any node, repeating links are not allowed within T. There is no repeating element in each row of L. This rule is made to ensure link combinations represented by each column are exclusive.
   d. ISLs are bidirectional from one node to another. So there is no repeating element in each column of L. Nodes are in pairs, so

$$l_{l_{i,j},j} = i \tag{1}$$

5. Delete unpractical links: Considering actual visibility of the generated links, the unpractical links composed of invisible nodes should be deleted. Links containing pseudo nodes should be deleted too. We set corresponding $l_{i,j} = 0$ for all invalid links.
6. Adjust links from ground station: Due to far distance, visibility relationship between ground station and satellites is much tougher than that between satellites. After deleting unpractical links, ground station has more empty time slots. This violates the target to guarantee data transmission between the ground station and satellites segment. So in this step, empty elements in the row representing ground station will be filled with visible satellites circularly. Accordingly, if the newly filled satellites have connected with other nodes in the column before, old links will be deleted. After this, K columns with the least 0 element will be chosen as the final time slot assignment matrix.

After steps mentioned above, time slot assignment matrix $L = \left[l_{i,j}\right] \in R^{N\times K}$ represents ISL network topology within T, where N is the total number of nodes including satellites and ground station, K is the number of slots in T. $l_{\mathrm{i,j}}$ denotes linking node of node i in time slot j, if $l_{\mathrm{i,j}} = 0$, this node has no link in time slot j.

3 Route Planning for BDS ISL Network

Based on network topology determined by link assigning algorithm put forward in Sect. 2, this section is focused on information route planning problem in BDS ISL network. Firstly, we adjust and apply contact graph routing (CGR) for path searching in this unique network. Secondly and most importantly, path combinational optimal algorithm based on simulated annealing is proposed. By combining path searching and path combinational optimization algorithm, a common route planning method for navigation related message transmission in BDS ISL network is provided.

To be consistent with link assignment period, T = 1 min is set as time duration of path combinational optimization period. Without doubt, the network is still the generalized inter-satellite link network composed of ground station nodes and 24 MEO satellites nodes of BDS-3.

3.1 Path Searching Algorithm

3.1.1 Characteristics of Navigation Related Message

Considering real scenarios of navigation satellite system, we choose 4 typical categories of information including telemetry data, autonomous navigation data, operation control data, and telecommand data. Basic attributes for all kinds of message are as follows: data size, priority, source node, destination node, hop limit, message generation time, and message survival time.

- Hop limit: Maximum hop for message transmission. If exceeded, completeness and correctness of transmitted message may not be ensured.
- Generation time: The moment when the message is generated. A message can only enter the network after it has been generated.
- Message Survival Time: The time duration from message generation time to message expiration time. If transmission can't be completed in message survival time, message expires.

3.1.2 Path Searching Algorithm for Single Message

To arrange information transmission by path combinational optimization, feasible paths for single message should be searched firstly. Contact graph routing (CGR) is a path searching algorithm brought forward by Burleigh [18]. This algorithm is often applied in interplanetary networks or satellites networks around the earth [19]. It is especially fit for delay-tolerant networks whose links are discontinuous and have long time delay [20]. Therefore, CGR can be applied in searching feasible paths for navigation related messages here.

Basic principle of CGR is to start from the destination node and constantly move to "transmit node" who has valid link with "current node". By recursively calling contact review procedure (CRP), the algorithm can find all feasible paths for the message considering its data size and network capacity.

It has to be noted that, so far, no CGR algorithm has been introduced in literature focusing on BDS ISL specifically. To meet unique messages attributes and constrictions in this problem, CGR is adjusted for BDS ISL here. We consider the link assignment as a contact plan for the network. The specific algorithm flow pseudo code and variable declaration of adjusted CGR are as follows (Table 1 and Fig. 2):

Table 1. CGR variables definitions

Variables	Definitions
$S_{exclude}$	Nodes that have been chosen and should not be included in the same path again
h_{limit}	Number of remaining hops of the path
h_{max}	Max hop of the message
t_{ddl}	The latest time for the message to be transmitted in current path
t_{in}	Message's generation time
$t_{survival}$	Message's longest living time before it expires
D	Current node
N_{src}	Source node of the message
N_{dest}	Destination node of the message
t_{slot}	Duration of one slot
XMT_D	Nodes that have chance to send messages to D according to contact plan
$t_{tranmit}$	Duration time needed to transmit the message
ECC	Data size of the message
$m_{linkrate}$	Data rate of the link whose transmitting node is m
m_{start}	Start time of the link whose transmitting node is m
m_{stop}	Stop time of the link whose transmitting node is m
P_D	Collection of all paths that start from source node and end at node D
P_{Dm}	Collection of all paths whose start node is the source node and last two nodes are m and D

Initialization

$S_{exclude} \leftarrow \emptyset,\ h_{limit} \leftarrow h_{max},\ t_{ddl} \leftarrow t_{in} + t_{survival},\ D \leftarrow N_{dest},\ P_D \leftarrow \emptyset$

CGR_CRP(CG,D)

$S_{exclude} \leftarrow \emptyset \cup D$
if $h_{limit} < 1$ **then**
  return;
end if
$i_{max} \leftarrow t_{ddl}/t_{slot}$
for $i \leftarrow i_{max}$ to 1 **do**
  $m \leftarrow XMT\_D_i$
  $t_{tranmit} \leftarrow 2 * ECC/m_{linkrate}$
    $t_{ddl} \leftarrow t_{ddl} - t_{tranmit}$
  if $m_{start} > t_{ddl}$ or ECC $> m_{linkrate}$ **then** continue
  else
    if $m = N_{src}$ **then**
      $t_{ddl} \leftarrow \min(t_{ddl}, m_{stop} - t_{tranmit})$
      if $t_{in} \geq t_{ddl}$ **then** continue
      else
        $P_{Dm} \leftarrow \{N_{src}, D\}$
      end if
    else
      if $m \in S_{exclude}$ **then** continue
      else
        $t_{ddl} \leftarrow \min(t_{ddl}, m_{stop} - t_{tranmit})$
        get P_m by executing CGR_CRP (CG,m)
        generate P_{Dm} by adding D to the end of all paths in P_m
    end if
  end if
  $P_D \leftarrow P_D \cup P_{Dm}$
end for

Fig. 2. Pseudo code of the adjusted CGR algorithm

3.1.3 Path Screening

After CGR, a great number of feasible paths may be searched out. In this situation, several paths with better performance are chosen and other "bad" paths will not join the follow-up combinational optimization process. Path screening can avoid the efficiency reduction caused by too many meaningless paths.

In this article, time delay and hop number are two indicators that determine paths performance. Considering the difference between their dimension units and physical meaning, we use the formula

$$P = delay/C + hop \tag{2}$$

to describe the comprehensive performance of planned paths, where *delay* denotes time delay of the path, *hop* denotes how many hops the path go through and *C* is a constant. The formula means, in our performance calculation rule, adding *C* seconds time delay has the same negative effect with adding one hop.

In a word, when too many paths are feasible than wanted, path screening can be executed by calculating the *P* value of all paths and choosing several needed paths with the minimum *P*.

3.2 Path Combinational Optimal Algorithm Based on Simulated Annealing

Feasible path set of all messages to be transmitted can be known by path searching. But due to limited network capacity, congestion occurs if all messages are transmitted according to their own optimal path. In other words, when some link is included in many messages' best path, summation data size of these messages will exceed the link capacity. To avoid path plan failure caused by such path conflict, optimization should be done in advance to make sure the planned path set for all messages are executable. The core principle is to arrange paths for as many messages as possible. Besides, performance of the planned path is also supposed to be optimized.

In this section, a heuristic framework based on simulated annealing is used for combinatorial optimization. The simulated annealing method has small computational complexity and high versatility [21]. When the number of iterations is large enough, it can converge with the probability of 1. The core idea of simulated annealing is to accept worse performed new solution with certain probability which decreases along the iteration process. Therefore, this method can probabilistically jump out of the local optimal solution and finally approach the global optimal solution. Flow chart of PCO-SA proposed in this paper is shown in the Fig. 3 below.

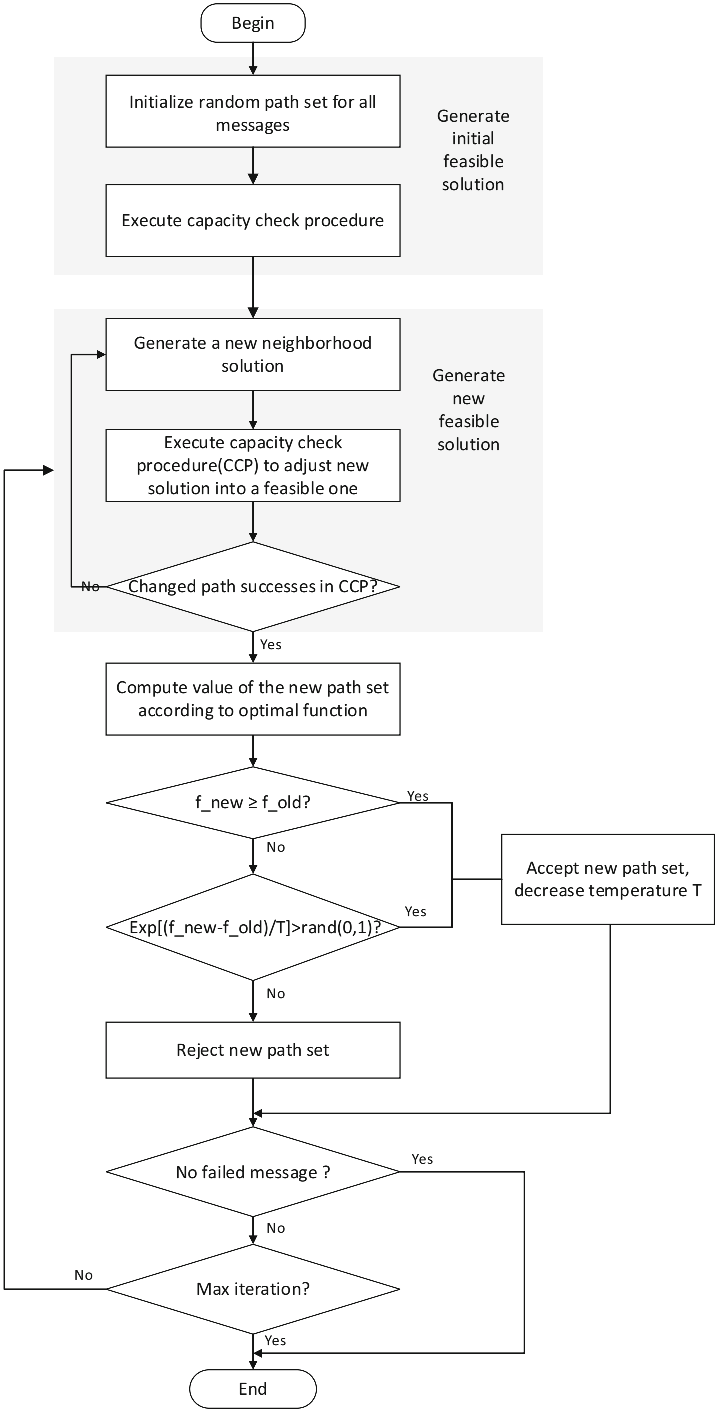

Fig. 3. The flow chart of PCO-SA

The PCO-SA algorithm will be introduced in detail in the following four aspects: the overall process, the solution generation method, link capacity check procedure, and objective function design.

3.2.1 Overall Process of PCO-SA

PCO-SA starts from a random initial solution and continuously generates one new solution in each iteration. Then, the objective function value corresponding to the new solution is calculated. If performance of new solution is superior to that of the old one, the new solution is accepted, and the follow-up iteration process starts from this new solution. Otherwise, the new solution still has a probability to be accepted. The probability is calculated according to the formula below.

$$Prob = e^{(f_{new} - f_{old})/T} \tag{3}$$

In this formula, f_{new} and f_{old} denotes performance value of the new and old path set respectively. T denotes temperature parameter used to control the simulated annealing process. The larger T is, the higher the accepting probability is. On the contrary, when T is small, the algorithm tends to accept new solution with worse performance with a small probability. Along with the simulated annealing iterative process, T will continue to decrease as shown by the formula below, so that iterative process will tend to be stable and no longer accept worse new solutions ultimately.

$$T_{new} = \alpha T_{old}, 0 < \alpha < 1 \tag{4}$$

In this formula, T_{new} and T_{old} are the temperature parameters after and before cooling procedure, respectively, and α is the temperature cooling rate, which is a constant within (0, 1).

3.2.2 Solution Generation Method

The basic solution generation method includes two steps. The first step is to generate a random path combination. And the second step aims to check and adjust the path combination through link capacity check procedure in order to ensure that the generated path set is a feasible solution which won’t cause link congestion. During the link capacity check procedure, if transmission paths of different messages overlap and cause conflict due to insufficient link capacity, corresponding paths are identified as failed. For the sake of optimization efficiency, new solution generated in each iteration should be different from the old one. In other words, if the newly changed path, i.e., difference between new and old path combination, is considered as failed, no actual changes is introduced in this iteration. For this reason, the generation process keeps being repeated until the newly changed path is considered as success in the link capacity check procedure.

In step one, two kinds of solution needs to be generated: initial solution and new solution in each iteration.

For M messages to be transmitted, we represent the whole feasible path set obtained by CGR with $R_i = \{r_{ij}\}(1 \leq j \leq p_i, 1 \leq i \leq M)$, where R_i is the path set of the i-th message, it has p_i paths in total, r_{ij} denotes the j-th path in feasible path set of the i-th message. Each path is actually a sequence of nodes with time information. So each path combination for all messages can be represented by

$$Pathcomb = [x_1, x_2, \ldots, x_M] \tag{5}$$

where x_i is the number x_i path in path set for the i-th message. If x_i is 0, it means the path chosen for the i-th message fails to pass link capacity check procedure.

Simulated annealing can start from any starting point, so this paper generates a random initial solution. That is, for each message *i*, an integer number $x_i(1 \leq x_i \leq p_i)$ is randomly selected to generate an initial path combination of M pieces of message.

In the follow-up new solution generation process in each iteration, message *m* is randomly selected, and the original chosen path number x_m is replaced with another random integer which is in the range of (1, p_m) and different from the original x_m. The obtained $Pathcomb_{new}$ is a neighborhood solution of $Pathcomb_{old}$.

After the first step mentioned above, link capacity check must be performed as follow-up step to adjust the generated solution to a feasible one.

3.2.3 Link Capacity Check Procedure

The core idea of the link capacity check is to check whether the total data to be transmitted will exceed the link capacity in the network according to path combination. If true, it decides some messages whose paths are engaged in conflict are successful and the remaining messages are failed.

The process of link capacity check procedure is as follows.

- First, generate the order for messages to go through the link capacity check. There are three principles for generating.
  - The checking order is generated according to priority. Messages that have higher priority ranks higher in the checking order.
  - For messages of the same priority, the checking order is randomly arranged.
  - Checking order corresponding to the message whose path has been replaced this time should be moved to the first place among messages with the same priority.

  These principles can ensure that overall the high-priority messages are more advantageous in the sequential checking. And the checking order generated in each iteration is different from each other, which can bring randomness to the exploration process. Besides, newly replaced path has a greater chance of being successfully arranged and jumping out of the solution generation loop thanks to a higher checking order.
- Then, perform link capacity check procedure according to the checking order. If the path chosen for certain message can be added without leading to insufficient link capacity, it is determined as successful. Message data size is added to corresponding occupied capacity of link included in the path. If the data to be transmitted

overflows after adding this message, path arrangement of this message fails. Link capacity of all links in the network is still the same as when the message was not added. This step is repeated until all messages have been checked.

There is a special case that may happen in BDS ISL network route planning worth mentioning. When a message is generated in current route planning period, but its effective lifetime ends at next period, some feasible paths of this message path will include links belongs to next period. Messages spanning across periods result in the problem that some links of current period are occupied by information generated in previous period, and some information occupies the link capacity of the next period. To solve this problem, "Folding Principle" is put forward and applied. If the path of certain message occupies links of the second period, when calculating the occupied capacity of network links, links in the second period are folded into the first period. Since the link topology of the second period is consistent with the first period, message size is subtracted from current link capacity of corresponding links in the first period. For BDS, generally, the visibility between nodes does not change substantially in 2 consecutive minutes. Based on this assumption that topology of the next period is the same as the previous one, interaction between periods is replaced by optimization within current period, this is called the "Folding Principle".

3.2.4 Objective Function

For the route planning issue of information in the satellite navigation system, we mainly focus on three indicators: success ratio, time delay, and hop number. Among them, Success ratio is the primary indicator used to evaluate the effect of route planning since key objective of route planning problem is to arrange as many messages as possible. Time delay and hop number reflect the performance of the successfully planned path. The smaller the delay is, the faster message reaches the destination node. The smaller hop number is, the better performance is. That is because too many transit node may cause unnecessary errors in the process of information unpacking and grouping.

Accordingly, when designing the objective function, we pay the most attention to improving the success ratio. Performance indicators of the successfully planned path are also take into consideration. For information that is successfully planed, we define its value function as:

$$S_m = (pri_m \times pri_m)/(hop_m + delay_m/C) \tag{6}$$

where pri_m is the priority of the message, hop_m and $delay_m$ denotes time delay and hop number of this path, C is the same constant as that in (2) which represents the proportional relationship between time delay and hop number on final performance.

For messages fails to be arranged, penalty function is as follows.

$$P_m = -(pri_m \times pri_m) \tag{7}$$

It means, when the information arrangement fails, the negative penalty for the total value is only related to its priority. The higher the priority is, the greater the penalty is.

For any path combination of M messages to be transmitted, the corresponding combined value function is

$$f_M = \sum\nolimits_{m \in SuccessMessage} S_m + \sum\nolimits_{m \in FailMessage} P_m \tag{8}$$

High-priority messages have a greater impact on the result, so the result is iterated toward the trend that high-priority messages are beneficial. And for the same message, penalty function calculates bigger than value function. Failure causes more significant influence to the whole value. Therefore, success ratio increases as the iteration process.

4 Computational Results

In this section, we simulate and analyze the performance of the two algorithms put forward respectively in Sects. 2 and 3, namely link assigning algorithm and PCO-SA. Algorithms are simulated based on real satellites constellation of the third generation BDS. Note that no ground station placement plan for the third generation BDS has been published so far. In this paper, only one ground station is included in generalized ISL network for the reason that one station is the most basic scene considering practical construction progress. Basic scene can be expanded to multiple ground stations with link assigning algorithm and PCO-SA running the same steps. Here we choose Beijing (39°55′N 116°23′E), the capital of China, as location of the only ground station. Distance between space segment and ground segment is far beyond distance between potential ground stations in China so ground station in Beijing can be typical representative.

The proposed methods were implemented using MATLAB. And the Ka-band ISL antennas have a pitch angle limit of 60°. The visibility and positions were calculated using STK software.

The basic simulation conditions are as follows (Table 2):

Table 2. Simulation condition

Simulation condition	Parameter
Simulation start time	20180101 00:00:00
Network Nodes	24 MEO satellites + 1 Ground station
T	1 min
K	20

Parameters used to simulate navigation related messages are as follows (Table 3):

Table 3. Parameters of messages to be transmitted

Message type	Priority	Generation rule	Data size	Hop limit	Message survival time
Telemetry information	4	One telemetry message from each satellite to ground station in each time slot	8192 bit	4	60 s
Auto-navigation information	3	One auto-navigation message from each satellite to its connecting satellites in each time slot	2048 bit	1	60 s
Telecommand data	2	Message from ground station to corresponding telecommand satellite within a uniform time distribution in every 60 s	102400 bit	4	60 s
Operating control information	1	Message from ground station to corresponding operating control satellite within a uniform time distribution in every 60 s	102400 bit	4	60 s

4.1 Performance of Link Assigning Algorithm

We generate the link assignment matrix for every minute according to the algorithm in Sect. 2.2. Then we calculate the average number of links, average PDOP and average hop between ground station and satellites. The results are shown as follows (Table 4):

Table 4. Performance of link assignment method

Performance index	Best	Worst	Average
Average number of distinct links for satellites	18.2917	17	17.6697
Average PDOP	1.0555	1.2570	1.1480
Average hop from ground station to satellites	1.5417	1.7500	1.6259
Average number of distinct links for ground station	11	6	8.9792

According to the simulation results, satellites build links with 17.6697 nodes on average, and the difference between the best and worst results is not big. The robust performance can satisfy the needs for satellite nodes to ranging with as many other satellites as possible. The average PDOP equals to 1.148. This is much smaller than 3, which is considered to represent a ranging geometric configuration good enough. High precision ranging can be guaranteed. Ground station builds links with 9 satellites on average, and the average communication hop is 1.6259. Space segment and ground segment are highly connected.

In conclusion, the proposed method can generate ISL network which not only satisfies the design principles mentioned in Sect. 2, but also provides promising network topology structure for the follow-up route planning. It is a quite practical method to apply in link assignment for BDS ISL network.

4.2 Performance of PCO-SA

4.2.1 Parameter Configuration of Objective Function

From Eq. (2), the objective function and, more specifically, the choice of the C determine the final optimization result including the hop number and the time delay. In order to determine appropriate value of C, we set the following simulation conditions: space segment is consisted of 24 MEO satellites of BDS, the ground station has 6 visible satellites, data rate of links between satellites is 102.4 Kbps, data rate of links between ground station and satellites is 204.8 Kbps. We calculate the average time delay and hop number under different C values. The results are shown as follow (Fig. 4):

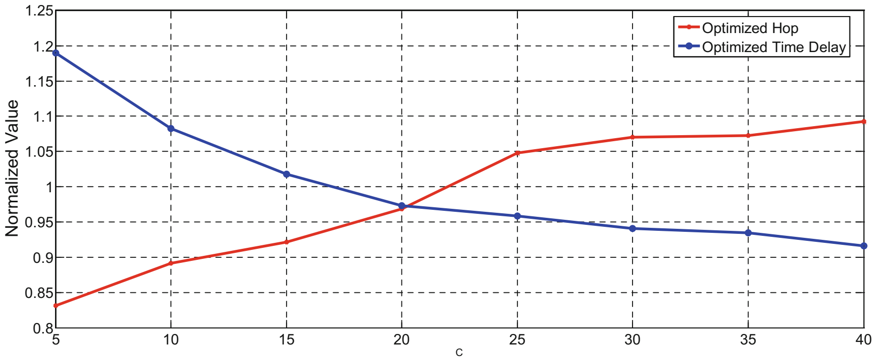

Fig. 4. The choice of the C value

It is obvious from the figure that when value of C equals to 20, the optimization result of hop number and time delay are in equilibrium. So, we choose C = 20 as the parameter in objective function.

4.2.2 Parameter Configuration of Simulated Annealing

After multiple simulations, we discover that 20000 is the most proper maximum iteration number for our problem to acquire results good enough without too long computational time. In the “cooling” process, we set $T_0 = 273$ as the initial temperature. Temperature decreasing parameter α is set to 0.9995.

4.2.3 Simulation on Telemetry Message Route Planning Using PCO-SA

Based on the generated ISL network topology and parameters set above, experiments on PCO-SA are performed. Firstly, gradual convergence trends of three indicators in the optimization process are shown. Secondly, we compare the performance of proposed PCO-SA with other path plan methods under different data rate. Thirdly, we compare the performance of PCO-SA with other methods with different number of ground station’s visible satellites.

Only one type of navigation related information can be selected in the simulation for the sake of single variable principle. Since telemetry information is generated continuously by satellites and needs to be transmitted to the ground in a short period of time, it's quite challenging to arrange the massive data. Also, telemetry information is of high transmission priority which exists in all navigation scenes. For these reasons, telemetry data of BDS is selected here.

The visible satellites number of ground station is set to 6. Data rate of links between satellites is 102.4 Kbps, data rate of links between ground station and satellites is 204.8 Kbps (Fig. 5).

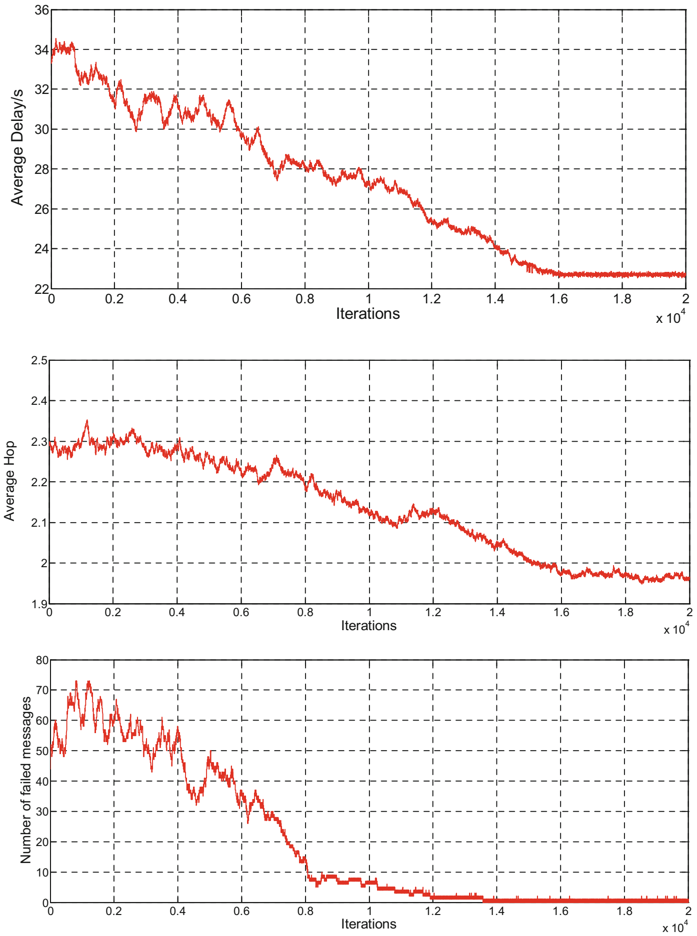

Fig. 5. Trends of indicators in the optimization process

According to the figure, the failed-to-plan paths number gradually decreases to 0 as the iteration goes. Average time delay and hop number of planed paths decrease and finally stabilize.

Then, we compared the performance of PCO-SA and other methods under different link data rates. As far as we know, no mature route planning method for BDS ISL has been proposed before. So three principles are used to generate path plan. MinDelay principle denotes to a scheme where all messages choose the minimum delay path for themselves. Similarly, all messages choose their minimum hop path in MinHop principle. Random principle denotes to random path combination. After generation process of these three principles, capacity check procedure mentioned in Sect. 3.2.3 is executed to adjust the solutions to feasible ones.

In this simulation, the visible satellites number of ground station is 6. Data rate of links between ground station and satellites is 204.8 Kbps. Data rates of links between satellites are 51.2 Kbps, 102.4 Kbps and 204.8 kbps respectively. All results are average values from 50 times of experiments. Results are shown in Fig. 6.

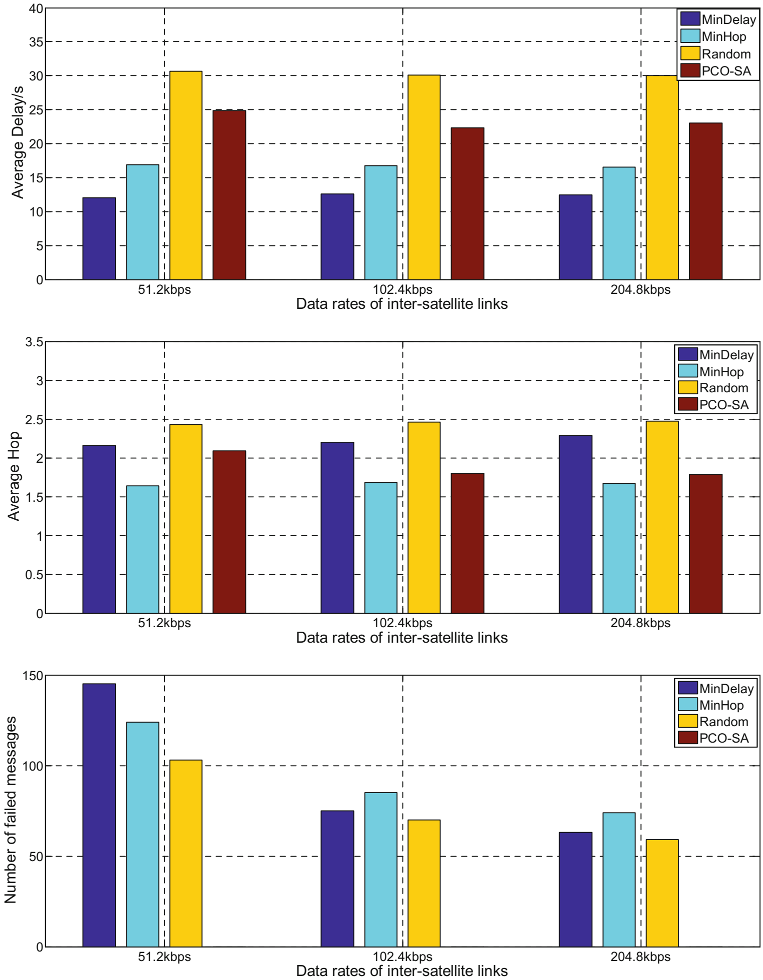

Fig. 6. Performance of algorithms with different ISL data rates

According to the simulation results, we can conclude that:

- Under different inter-satellite link rates, all messages' paths are successfully planned using PCO-SA with. PCO-SA has absolute advantage in success ratio among other principles.
- Compared with random principle, PCO-SA has little optimization on time delay and hop number under ISL link data rate of 50.2 Kpbs. Due to limited link capacity, performance on these two aspects is sacrificed to improve the success ratio. When network capacity is sufficient with data rate of 102.4 Kpbs or 204.8 Kpbs, PCO-SA can significantly improve the performance of successfully planned path.
- Compared with MinDelay principle, PCO-SA doesn't have advantages in time delay. Compared with MinHop principle, PCO-SA has no advantages in hop number. But it achieves balance in these two aspects. Also, results of PCO-SA can satisfy the requirements in transmitting telemetry data.

Then, this paper analyzes the influence of ground station's visible satellites number on these algorithms. Performances under 6, 7, 8, 9, and 10 visible satellites are compared. Based on the results of different link rate, a sufficient network condition with 102.4 Kbps ISL data rate is selected. All results are average values from 50 times of experiments. The simulation results are as follows (Fig. 7):

The simulation results show that under the premise of sufficient link capacity, PCO-SA can effectively reduce failed messages number to 0. PCO-SA always has the absolute advantage on success ratio. The time delay of the three methods almost does not change with the number of visible satellites. As for hop number, only PCO-SA performs stably with different number of visible satellites. In summary, for different numbers of visible satellites, PCO-SA has robust performance in all aspects. Under all these circumstances, it shows good optimization results.

In conclusion, experiments are performed on telemetry information and results show that under various situations we simulated according to real work scenarios in BDS, PCO-SA performs stably and always has a significant advantage in success ratio. All telemetry data generated by satellites can be downlinked to ground station. Also, when network capacity is sufficient, PCO-SA optimizes delay and hop of planned routes comprehensively.

4.2.4 Simulation on Multiple Navigation Message Route Planning Using PCO-SA

Finally, we simulate and compare the performance of the PCO-SA with multiple kinds of information. According to the task of BDS, four information types with various priority (the telemetry data, the autonomous navigation data, the telecommand data, and the operation control data) are chosen for this simulation. All results are average values from 50 times of experiments. Simulation results are as follows (Fig. 8):

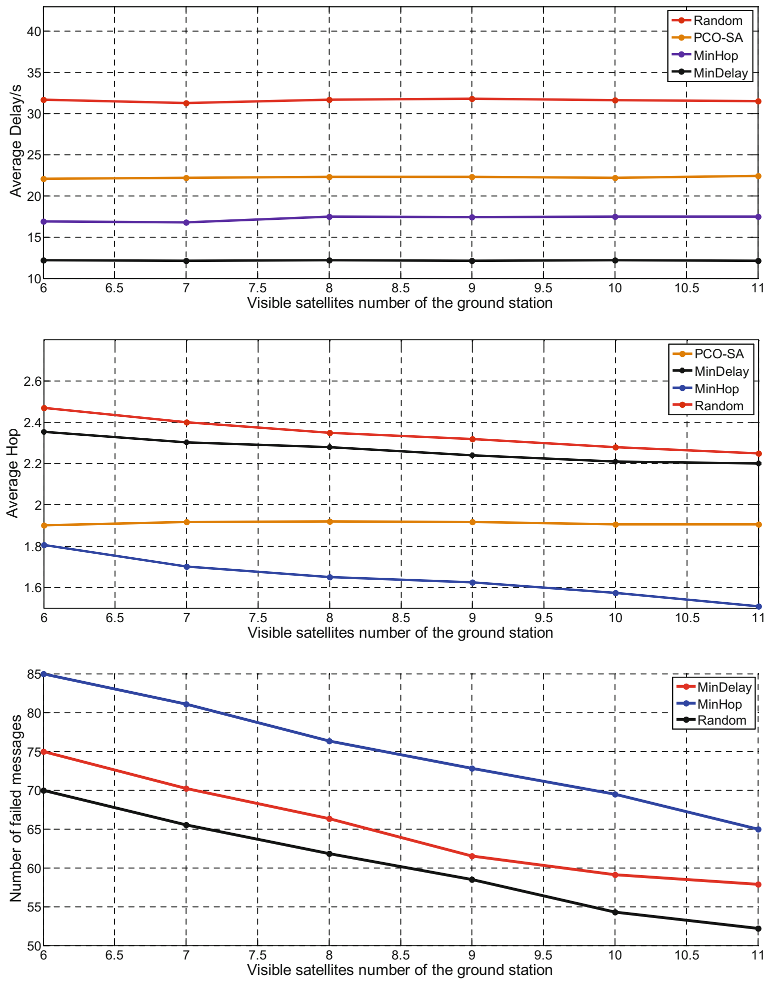

Fig. 7. Performance of algorithms with different number of ground station's visible satellites

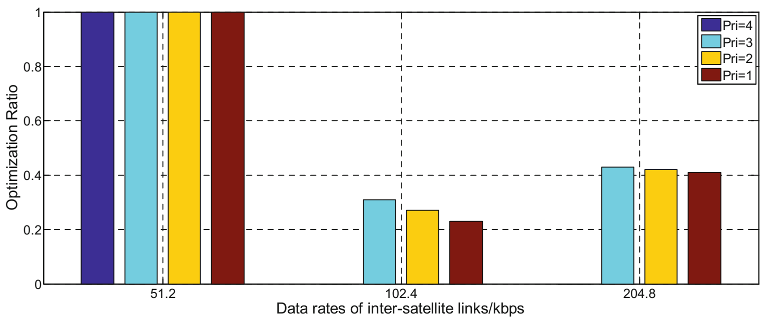

Fig. 8. Performance of different information using PCO-SA

The results show that success ratio of every data type reaches 100% in the end. And message type with higher priority has more advantage in time delay and hop number.

Through all experiments in Sect. 4.2, we can draw the following conclusions: PCO-SA can significantly increase success ratio for route planning in various situations according to the work scenarios and parameters we set, especially when the information load is heavy compared to network capacity. The primary task, transmitting as many messages as possible, can be guaranteed. When network link capacity is abundant, time delay and hop number of the planned path can be comprehensively optimized by PCO-SA.

In conclusion, given the path set for all messages searched by adjusted CGR, PCO-SA can successfully perform route planning for all types of data in various situations which are set to simulate the real work scenes of BDS ISL. It can provide high success ratio of route planning and optimize transmission delay and hop comprehensively for information. The route planning scheme of combining CGR and PCO-SA is very suitable for routing problem in BDS. It not only solves the problem of transmitting all task information in limited time and hop, but also optimize the indicators.

4.3 Verification

For verification, satellites and ground station operation simulation system in data level is implemented using C++. Link assignment generated in Sect. 2 and route plan generated by methods in Sect. 3 are converted to standard table format. Parameters are set to be same with those in experiments in Sect. 4.2. Satellite and ground station nodes link with other nodes according to the topology table and information are received or transmitted by corresponding nodes as specified in route table. Meantime, telemetry information is contentiously generated by the same rule used in experiments before. Results show that in the process, actual remaining data amount in every node are just as planned. And telemetry data are successfully downlinked to ground station finally. The algorithms proposed in Sects. 2 and 3 are demonstrated to have practical meanings.

5 Conclusion

In accordance with specific characteristics of BDS ISL network, this paper firstly concludes the link assignment principles and proposes a link assigning method. Simulation results show that the method can generate ISL network topology with high average link number, low PDOP and high connectivity between ground station and satellites. After determining the ISL network topology, path combinational optimization based on simulated annealing is put forward. This algorithm is based on the heuristic simulated annealing frame. We design the objective function at the purpose of comprehensively optimizing route planning success ratio, average time delay, and average hop number. By combining adjusted contact graph routing for path searching and PCO-SA, a common framework for routing problem in BDS ISL network is introduced. Simulation results show that PCO-SA has significant advantage in success ratio of route planning compared with other three principles. Time delay and hop number can also be optimized through PCO-SA. In addition, PCO-SA has great stability under various situations including different link data rate and different visibility condition of ground station. At last, we compare the performance among different information using PCO-SA. In addition of guaranteed high success ratio, messages with high priority can take more advantages in time delay and hop number.

In conclusion, link assignment method and route planning scheme of combining CGR and PCO-SA put forward in this paper are demonstrated to perform advantageously in solving the topological design and routing problem in BDS ISL network.

Algorithms introduced in this paper are specifically targeted at inter-satellite link network composed of MEO satellites and ground station in BDS. Under the trend of air and space integration, future work on more complicated network including GEO, IGSO or even communication satellites still remains to be accomplished.

References

1. BeiDou Navigation Satellite System Signal In Space Interface Control Document Open Service Signal B1C (Version 1.0). http://en.beidou.gov.cn/SYSTEMS/Officialdocument/. Accessed 15 Oct 2018
2. Abusali, P.A.M., Tapley, B.D., Schutz, B.E.: Autonomous navigation of global positioning system satellites using cross-link measurements. J. Guidance Control Dyn. **21**(2), 321–327 (2015)
3. Fisher, S.C., Ghassemi, K.: GPS IIF-the next generation. In: Proceedings of the IEEE, Seal Beach, CA, pp. 24–47 (1999)
4. Vasavada, Y., Gopal, R., Ravishankar, C.: Architectures for next generation high throughput satellite systems. Int. J. Satellite Commun. Network. **34**(4), 523–546 (2016)
5. Wu, Y.L., Yang, J., Chen, J.Y.: Route analysis of satellite constellation based on directional crosslink with narrow-beam antenna. In: Wang, Y., Li, T. (eds.) Practical Applications of Intelligent Systems. AINSC, vol. 124, pp. 639–650. Springer, Berlin (2011). https://doi.org/10.1007/978-3-642-25658-5_76
6. Maine, K., Anderson, P., Bayuk, F.: Communication architecture for GPS III. In: IEEE Aerospace Conference Proceedings (2004)
7. Fernández, F.A.: Inter-satellite ranging and inter-satellite communication links for enhancing GNSS satellite broadcast navigation data. Adv. Space Res. **47**(5), 786–801 (2011)
8. Wang, D.X., Jie, X., Feng, X., Rui, G., Xie, J.S., Chen, J.P.: Development and prospect of GNSS autonomous navigation based on inter-satellite link. J. Astronautics **37**, 1279–1285 (2016)
9. Yang, Y., Yangyin, X., Jinlong, L., Yang, C.: Progress and performance evaluation of BeiDou global navigation satellite system: data analysis based on BDS-3 demonstration system. Sci. China Earth Sci. **61**(5), 614–624 (2018)
10. Harathi, K., Krishna, P., Newman-Wolfe, R.E., Chow, Y.C.: A fast link assignment algorithm for satellite communication networks. In: Twelfth International Phoenix Conference on Computers and Communications, pp. 401–408. IEEE (1993)
11. Noakes, M.D., Cain, J.B., Nieto, J.W., Althouse, E.L.: An adaptive link assignment algorithm for dynamically changing topologies. IEEE Trans. Commun. **41**(5), 694–706 (1993)
12. Markus, W., Jochen, F., Frédéric, W., Gérard, M.: Topological design, routing and capacity dimensioning for ISL networks in broadband LEO satellite systems. Int. J. Satellite Commun. **19**(2001), 499–528 (2001)

13. Liu, Z., Guo, W., Deng, C., Hu, W.: Perfect match model based link assignment for optical satellite network. In: IEEE International Conference on Communications, pp. 4149–4153. IEEE (2014)
14. Chang, H.S., Kim, B.W., Chang, G.L., Min, S.L.: FSA-based link assignment and routing in low-earth orbit satellite networks. IEEE Trans. Veh. Technol. **47**(3), 1037–1048 (1997)
15. Yang, D., Yang, J., Xu, P.: Timeslot scheduling of inter-satellite links based on a system of a narrow beam with time division. GPS Sol. **21**, 1–13 (2016)
16. Sushant, J., Kevin, F., Rabin, P.: Routing in a delay tolerant network. In: Proceedings of the 2004 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications, pp. 145–158. ACM (2004)
17. Jones, E.P.C., Li, L., Schmidtke, J.K., Ward, P.A.S.: Practical routing in delay-tolerant networks. IEEE Trans. Mob. Comput. **6**(8), 943–959 (2007)
18. Burleigh, S.: Contact Graph Routing. http://tools.ietf.org/html/draft-burleigh-dtnrg-cgr-01. Accessed 15 Oct 2018
19. Birrane, E., Burleigh, S., Kasch, N.: Analysis of the contact graph routing algorithm: bounding interplanetary paths. Acta Astronaut. **75**(2), 108–119 (2012)
20. Araniti, G., Bezirgiannidis, N., Birrane, E., Bisio, I., Burleigh, S., Caini, C.: Contact graph routing in DTN space networks: overview, enhancements and performance. IEEE Commun. Mag. **53**(3), 38–46 (2015)
21. Bertsimas, D., Tsitsiklis, J.: Simulated annealing. Stat. Sci. **8**(1), 10–15 (1993)