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Satellite-Ground Link Planning for LEO Satellite Navigation Augmentation Networks

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ABSTRACT Navigation augmentation using low-orbit satellites is a low-cost, high-precision technique. Efficient transmission of data between the satellites and ground station is a prerequisite to ensure that this technique can be achieved. Satellite-ground link planning directly affects the transmission efficiency. In addition, appropriate planning of the links enables the reduction in the routing calculation and link switching overhead. In view of the data transmission characteristics of a satellite navigation augmentation network, this paper optimizes the ground-satellite link planning with respect to three aspects: link switching frequency, routing update frequency, and relay satellite configuration. By focusing on the above three aspects, we propose a link planning algorithm with the minimum number of link switching times, minimum number of route updates, and relay satellite configuration constraints. Finally, the simulation results are presented to demonstrate the performance of the proposed algorithm.

INDEX TERMS Low-orbit satellite, navigation augmentation, satellite network, link planning.

I. INTRODUCTION

Rapid geometric position variation and short propagation delay are characteristics of low-earth orbit (LEO) satellites, which make them a low-cost and high-precision solution for navigation augmentation. LEO satellites move quickly relative to the ground, thereby resulting in rapid geometric position variation, which facilitates the rapid determination of carrier ambiguity parameters and improves the use of carrier data. Additionally, owing to the short propagation delay of the LEO satellites, users are supported by inter-satellite links (ISL) to realize near-real-time data transmission between satellites and terrestrial systems. They provide real-time transmission support for real-time precision ephemeris generation and broadcast, and reduce user positioning initialization time.

The general process of LEO augmentation system is as follows. The LEO satellites are equipped with high-precision global navigation satellite system monitoring receivers. The observation data of a monitoring receiver is transmitted to the domestic central processing station through ISLs and satellite-ground links (SGLs). Using this observation data, the central processing station generates a precise ephemeris, which is then uploaded to the satellites through ISLs and SGLs. Finally, the LEO satellites broadcast the precise ephemeris to the ground users. The user realizes the acquisition of the precise ephemeris by receiving the navigation enhanced signal broadcasted by the satellite, and realizes the global precise single point positioning.

It can be observed from the above process that ensuring the efficient transmission of data between the satellites and ground station is fundamental to realizing such a solution. To increase the network capacity, communications between a satellite and the ground can pass through multiple relay satellites. Owing to the cost of the ground station construction, the number of ground stations and antennas must be reduced as much as possible. However, the selection of the visible satellites to construct the SGLs is a problem. Satellite-ground link planning (SGLP) solves this selection problem, which directly affects the performance of the routing algorithm. In addition, through the proper planning of the link, the routing calculation and link switching overhead can be reduced. However, to the best of our knowledge, no studies have been conducted on SGLP for LEO satellite navigation augmentation networks (SNANs).

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Much related research has been devoted to the satellite handover and satellite scheduling problems. Because the user service duration may be greater than the coverage time of an LEO satellite, the user may be handed over to another visible satellite to prevent interruption of the ongoing communication [1]. The ongoing connection should seamlessly be served by a number of satellites [2], which may result in some conflicts of access service resources. Three criteria are proposed in [3], i.e., the maximum service time, maximum number of free channels, and minimum distance for the selection of the satellites. In addition, the signal strength which is related to the elevation angle is considered as another satellite handover criterion in [4], [5]. The coverage time for the users in LEO satellite networks is analyzed and a lower bound for the expected quantity of ISL handover is initially derived in [6]. The foregoing ISL handover criteria were concluded, and a graph-based ISL handover prediction framework [7] was proposed to incorporate all the existing satellite handover criteria flexibly. To resolve the multiple link states of the satellite change with the users' movements, the dynamic satellite handover prediction problem is studied in [8]. SGLP for SNAN is similar to the satellite handover problem. However, there are some differences between them. The satellite handover problem is based on the premise of a limited number of satellite access users. It focuses on how to access the handover satellite to ensure that the user service is not interrupted and the success rate of user access is improved. On the other hand, in SGLP, more than one user which represents the antennas on the ground needs to be seamlessly served by relay satellites. The routing calculation and link switching overhead must be considered in SGLP, which are neglected in the satellite handover problem. Excessive routing calculation and link switching will consume on-board computing resources and reduce transmission efficiency. The satellite handover problem does not consider these issues.

Satellite-scheduling problems oftentimes involve periodic tasks, variable length tasks, and tasks that can be preempted. In addition, satellite-scheduling problems are usually over constrained. Thus, satellite scheduling can usually be viewed as a constraint-optimization problem rather than a constraint-satisfaction problem [9]. There are several satellite scheduling variants, such as LEO satellite scheduling [10], satellite range scheduling [11], [12], satellite downlink scheduling [13], satellite broadcast scheduling [14], satellite scheduling data downloads [15], which are defined under different satellite types and application requirements. All of the satellite scheduling variants remain computationally NP-hard to solve for optimality, and therefore, heuristics and meta-heuristics can be employed to tackle them [16]–[18]. The various priority levels that different tasks have are considered in [19]. Reference [20] proposed a mixed integer linear programming model for multi-satellite scheduling. Most of these researches are focused on how to maximize the number of served communication requirements between spacecraft and ground stations during their correspond visibility time window. They are not fully applicable to SGLP, in which each satellite does not have a specific task. The satellites connected to the ground station only serve as relay nodes to realize data transmission between the ground and the satellite network. For the station, the concern is not to complete a specific task on a certain satellite as soon as possible, but to select which satellite can complete the information transmission task of the entire network more efficiently. In SGLP, the degree of aggregation of relay nodes needs to be considered to spread traffic to different areas of the network as much as possible to avoid congestion. This factor was not considered in the above researches.

To overcome with the challenges posed by SGLP, we investigate it with respect to three aspects, namely, link switching frequency, routing update frequency, and relay satellite configuration. In addition, the optimal algorithms are proposed for these three aspects. Section 2 of this paper describes the problem of SGLP. Section 3 proposes three algorithms for minimum link switching times, minimum number of route updates, and relay satellite configuration constraints, respectively. The theoretical proof and explanation are provided. Section 4 evaluates the performance of the proposed algorithm through simulation experiments, and Section 5 summarizes the whole thesis. In this paper, some important hypotheses are listed as follows:

- The number of SGLs is constant, and the handover is seamless, which implies that the handover takes no time.
- The number of visible satellites is greater than that of the SGLs.
- Only one ground station is considered. Each antenna of the ground station can only establish one SGL with one satellite, and one satellite can only establish one SGL at the same time.

II. PROBLEM STATEMENT

SGLP focuses on solving the problem of selecting the satellite with which the ground station must establish an SGL to transmit information. The ground station may be simultaneously visible to multiple satellites. Each ground station contains multiple antennas. The data generated in real time on the satellites need to be transmitted to the ground through the ISLs and SGLs in time, as well as the data on the ground need to be transmitted to the satellites. This requires all antennas on the ground to be seamlessly covered by relay satellites. On this basis, we investigate how to reduce the overhead of the routing updates and link switching, and improve the transmission efficiency.

Let us assume that the link planning period is T. The satellites that are visible to the ground station and establish an SGL are called relay satellites, the set of which is denoted as R. The number of relay satellites is defined as $|R| = m$. A satellite that has an ISL with a relay satellite, i.e., a neighboring satellite of a relay satellite, is called a secondary relay satellite, the set of which is denoted as SR. The visual relationship between the ground station and the satellite is described by a series of visible time windows. A visibility time window of satellite k can be represented by the triplet $v_i^k = < k, t_s, t_e >$, where i is the time window number, and t_s and t_e are the starting and ending times of the visible time windows, respectively. Apparently, $ts < te$. Therefore, visibility time windows set between the ground station and the satellite k can be represented as $V_k = \left\{v_i^k | i = 1, 2, 3 \cdots\right\}$, and the visibility time windows between the ground station and all the satellites can be expressed as $V = \bigcup_i V_i$. V denotes the starting and ending times of all the visibility time windows for the ground station and each satellite.

Similarly, a link plan is also composed of a series of visible time windows. A plan slice window can be defined by the triplet $g_i = < k, p_s, p_e >$, where k is the relay satellite of the current visible time window, and p_s and p_e respectively represent the starting and ending times of the current link plan slice window, $p_s < p_e$. The entire link plan can be expressed as $G = \{g_i | i = 1, 2, 3 \cdots\}$. Each plan slice in the link plan is sorted by the ending time from small to large, i.e. $g_i.p_e \leq g_{i+1}.p_e$. Obviously, a valid link plan slice must be within the visibility time window of the ground station and the corresponding satellite. $g_i = < k, p_s, p_e >$ is valid if it satisfies the condition $\exists v_j^k, g_i.p_s \geq vj^k.t_s, g_i.p_e \leq v_j^k.t_e$, which is denoted as $g_i \prec (v_j^k)$. Specifically, according to the relationship between the starting time of the plan slice and the visibility time window, we define that $g_i \prec (v_j^k] \Rightarrow g_i.p_s \geq v_j^k.t_s, g_i.p_e = v_j^k.t_e$, $g_i \prec [v_j^k) \Rightarrow g_i.p_s = v_j^k.t_s, g_i.p_e \leq v_j^k.t_e$, $g_i \prec [v_j^k] \Rightarrow g_i.p_s = v_j^k.t_s, g_i.p_e = v_j^k.t_e$. A valid link plan must satisfy the m-coverage of the ground station at any time during the planning period T, i.e. there exists m SGLs at any time. $\forall t < T, \exists G_t' \subseteqq G, s.t. g_i.p_s \leq t \leq g_i.p_e$ and $|G_t'| = m$, where $g_i \in G_t'$. Therefore, m relay satellites at time t can be expressed as $R = \bigcup_{i=1}^{m}\{g_i.k\}$, where $g_i \in G_t'$.

According to the characteristics of SNAN, this study mainly considers the following factors.

(1) Satellite handover frequency: As the orbital height of an LEO satellite is low, the relative position of the satellite changes drastically, and the SGL is frequently switched. In the actual system when the link is switched, the ground station antenna needs to be re-aligned, captured, and tracked due to the change in the link-building object. This process requires sufficient time and reduces the antenna information transmission efficiency. Link switching also introduces additional system overhead and increases the failure rate caused by handover. Therefore, the number of SGL switchovers must be minimized, i.e.,

$$\min |G|$$

(2) Number of routing updates: When the SGL is switched, the relay satellites are changed, resulting in a change in the path between satellites and the ground station. Therefore, the route must be recalculated and updated on the satellite. Routing updates involve a certain amount of resource consumption. Because there are limited computing resources on the satellite, the number of link switches must be reduced as much as possible. Additionally, the switching may also a cause large delay variation. To avoid such variation, reducing the number of route updates is essential. This factor is similar to the aforementioned factor, however, the difference is that when multiple SGLs are simultaneously switched, the route needs to be recalculated once; hence, the number of route updates is not exactly the same as the number of handovers. The number of updates will not be greater than the number of antenna switches. The starting and ending times of all the plan slice windows are recorded with $U = \bigcup_i\{g_i.p_s\} \bigcup_i\{g_i.p_e\}$, and arranged from small to large. Thus, the optimization goal of this factor is

$$\min |U|$$

(3) Relay satellite shape: The mutual transmission between the satellites and the ground station must be completed by the transfer of the relay satellites. As illustrated in FIGURE 1, if the selection of the relay satellites is too concentrated in a certain area of the network, it will undoubtedly concentrate a large amount of traffic in that area of the network, thereby resulting in the risk of network congestion or even packet loss. Therefore, we aim to analyze how to select relay satellites to maximize the flow of traffic by spreading them in different areas of the network. The degree of aggregation of the relay satellites can be measured by the number of secondary relay satellites. In this study, the relay satellite shape is considered as a constraint. The relay satellite set is denoted as R, and the secondary relay satellite is defined as $SR = r(R)$. Thus, the configuration constraint can be expressed as

$$\forall t < T, \quad r(G_t'.K) \geq d$$

where d is the lower bound number of the secondary relay satellites.

III. LINK PLANNING ALGORITHMS

A. MINIMUM HANDOVER TIMES ALGORITHM

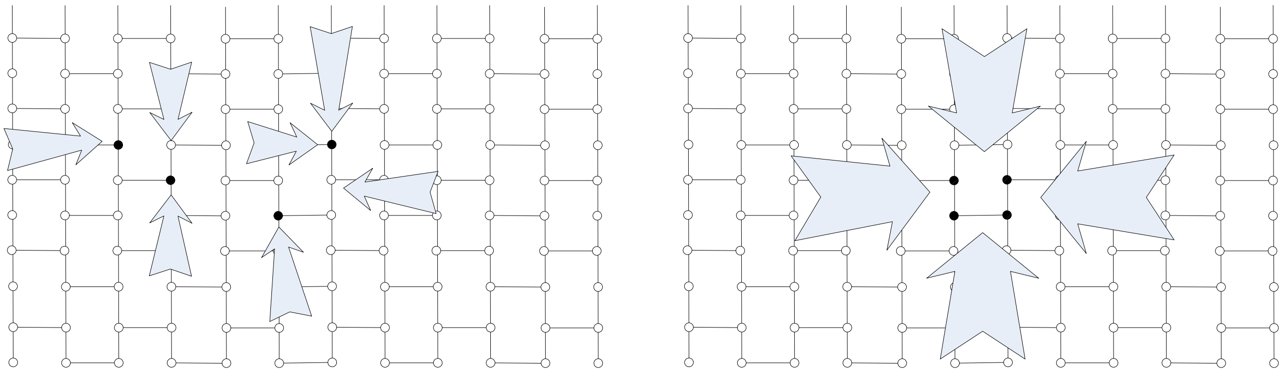
In this section, we optimize the SGLP by minimizing the number of satellite handover times. First, we state the following theorem.

Theorem 1: Assume that G is an optimal link plan. If $\exists g_i \in G, v_j^k \in V$, *s.t.* $g_i \prec (v_j^k)$, *and* $g_k.p_s = g_i.p_e$, *then if* g_i, g_k *is replaced by* $g_i' = < g_i.k, g_i.p_s, v_j^k.t_e >, g_k' = < g_k.k, v_j^k.t_e, g_k.p_e >$, *G is still an optimal link plan.*

Proof: Obviously, $g_i.p_e < v_j^k.t_e < g_k.p_e$, time window $< v_j^k.t_e, g_k.p_e >$ must also be within a visible time window. Thus, g_k' is a valid link plan slice. As $g_i' \prec (v_j^k)$, g_i' is also a valid link plan slice. Obviously, after the replacement, the number of handover times is equal to that of the original scheme, and hence, it is still an optimal link plan. □

Theorem 1 illustrates that there is no disadvantage in reducing the number of handover times to select the ending time of the visible window as the switching time. However, not all the switching times of an optimal plan are at the end of a visible time window.

Theorem 2: $\mathbb{G}$ *is the set of all valid link plans under a specific number of relay satellites. If* $\exists G^* \in \mathbb{G}$, *for any* $G \in \mathbb{G}, i = 1, 2, 3...$ *s.t.* $g_i^*.p_e >= g_i.p_e$, *where* $g_i^* \in G^*$, $g_i \in G$, *then* G^* *must be an optimal link plan.*



(a) Scattered relay satellites (b) Concentrated relay satellites

FIGURE 1. Relay satellite shape may cause congestion. If the relay satellites are concentrated in a certain area of the network, and congestion will occur, as shown in (b).

Proof: Les us assume that there exists a link plan G', and its number of handover times is n. The number of handovers of G^* is m, $n < m$. Then $g^*_m.p_e = g'_n.p_e = T$ where $g'_n \in G'$. Since $g^*_n.p_e < g^*_m.p_e$, we have $g^*_n.p_e < g'_n.p_e$, which contradicts the conditions for the establishment of G^*. Hence, the assumption is not true. □

Theorem 2 shows that if the ending time of each handover can always guarantee to be not less than any of the other ending times with the same number of handovers, then the plan must be an optimal one. However, the opposite is not true; an optimal solution does not guarantee that the ending time of each handover is the largest.

Based on the above two theorems, this section proposes the maximum service time algorithm (MST) and the graph-based minimum handover times algorithm (GMH).

1) MAXIMUM SERVICE TIME ALGORITHM (MST)

To minimize the number of switchings, the intuitive idea is to select the m satellites with the longest visible time window at the initial moment. When a satellite arrives at the ending time of the visibility time window and is not visible to the ground station, the ground station selects the satellite with the longest residual visible time from the visible satellites that have not established an SGL at the current time. The pseudo code for the above process is provided in Algorithm 1.

Algorithm 1 Maximum Service Time Algorithm

Input: Visible Set V, Relay node number m

1: current time $t = 0$
2: slot number $s = 1$
3: compute the valid visible timeslot, set V' at time t
4: choose m satellites C_s with the largest $v.t_e$, where $v \in V'$
5: **while** $t < T$ **do**
6: $s = s + 1$
7: $t = \min v.t_e$, where $v \in C_s$
8: compute the valid visible timeslot, set V' at time t
9: choose the satellite w, where $w.t_e = \max v.t_e$, $v, w \in V'$, and $v, w \notin C_s$
10: update C_s by replacing v with w, where $v.t_e = t$, $v \in C_s$
11: **end while**

The question now is whether the above algorithm can guarantee the optimality of the results or not. The problem is explained below.

Theorem 3: The link plan obtained by Algorithm 1 is an optimal plan with the least number of handover times.

Proof: It can be seen from Theorem 2 that if all the plan window slice ending times of a plan can be guaranteed to be not less than those of other plans with the same sequence number, then the plan scheme must be an optimal one. The following proves that plan G^* obtained according to Algorithm 2 satisfies the condition of Theorem 2. Let us assume that there exists a plan G with a larger ending time of the same sequence number slice, then there must be a certain plan slice number x, such that $g^*_x.p_e < g_x.p_e$, $g^*_{x-1}.p_e = g_{x-1}.p_e$. This implies that in the time slice $[g_{x-1}.p_e, g_x.p_e]$, m relay satellites can be guaranteed continuous connection without handover. However, $g_{x-1}.p_e < g*_x.p_e < g_x.p_e$, which contradicts step 9 of Algorithm 1; therefore, the assumption is not true, i.e., plan G^* obtained according to Algorithm 1 satisfies the condition of Theorem 2, and is an optimal plan. □

2) GRAPH-BASED MINIMUM HANDOVER TIMES ALGORITHM (GMH)

In [7], a graph-based switching strategy is proposed. By constructing a directed graph, they transform the longest satellite service time switching strategy into the shortest path in the directed graph. This algorithm provides a new solution to the problem of choosing the switching satellites. However, the literature [7] considers only one user's access satellite selection handover problem, and does not consider the problem that the same satellite may appear multiple times in the network diagram when the planning period is long. Based on this research, we consider the switching choice of multiple satellites. According to the visibility relationship between the satellites and the ground station, the network directed graph is constructed. On this basis, SGLP is transformed into the minimum cost maximum flow problem, and the link plan with the least number of handover times is obtained. This method theoretically guarantees the optimality of the results.

Algorithm 2 Graph Construct Process

Input: Visible Set V, Relay node number m

current time $t = 0$
$Queue = \emptyset$
virtual node $NodeNumber = 0$
current node $CurrentNode = 0$
Push $nodenumber$ to $Queue$
while $t < T$ **do**
  compute all the visible satellites V at time t and |V| = n
  for $i = 1 : n$ **do**
    if $v_i \notin Queue$ **then**
      NodeNumber++
      Push v_i to $Queue$
      Record v_i, attached virtual node $g(v_i)$, visible timeslot start time t_s, timeslot end time t_e
      Add edge $(CurrentNode, NodeNumber)$
    else
      Add edge $(CurrentNode, g(v_i))$
    end if
  end for
  Pop up $currentNode$ from $Queue$
  $t = \min v.t_e$, where $v \in Queue$
  $currentNode = v$, where $v.t_e = t$
end while

Algorithm 2 describes the construction process of a directed graph. The following are some important points regarding the construction of the directed graph.

1) The start node and the end node respectively indicate the start and end of the plan, and do not represent the specific link plan. As shown in FIGURE 2, nodes 0 and 6 represent the source node and the destination node of the directed graph, respectively. The edge connected to the start node and the end node has a cost of 0 and a capacity of m.
2) Adding nodes: At each switching moment, the visible satellites of ground station will be assigned a virtual node number at the current moment. Both the virtual node number and the actual satellite number are saved, which make it convenient for restoring the link planning result according to the calculation result. If only the actual node number is recorded, when a satellite is visible to the ground station again, the edges in the network graph cannot be distinguished. The edges of the node are added in multiple different visual periods, which may cause confusion. Therefore, the virtual nodes in the final network graph may all correspond to the same satellite node. Both nodes 1 and 5 in FIGURE 2 correspond to satellite A; however, they correspond to two different visible time windows of satellite A.

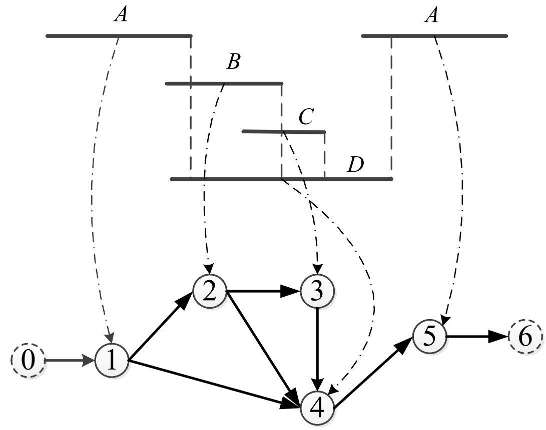


FIGURE 2. Constructed directed graph based on visible relationship of satellites.

3) Adding edges: As depicted in FIGURE 2, when there is an intersection between the visibility time windows of two satellites, the ground antenna can be switched between the two satellites during this intersection period. It can be seen from Theorem 1 that switching at the end time of the visible time window is advantageous for reducing the number of switching times. Therefore, when constructing the directed graph, we examine whether the end time of each visible time window is visible in other satellites. If it is, then a directed edge is added, and the direction of the edge is depicted in FIGURE 2. The edge has a capacity of 1 and a cost of 1. To obtain a link plan from the constructed directed graph, some information must be recorded while constructing the directed graph. Each node in the directed graph represents a visible time window of a satellite, and the satellite number and the starting and ending times of the visible time window need to be recorded.
4) Node splitting: Each satellite can only access one ground antenna at a time, i.e., the capacity of the node in the constructed directed graph is 1. The minimum cost of the current network graph does not consider the node capacity, which needs to be converted into the capacity of the edge. Therefore, each node v in the original graph, except for the start and end nodes is split into two nodes, v_1 $andv_2$, which are connected by one edge. The capacity of the edge is 1, and its cost is 0. As depicted in FIGURE 3, the edge that flows into v in the original graph is connected to v_1, and the edge that flows out of v is connected to v_2.

In the directed graph constructed by the above method, a mature algorithm is currently available to obtain the minimum cost with a traffic flow of m. The link plan is easily obtained based on the obtained minimum cost flow and

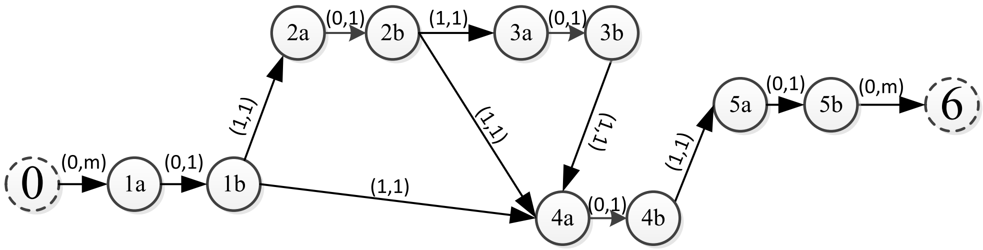


FIGURE 3. Each node v in the original graph, except for the start and end nodes 0, 6, is split into two nodes.

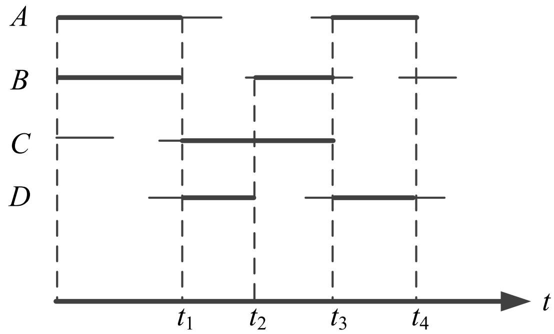


FIGURE 4. Reduction of the number of route updates by merging some SGL switchings into one moment, e.g. A, B at t_1.

related information recorded during the graph construction. According to the cost and capacity setting of each edge of the constructed directed graph, it is obvious that the obtained cost is the total number of handover times, and the flow of each unit represents the complete coverage of the ground station in the full planning period. The minimum cost flow of m guarantees the m-coverage of the satellites to the ground station in the full planning period, and the cost is the lowest. Therefore, the minimum cost flow of the graph constructed by Algorithm 2 corresponds to a link plan with a minimum number of handover times. When $m = 1$, the minimum cost maximum flow algorithm degenerates into the shortest path algorithm, which is considered in [7].

B. MINIMUM ROUTING UPDATE FREQUENCY ALGORITHM (MRU)

As mentioned above, when the satellite link is switched, it inevitably causes the update of the route, which results in resource consumption and delay variation. To reduce the number of route updates as much as possible, some SGL switchings are merged into one moment, which may cause some visible satellites to switch in advance within the visible range of the ground station. This may increase the number of satellite handovers, but reduces the number of route updates. As depicted in FIGURE 4, satellite A switches with satellite B in advance at time t_1. In some application scenarios, reducing the number of route updates may be more important than reducing the number of satellite switches.

Obviously, switching m satellites simultaneously can reduce the number of routing updates. This implies that the switching needs to be performed in advance before the end of the visible time window, which will undoubtedly increase the number of satellite switchings. As each plan window slice is shortened, the number of route updates is also increased to some extent. This study adopts a similar idea to that of Algorithm 1, and proposes a planning algorithm that can guarantee the minimum number of route updates. The idea of the algorithm is to select the m satellites with the longest residual visible time at the current time, and then switch at the end of the current shortest visible window of the m satellites. At the moment, m satellites switch simultaneously, and m satellites with the longest residual visible window at the current time are selected. If these m selected satellites coincide with the previously selected m satellites, it implies that the coincident satellites have a long visible time and can cover two plan slices. To reduce the number of handovers, these satellites continue to be connected without handover. As illustrated in FIGURE 4, satellite C covers two time plan slices $[t_1, t_2]$ and $[t_2, t_3]$. Algorithm 3 describes the specific calculation process.

Algorithm 3 Minimum Routing Update Frequency Algorithm

Input: Visible Set V, Relay node number m

```
current time t = 0
slots number s = 1
while t < T do
    Compute the valid visible time-slot, set V' at time t
    Choose m satellites C_s with the largest v.te, where v ∈ V'
    if i ∈ C_s ⋂ C_{s−1} ≠ ∅ then
        Combine the time slot s with s − 1 for satellite i
    end if
    t = min v.t_e, where v ∈ C_s
    s = s + 1
end while
```

To prove the optimality of Algorithm 3, the following theorem is proposed.

Theorem 4: $\mathbb{G}$ *is the set of all valid link plans under a specific number of relay satellites, if* $\exists G^* \in \mathbb{G}$, *for any* $G \in \mathbb{G}$, $i = 1, 2, 3 \cdots$ *s.t.* $u_i^* >= u_i$, *where* $u_i^* \in U^*$, $u_i \in U$, *and* U^* *and* U *are the union of all the ending moments of* G^* *and* G, *respectively, which are sorted from small to large,* *then G^* must be an optimal link plan with minimum route update times.*

Proof: Let us assume that there is a link planning scheme G', and its number of route updates is n. The number of route updates of G^* is m, $n < m$. Then $u_m^* = u_n' = T$. Since $u_n^* < u_m^*$, we have $u_n^* < u_n'$, which contradicts the conditions for the establishment of G^*. Hence, the assumption is not true. □

Theorem 5: The link plan obtained by Algorithm 3 is an optimal scheme with the least number of route updates.

Proof: Let us assume that there is a plan G with a larger ending time of the same sequence number slice, then there must be a certain plan slice number x, such that $u_x^* < u_x$, $u_{x-1}^* = u_{x-1}$. This shows that in the time slice $[u_{x-1}, u_x]$, m relay satellites can be guaranteed continuous connection without handover. However, $u_{x-1} < u_x^* < u_x$, which contradicts step 5 of Algorithm 3. Hence, the assumption is not true, i.e., the plan G^* obtained according to Algorithm 3 satisfies the condition of Theorem 4, and is an optimal plan. □

C. RELAY-NODES-SHAPE-CONSTRAINT MINIMUM ROUTING UPDATE FREQUENCY ALGORITHM (SC-MRU)

As mentioned above, because the shape of the relay satellites directly affects the network capacity, the relay satellite shape needs to be considered in the link planning. The shape of the relay satellites can be directly measured by the number of secondary relay satellites, i.e., the number of neighboring nodes of the relay satellites. The greater the number of secondary relay satellites, the higher the number of ISLs that can transmit data passing through the relay satellites.

Intuitively, similar to Algorithm 1, at each switching moment, the satellite with the largest number of secondary relay satellites can be selected as the relay satellite in the current moment, regardless of the length of the residual visible time. This algorithm only considers the configuration, which may increase the link switching overhead or routing update overhead. This algorithm is called Best Relay Nodes Shape Algorithm (BRS).

However, this study only optimizes the shape of the relay satellites as a constraint based on the MRU. Specifically, it is assumed that the number of secondary relay satellites is at least n. At each switching time, the m satellites with the longest visible times are selected according to Algorithm 3, and it is determined whether the number of secondary relay satellites satisfies the requirement. If not, the satellites with the shorter visible times are selected until the shapes of relay satellites satisfy the constraint. If all the current visible satellites cannot meet the minimum number of secondary relay satellites, the shape constraint is relaxed. The specific algorithm is described in Algorithm 4.

Algorithm 4 Relay-Nodes-Shape-Constraint Minimum Routing Update Frequency Algorithm

Input: Visible Set V, Relay node number m, Network Topology P, Relay node Shape Constraint n

current time $t = 0$
slots number $s = 1$
while $t < T$ **do**
  Compute the valid visible timeslot, set V' at time t and$|V'| = M$
  Choose m satellites C_s with the largest $v.te$, where $v \in V'$
  $n' = n$
  while C_s does not satisfy Shape Constraint n' **do**
    if *then*C_s does not satisfy Shape Constraint n'
      Try all possible combinations C_s with m satellites in V'
    end if
    if *then*C_s still does not satisfy Shape Constraint n'
      $n' = n' - 1$
    end if
  end while
  if $i \in C_s \bigcap C_{s-1} \neq \emptyset$ **then**
    Combine the time slot s with $s-1$ for satellite i
  end if
  $t = \min v.t_e$, where $v \in C_s$
  $s = s + 1$
end while

IV. PERFORMANCE EVALUATIONS

A. SYSTEM SETTING

We use a Walker 120/12/1 LEO satellite network with an orbital height of 970 km and an orbital inclination of 55°. The ground station is located in Beijing ($E116.46°, N39.92°$), and the minimum elevation angle of the ground station antenna is 10°. Each satellite has four permanent ISLs. Two of the ISLs are intra-plane ISLs, whereas the other two are inter-plane ISLs. The number of SGLs is 4, i.e., there are 4 relay satellites.

B. RESULTS AND ANALYSIS

To illustrate the necessity of reducing the handover frequency, we first explain the delay variation of the data packet due to handover through OPNET simulation. Then, we compare the performance of the proposed algorithms. As illustrated in FIGURE 5, when the SGL is switched at 319 s, 670 s, and 955 s, the delay variation is significantly increased. The relay satellites change because of the handover, resulting in the change of the data transmission path between the satellites and ground station. A large delay variation is disadvantageous for certain time-critical data transmissions. Thus, it is necessary to reduce this variation. This study mainly focuses on reducing the probability of variation occurrence by reducing the number of handovers.

For the number of handover times, two optimal methods are proposed in this study, which are based on MST and GMH. As illustrated in FIGURE 6, the number of handover times for MST and GMH is equal, and is the least compared

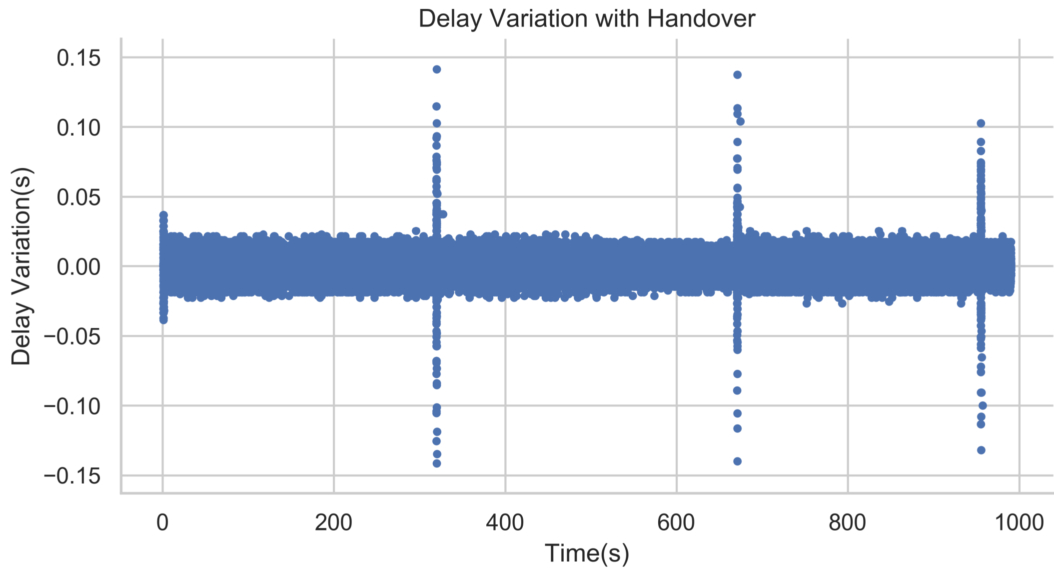


FIGURE 5. Delay variation caused by SGL handover at times of 319 s, 670 s, and 955 s.

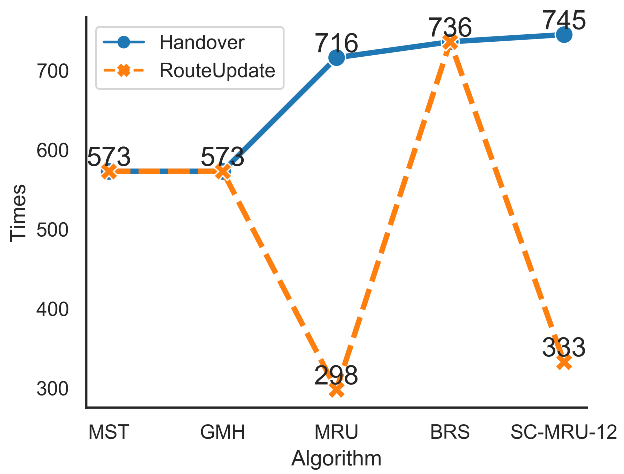


FIGURE 6. Number of handover and routing updates for different algorithms.

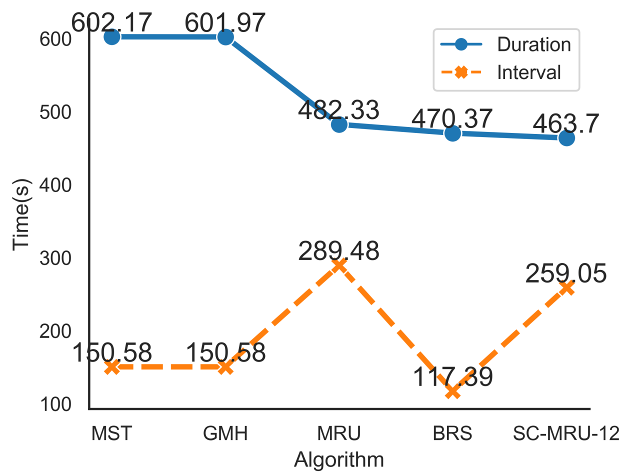


FIGURE 7. Duration and interval time of different algorithms.

to the other algorithms, which further verifies the correctness of the two algorithms. In addition, the number of route update times and the link duration for MST and GMH are the same. This implies that although MST and GMH are based different ideas and have different methods, the results are the same.

For the number of route updates, this study proposes the MRU algorithm. As illustrated in FIGURE 6, MRU has the least number of route updates, which is much lower than the number of handover times. However, the number of handover times for MRU is greater than that for MST and GMH. The number of route updates of other algorithms, such as MST, GMH, and BRS, is equal to the number of link switches. This is because the MRU reduces the number of route updates by merging some SGLs that can be switched together. Thus, the number of route updates for the MRU is less than the number of handovers. As the switch merge is considered, it is inevitable to waste some of the visible time, and hence, the number of switching times for the MRU increase to 716. MST, GMH, and BRS do not consider the switch merge of SGL; therefore, each switch corresponds to one route update, i.e., the number of handover and route update times are equal.

In addition, we also tested link average duration time and interval time performances of all the proposed algorithms, which is shown in FIGURE 7. Link duration describes the average service time of SGL, and link interval indicates the average interval between each adjacent switchings. As we expected that the more link switching times, the shorter the link duration is, and the least handover frequency means the longest duration time, such as MST and GMH. Because of the switch merge, MRU has the least route update frequency and the longest interval time. BRS has the shortest link interval and largest handover frequency due to its preference for relay nodes shape.

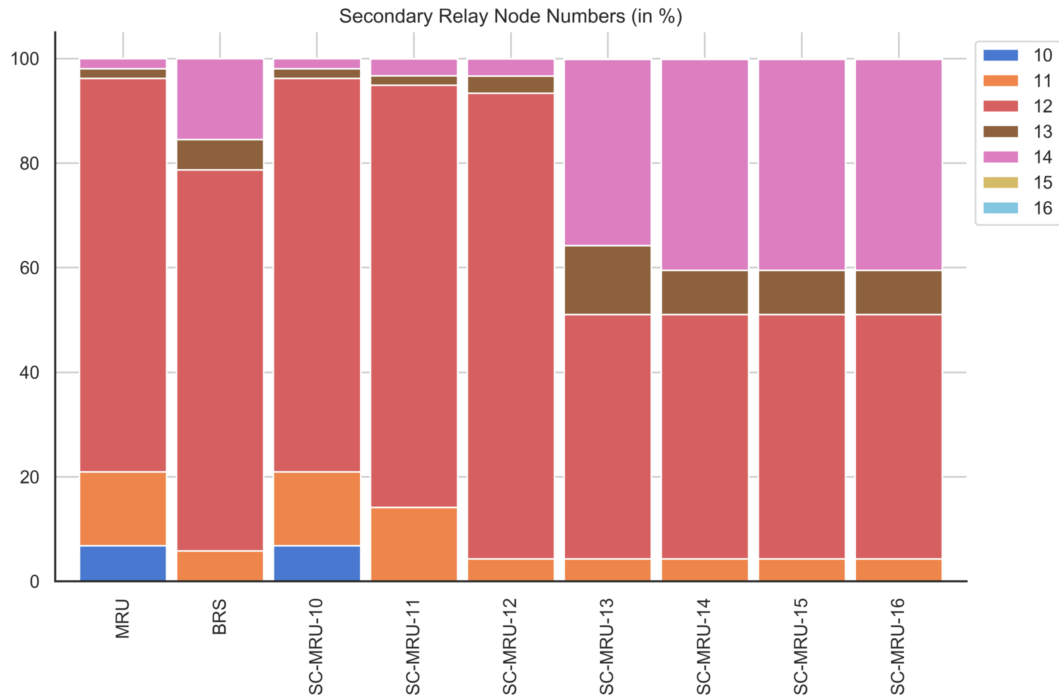


FIGURE 8. Number and proportion of secondary relay satellites for SC-MRU with $n = 10 \sim 16$.

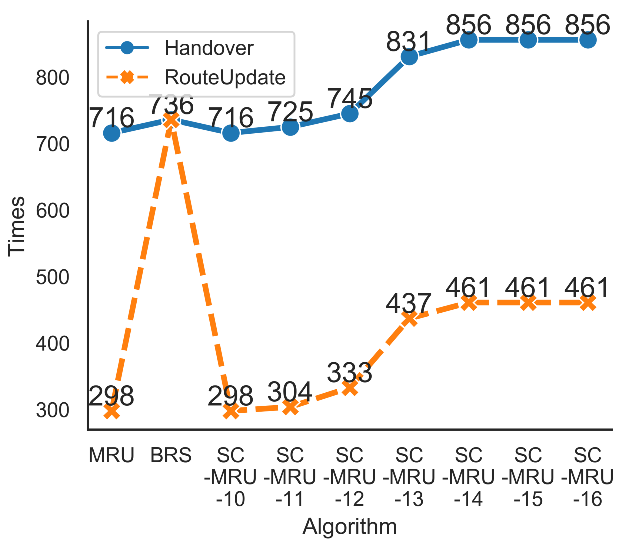


FIGURE 9. Handover and routing update times for SC-MRU with $n = 10 \sim 16$.

Aiming at the configuration optimization of the relay satellites, this study proposes SC-MRU. We examine the change of SC-MRU performance with $n = 10 \sim 16$. As illustrated in FIGURE 8, the number of secondary relay satellites for MRU and BRS are also compared, and the number of their handovers is depicted in FIGURE 9. As expected, BRS only considers the configuration factor, and the number of secondary relay satellites remains high, but the number of route updates is much higher than that of the other methods. When $n = 10$, the performances of SC-MRU and MRU are equivalent. This is because when $n = 10$, the constraint on the configuration is weak, and it basically does not work, and the link planning result is not affected. With the increase of n, the number of secondary relay satellites gradually increases, and the number of route updates increases gradually as well. However when $n = 14$, the number of secondary relay satellites reaches saturation, and no longer increases. Considering the number of route updates and the relay satellite configuration, when $n = 12$, the performances of the above two aspects are better.

V. CONCLUSION

In view of the data transmission characteristics of LEO SNAN, this study optimizes the SGLP problem with respect to three aspects, i.e., number of link switching times, number of route updates, and relay satellite shape. We propose MST, GMH, MRU, and SC-MRU for each of the above three aspects, wherein MST, GMH, and MRU can guarantee the optimality in theory. The simulation results verify that MST and GMH can guarantee the least number of switching times and the results are consistent. MRU reduces the number of route updates compared to MST and GMH by nearly 60%. SC-MRU with $n = 12$ significantly improves the configuration of the relay satellites and improves the network capacity. In addition, the number of routing updates is reduced. To the best of our knowledge, this is the first study on SGLP for LEO SNAN.

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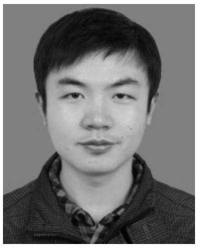

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