Multi-objective Handover Strategy for Space Earth Integrated Network

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(Received 30 March 2023; revised 8 June 2023; accepted 10 June 2023)

Abstract: Efficient information transmission is crucial for the development of space-ground integrated network (SGIN), especially with the growing complexity of low Earth orbit (LEO) satellite architectures. This study aims to optimize the handover process between terrestrial users and satellites by considering metrics such as handover times, elevation angle, and available channels. The proposed mathematical model divides the Earth into multiple regions, and the optimization objective is a weighted sum of the number of handovers and load balance, which determines the weighted coefficients based on different scenarios. The elevation angle can be optimized by setting a threshold that indicates the quality of information transmission. The study transforms the SGIN handover problem into an integer linear programming (ILP) problem and solves it by using mathematical tools to provide an optimal solution. However, due to the high algorithmic complexity of the ILP-based strategy in practical engineering applications, a heuristic handover strategy based on bipartite graphs is also proposed. Simulations on a typical LEO satellite constellation (Globalstar) validate the effectiveness of the proposed handover strategies.

Key words: low Earth orbit (LEO); space-ground integrated network(SGIN); multi-objective; handover

CLC number: TN927.2 **Document code:** A **Article ID:** 1005-1120(2023)04-0447-13

0 Introduction

With the rapid development of mobile communication, satellite networks are expected to provide seamless wireless coverage[1-3]. However, a significant number of terrestrial users accessing fixed ground stations before connecting to the satellite network can reduce the overall network's user connectivity capacity and increase transmission delay. To solve the contradiction between the growing demand for communication in wireless networks and the limited assignable resources, an information network architecture that can support high-speed bandwidth and high capacity has been developed, i.e. the space-ground integrated network (SGIN). SGIN is a heterogeneous network with a satellite network as the backbone, usually consisting of satellites deployed in different orbits and terrestrial users (e.g., ground stations and mobile terminals with satellite communication capabilities)[4]. SGIN can cover terrestrial users in remote areas and enhance the connectivity and resistance to destruction in areas with weak terrestrial communications. Fig.1 shows that in SGIN, space-based networks achieve global communication coverage through the interoperability of satellites of different altitudes, performances, and orbits, which are expected to be incorporated with terrestrial cellular networks in the future[5-6]. Depending on their orbital altitude, satellites can be divided into three main categories. In recent years, low Earth orbit (LEO) satellites have attracted extensive research interest due to their low propagation delay in wireless communication[7-9]. Compared with geostationary Earth orbit (GEO) satellites and medium Earth orbit (MEO) satellites, LEO satellites feature low energy consumption and signal at-

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How to cite this article: TANG Chengwen, NING Qian, HUANG Linyu, et al. Multi-objective handover strategy for space earth integrated network[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2023, 40(4):447-459.

http://dx.doi.org/10.16356/j.1005-1120.2023.04.006

tenuation, which help to reduce power consumption for terrestrial nodes. It is even possible to achieve direct communication between users and LEO satellites, significantly reducing transmission loss. Several projects on LEO satellites, e.g., Starlink, OneWeb, and Kuiper, have made significant progress recently[10-11]. Thus, it is substantial to investigate the wireless communication-related problems in LEO satellites.

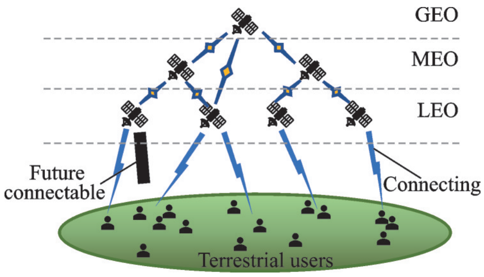

Fig.1 Architecture of SGIN

The space-ground network architecture consists of rapidly moving LEO satellites in relation to terrestrial users. The high dynamic of SGIN would cause the handover problem. The terrestrial users need to switch among satellites to ensure continuous communication uninterrupted. They need to cut out the current connection and establish a new connection to another connectable candidate satellite called satellite-ground handover. However, ineffective handover strategies may influence the quality of experience, such as short remaining visible time, small channel gain, and a poor number of available channels. Therefore, the satellite-ground handover management must be optimized for the space-ground integrated network to provide uninterrupted and consistent high-quality network services.

The key to optimizing the above handover management problem is to simultaneously optimize three metrics: The remaining visible time, the channel gain, and the number of available channels[12-14]. As the remaining visible time decreases, the likelihood of connection interruption increases. This, in turn, leads to a greater frequency of handover events under the handover strategy[15]. Previous studies[16] used a ray-tracing-based channel modeling method. The satellite channel gain response between the LEO satellite j and node i at time slot t and frequency f can be represented by

$$G_{ij,t}=\left(\frac{c}{4h/\sin(\theta_t)f}\right)^2 A(d) \tag{1}$$

where c is the speed of light, h the orbit altitude, θ_t the elevation angle at moment t, and $A(d)$ the atmospheric fading. It can be found that the satellite channel gain is positively related to the elevation angle. Maximizing the elevation angle can optimize the transmission quality. The maximum number of available channels can achieve a balanced load in the LEO satellite networks[17]. Thus, the optimization goal shifts to minimize the number of handover times, maximize the elevation angle, and achieve satellite load balancing as much as possible. Designing a multi-objective satellite-ground handover strategy optimization is significant. This paper focuses on the multi-objective optimization of satellite-ground handover for larger-scale terrestrial users. The main work of this paper is given as follows.

(1) We assume that all ground users have direct communication access to LEO satellites. Additionally, we consider a small geographical region where all users within the area share the same satellite parameters, such as the elevation angle, the distance, the satellite position, and the number of connected users, etc.

(2) We have mathematically modeled the switching issue as an integer linear programming (ILP) problem, which can be solved using mathematical optimization techniques to obtain the optimal solution.

(3) Since obtaining an optimal solution through mathematical calculations can be time-consuming, we propose the development of a heuristic algorithm. This algorithm aims to find a suboptimal solution while significantly reducing the computational time required.

The rest of the paper is organized as follows. Section 1 surveys and analyzes the related work. The system model and problem formulation based on ILP are presented in Section 2. Section 3 explores the heuristic algorithm proposed in this paper. In Section 4, simulations are conducted to compare the proposed strategies with existing ones. Finally, Section 5 draws conclusions.

1 Related Work

In recent years, satellite communications have become increasingly important for some applications such as long-distance information transmission and navigation. A significant portion of existing research has focused on LEO satellite networks and SGIN[18-19].

Some existing work only considers one of the metrics mentioned above. For example, Wang et al.[20] investigated the handover problem by considering the received signal strength to improve channel gain, but this approach might cause an unbalanced satellite load in which many terrestrial users simultaneously connect to a specific satellite. Papapetrou et al.[21] proposed a dynamic handover scheme to address the load issue based on predicting satellite load, but the above letters only optimized a single handover metric and were hard to apply to complicated handover scenarios nowadays. Wu et al.[17] proposed a graph-based handover strategy that can optimize different metrics by changing the edge weight, and reducing the number of handovers for ground users. However, this approach may lead to problems such as low channel gain and unbalanced load.

Designing a multi-objective optimization algorithm is significant to consider the above three metrics simultaneously. Wu et al.[22] proposed a handover strategy based on the potential game, which considered the trade-off between the number of handovers and load balance. However, setting edge weights for different handover scenarios was difficult. Zhang et al.[23] formulated satellite handover as a multi-objective optimization problem and determined weights based on entropy, which can transform the multi-objective problem into an objective function representation. Zhang et al.[24] considered all three metrics using an entitled TOPSIS scheme to determine weights. However, the entropy and TOPSIS methods did not consider the different requirements in many comprehensive global handover scenarios. Reinforcement learning has been proposed as a method to solve the optimization problem[25-27], but the training costs are high in complex satellite networks. A heuristic algorithm has been adopted to solve the multi-objective problem in satellite networks[28-30]. Therefore, obtaining an optimal multi-objective calculation result that satisfies different requirements is essential three metrics simultaneously.

2 System Model and Problem Formulation

2.1 System model

The satellite network is considered to consist of M LEO satellites. The ith satellite is denoted by S_i, $i \in \{1, 2, 3, \cdots, M\}$. The maximum capacity of S_i is assumed to be P_i connections. The whole earth is divided into N regions, as shown in Fig.2. Let R_k denote the kth region. Taking into account the non-uniform distribution of real-world ground users, we assume that the number of users in each region follows a random distribution. Let U_k denote the number of users in R_k. The satellite coverage information for users in one region is assumed to be the same. The handover problem in the following T slots is studied in this paper. We define a $N \times M \times T$ 3D matrix $\boldsymbol{E} = [e_{kit}]$, where e_{kit} represents the elevation angle between users in R_k and S_i at the tth slot. We define a 4D matrix $\boldsymbol{C} = [c_{kijt}]$ whose dimension is $N \times M \times M \times T$, where c_{kijt} denotes the number of users switching from S_i to S_j in R_k at the tth slot. $\boldsymbol{C}$ is called the assignment matrix throughout the paper. For a given k' and t', if i equals j, the value of $c_{k'ijt'}$ indicates the number of users that still connect to S_i.

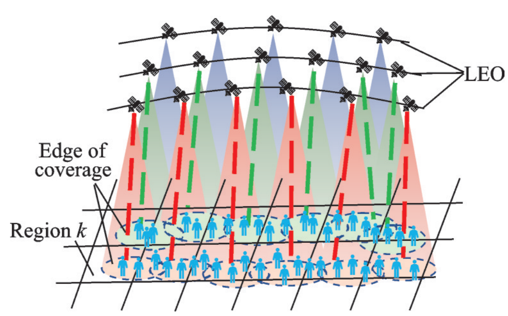

Fig.2 System model

By executing the handover strategy to change the assignment matrix $\boldsymbol{C}$, we obtain the connection status of all users in T slots. The assignment matrix

$\boldsymbol{C}$ represents the optimized result of the strategy. The handover strategy optimized will be transmitted from the regional control centers to all users within the region. Users will automatically switch and connect to the corresponding satellite based on the instructions, which are similar to the flow table information in network routing.

Subsequently, we conduct a modeling analysis on three metrics, including the number of handovers, the elevation angle, and the load balancing degree.

2.2 Problem formulation

2.2.1 Number of handovers

The number of handovers is an important metric. On one hand, it represents establishing and dismantling communication links between satellites and users. On the other hand, for a particular node within a given interval, connecting to the satellites with a smaller number of handovers means less waste of resources. We define an auxiliary 4D matrix $\boldsymbol{A}=[a_{kijt}]$, whose dimension is $N\times M\times M\times T$. a_{kijt} denotes whether it is possible to switch from S_i to S_j for users in R_k at the tth slot. If the user can switch, then $a_{kijt}=1$, otherwise $a_{kijt}=0$. However, the ability to perform a handover is conditional. When $i=j$, no handover is possible and $a_{kijt}=0$. Additionally, if the elevation angle e_{kit} between the users in R_k and S_j does not meet communication requirements, a connection cannot be established and a handover cannot occur. The value of a_{kijt} is defined as

$$a_{kijt}=\begin{cases}1 & i\neq j \text{ and } e_{kit}\neq 0,\ e_{kjt}\neq 0\\ 0 & \text{Otherwise}\end{cases} \tag{2}$$

So, $c_{kijt}a_{kijt}$ denotes the number of ground users who switch from S_i to S_j in R_k at the tth slot. The total number of handovers in R_k at the tth slot can be calculated by

$$\sum_{j=1}^{M}\sum_{i=1}^{M}c_{kijt}a_{kijt} \tag{3}$$

Across varying network scales, the number of users can influence the overall frequency of network handovers. Therefore, we adopt the average number of handovers per user as the objective function. The average number of handovers in N regions within T slots is

$$\frac{\sum_{k=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{M}\sum_{i=1}^{M}c_{kijt}a_{kijt}}{\sum_{k=1}^{N}U_k} \tag{4}$$

2.2.2 Elevation angle

The assignment matrix $\boldsymbol{C}$ serves as both the result of policy optimization and an independent variable in the model. $\sum_{i=1}^{M}c_{kijt}$ denotes the number of users switching their connections from all satellites to S_j in R_k at the tth slot. In R_k at the tth slot, the total elevation angle of U_k connected to all LEO satellites can be calculated by

$$\sum_{j=1}^{M}\sum_{i=1}^{M}c_{kijt}e_{kjt} \tag{5}$$

Since the total number of the nodes in all users is $\sum_{k=1}^{N}U_k$, the average elevation angle of all users in the network during a communication period T is

$$\frac{\sum_{k=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{M}\sum_{i=1}^{M}c_{kijt}e_{kjt}}{\sum_{k=1}^{N}U_k} \tag{6}$$

2.2.3 Degree of load balancing

The lower the number of available satellite channels, the higher the load value of the satellite, and implementing load balancing can reduce the occurrence of this situation[31]. At the tth slot, $\sum_{k=1}^{N}U_k/M$ can calculate the average number of connections per satellite. The total number of users connected to S_j at the tth slot can be calculated by $\sum_{k=1}^{N}\sum_{i=1}^{M}c_{kijt}$. The term "degree of load balancing" refers to taking the average difference between all satellite load values at a given time and the average load value of the entire network. In other words, the smaller the average difference value, the more balanced the satellite network load. The following indicator is defined to measure the degree of load balancing in N regions at the tth slot, shown as

$$\frac{\sum_{j=1}^{M}\left|\sum_{k=1}^{N}\sum_{i=1}^{M}c_{kijt}-\sum_{k=1}^{N}U_k/M\right|}{M} \tag{7}$$

Therefore, the average load balance degree over all the regions during T time slots can be calculated by

$$\frac{\sum_{t=1}^{T}\sum_{j=1}^{M}\left|\sum_{k=1}^{N}\sum_{i=1}^{M}c_{kijt}-\sum_{k=1}^{N}U_k/M\right|}{MT} \tag{8}$$

2.2.4 Modeling with linear programming

This paper considers the average elevation angle, the number of handovers, and the degree of load balancing when making handover decisions. And a threshold is set for the elevation angle. That is, when the elevation angle is higher than a certain threshold, it can be regarded that the transmission quality is acceptable at this time. The objective function is to minimize a weighted sum of the number of handovers and the load balancing degree.

The objective function is a trade-off between the number of handovers and the degree of load balancing. A weight coefficient $\delta\in[0,1]$ is defined as a weighted sum of the number of handovers and degree of load balance. The value of δ can be selected based on the actual requirements of application scenarios. When $\delta=1$, the objective is only to minimize the number of handovers. When $\delta=0$, the aim is only to balance the network load. In other cases, the trade-off between them is considered. The objective function of optimization is

$$\min\ \delta\frac{\sum_{k=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{M}\sum_{i=1}^{M}c_{kijt}a_{kijt}}{\sum_{k=1}^{N}U_k}+(1-\delta)\cdot\frac{\sum_{t=1}^{T}\sum_{j=1}^{M}\left|\sum_{k=1}^{N}\sum_{i=1}^{M}c_{kijt}-\sum_{k=1}^{N}U_k/M\right|}{MT} \tag{9}$$

However, the above formula is nonlinear as it contains an absolute value function. To make a linear transformation, let $H_{jt}=\left|\sum_{k=1}^{N}\sum_{i=1}^{M}c_{kijt}-\sum_{k=1}^{N}U_k/M\right|$. The absolute value function can be replaced by

$$\begin{cases}\sum_{k=1}^{N}\sum_{i=1}^{M}c_{kijt}-\sum_{k=1}^{N}U_k/M\leqslant H_{jt}\leqslant\\ \qquad\sum_{k=1}^{N}U_k/M-\sum_{k=1}^{N}\sum_{i=1}^{M}c_{kijt}+Q\delta_{jt}\\ \sum_{k=1}^{N}U_k/M-\sum_{k=1}^{N}\sum_{i=1}^{M}c_{kijt}\leqslant H_{jt}\leqslant\\ \qquad\sum_{k=1}^{N}\sum_{i=1}^{M}c_{kijt}-\sum_{k=1}^{N}U_k/M+Q\varepsilon_{jt}\\ \delta_{jt}+\varepsilon_{jt}=1,\quad \delta_{jt},\ \varepsilon_{jt}\in[0,1]\end{cases} \tag{10}$$

where δ_{jt} and ε_{jt} are binary variables, and Q is a sufficiently large number. In this case, it can be chosen as $\min\left\{\sum_{k=1}^{N}U_k/M,\ \ \max\{P_1,P_2,P_3,\ \cdots,P_M\}\right\}$. Finally, the optimization problem can be written as follows

$$\min\ \delta\frac{\sum_{k=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{M}\sum_{i=1}^{M}c_{kijt}a_{kijt}}{\sum_{k=1}^{N}U_k}+(1-\delta)\frac{\sum_{t=1}^{T}\sum_{j=1}^{M}H_{jt}}{MT} \tag{11}$$

$$\text{s.t.}\quad c_{kijt}\leqslant U_k a_{kijt}\quad \forall k,\ \forall i,\ \forall j,\ \forall t \tag{12}$$

$$\sum_{m=1}^{M}c_{kmit}=\sum_{j=1}^{M}c_{kij(t+1)}\quad \forall k,\ \forall i,\ \forall t\in[1,T-1] \tag{13}$$

$$\sum_{k=1}^{N}\sum_{i=1}^{M}c_{kijt}\leqslant P_j\quad \forall j,\ \forall t \tag{14}$$

$$\eta_{\text{th}}\leqslant\frac{\sum_{k=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{M}\sum_{i=1}^{M}c_{kijt}e_{kjt}}{\sum_{k=1}^{N}U_k} \tag{15}$$

$$\sum_{k=1}^{N}\sum_{i=1}^{M}c_{kijt}-\sum_{k=1}^{N}U_k/M\leqslant H_{jt}\leqslant\sum_{k=1}^{N}U_k/M-\sum_{k=1}^{N}\sum_{i=1}^{M}c_{kijt}+Q\delta_{jt} \tag{16}$$

$$\sum_{k=1}^{N}U_k/M-\sum_{k=1}^{N}\sum_{i=1}^{M}c_{kijt}\leqslant H_{jt}\leqslant\sum_{k=1}^{N}\sum_{i=1}^{M}c_{kijt}-\sum_{k=1}^{N}U_k/M+Q\varepsilon_{jt} \tag{17}$$

$$\delta_{jt}+\varepsilon_{jt}=1\quad \delta_{jt},\ \varepsilon_{jt}\in[0,1] \tag{18}$$

Constraint (12) is used to limit in R_k, the value of the assignment matrix $\boldsymbol{C}$ cannot exceed the total number of users U_k. In constraint (13), the left-hand side of the equation represents the number of ground users connected to S_i in R_k at the tth slot, while the right-hand side represents the sum of the number of users switching from S_i to other satellites in R_k at the $(t+1)$th slot and the number of users continuing to connect to S_i. These two quantities are equal. Constraint (14) is used to ensure that the number of nodes connected to each LEO satellite in any region at any time will not exceed the upper limit of its load capacity. Constraint (15) ensures that the average elevation angle is higher than the threshold constant η_{th} to provide better transmission quality. The constraints (16—18) successfully convert the absolute value part of the objective function from nonlinear to linear, and $Q=$

$$\min\left\{\sum_{k=1}^{N} U_k/M,\quad \max\{P_1, P_2, P_3, \cdots, P_M\}\right\}.$$

The above optimization problem is a standard ILP problem, which can be solved by common mathematical tools. We then utilize the "optimize" function in YALMIP to define the objective function and constraints, employing CPLEX as the solver to obtain the optimal solution $\boldsymbol{C}$. The matrix $\boldsymbol{C}$ represents the optimal satellite-user connection results, which can be utilized to derive specific metrics such as switching count and load balancing.

3 Heuristic Handover Strategy

This section proposes a heuristic algorithm-based handover strategy (HSHA) to improve the computational efficiency of the algorithm. Similar to the ILP handover model, the approach considers N regions, with the kth region represented by R_k, and each region has M satellites. Fig.3 depicts the handover model based on a bipartite graph in R_k, where S_{it} denotes the ith satellite in the tth time slot, L_{it} denotes the load of S_{it}, and the upper load limit of S_i is P_i.

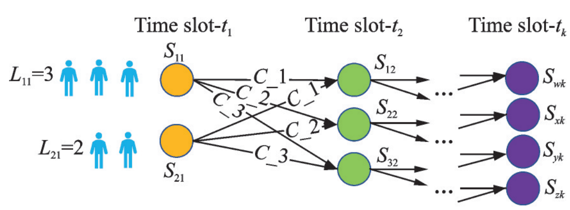

Fig.3 Handover model based on bipartite graph in R_k

The proposed HSHA works as follows. Initially, the number of terrestrial users in each region is randomly distributed, and there are U_k users in R_k. Then, at each time slot per satellite, the user selects the path with the lowest cost C_z to the next time slot. Finally, the cycle is completed. This approach significantly reduces the computational complexity, making it suitable for practical engineering applications.

Setting the elevation threshold η_{th} to obtain the connectable satellites with high channel gain. We set $\bar{U}=\sum_{k=1}^{N} U_k/M$ to be the intermediate mean value for load balance. Assessing the cost function $C_j = C = \delta C_1 + (1-\delta)C_2$, where C_1 is the cost of handover, and C_2 is the cost of the difference between S_{it} load value and $\bar{U}$. All users in all regions are assigned cyclically, and the step with the lowest cost is selected each time. At each time slot, an allocation matrix $\boldsymbol{L}$ is generated by assigning each terrestrial user. This allocation matrix $\boldsymbol{L}$ represents the final handover results obtained by the heuristic algorithm. The pseudo-code of this algorithm is shown below.

Algorithm 1 Handover strategy based on heuristic algorithm

Input: S_{mt}, δ, T, $\overline{U}$, L

Output: num, L_{num}

Initialize U_k, $\boldsymbol{L}(i,1)$

for $u = 1 \rightarrow \sum_{k=1}^{N} U_k$ do

  for $t = 2 \rightarrow T$ do

    for $j = 1 \rightarrow M$ && $\boldsymbol{L}(j,t) < P_i$ do

      if $i \neq t$ then

        $C_1 = 0$

      else

        $C_1 = 1$

      end if

      $C_2 = (1 + \boldsymbol{L}(l,t) - \bar{U})^2 - (\boldsymbol{L}(j,t) - \bar{U})^2$

      $C\_j = C = \delta C_1 + (1-\delta)C_2$

    end for

    $C\_z = \min\{C\_1,\ C\_2,\ \cdots,\ C\_M\}$

    $\boldsymbol{L}(z,t) = \boldsymbol{L}(z,t) + 1$

    if $i \neq z$ then

      $num = num + 1$

    end if

  end for

end for

for $i = 1 \rightarrow M$ do

  for $t = 1 \rightarrow T$ do

    $L_{num} = L_{num} + \left|\boldsymbol{L}(i,t) - \bar{U}\right|$

  end for

end for

$L_{num} = L_{num}/(MT)$

$num = num/\bar{U}$

Compared with the ILP method, HSHA cannot find a globally optimal solution. However, HSHA can only provide a feasible solution within acceptable costs (referring to computation time and space), and this feasible solution can closely approximate the optimal solution. In practical engineering applications, HSHA can provide a solution with the advantage of low algorithm complexity and short computation time. Algorithm 1 mainly contains three levels of nested loops: The number of IoT nodes, LEO satellites, and simulation time. Therefore, the algorithm's complexity can be obtained as $O(TMU)$.

4 Simulation Analysis

4.1 Simulation scene selection

This section evaluates the performance of the proposed satellite handover strategy via simulations. It is necessary to ensure that many satellites can be connected at each time slot for a particular region. To accomplish this, we employ the Globalstar constellation[32], an operational real-world satellite network. The relevant simulation parameters are shown in Table 1.

The satellite tool kit (STK) is employed to obtain satellite coverage and elevation angles in the Globalstar constellation. As shown in Fig.4, throughout a 30 min experimental period, the Globalstar constellation has four or more satellites covering the region simultaneously. This ensures that all ground users can connect to the LEO satellites, avoiding the situation that the connection is interrupted and cannot be switched.

Table 1 Parameters for simulation

Parameter	Value
Orbit altitude/km	1 389
Orbit inclination/(°)	52
Orbital plane number	6,8,10
Number of satellites per orbit	6
Semimajor axis/km	7 767
Minimum elevation value of link connection/(°)	10
Elevation threshold/(°)	15

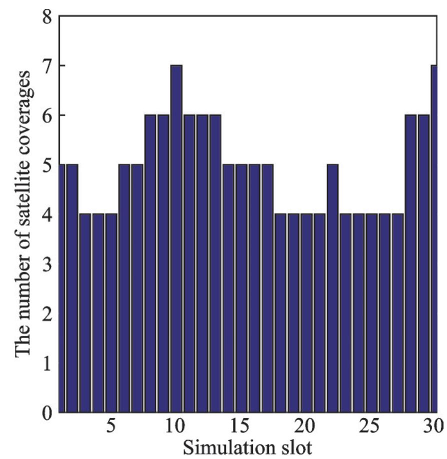

Fig.4 Satellite coverage analysis in Globalstar constellation

Fig.5 illustrates the coverage of ground terminals by LEO satellites within the Globalstar constellation. The blue lines represent the orbital paths of the satellites, while the orange curves depict the coverage range of the satellites at a given moment. This visualization provides a more intuitive representation, indicating that at a specific time, certain regions may be simultaneously covered by multiple satellites. Furthermore, locations closer to the center of satellite coverage exhibit higher elevation angles, resulting in higher channel gains.

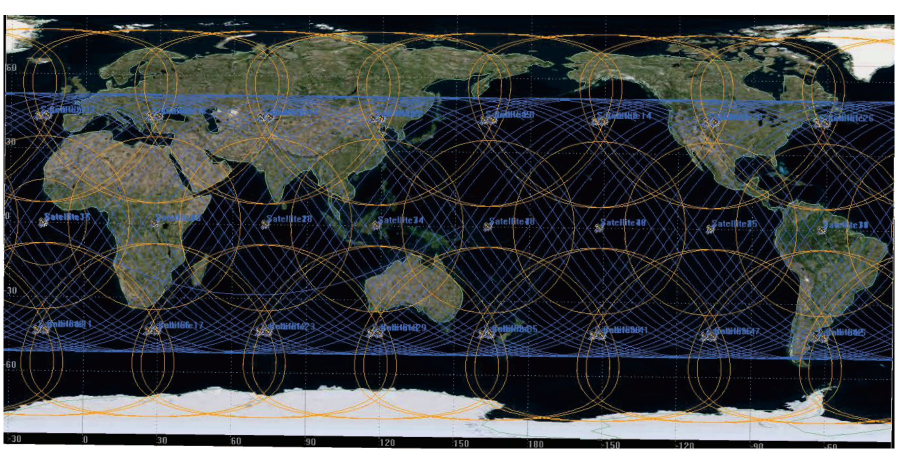

Fig.5 Communication range of LEO satellites in Globalstar

4.2 Optimize weight selection

The optimization objective function is given in Section 2. We use Eq.(11) as the objective optimization function and Eqs.(12—17) as constraints, use the YALMIP toolkit in Matlab 2019a to solve the integer linear programming to obtain the optimal solution matrix $\boldsymbol{C}$, and then bring the result of matrix $\boldsymbol{C}$ into Eq.(4) and Eq.(8) to get the average handover times ($E(N)$) and load balancing degree ($L(N)$). We found that the optimization results change with different values of δ. As illustrated in Table 2, it can be found that with the change of δ, the changing trend of handover times and load balancing degree is opposite. This is because when the average number of handovers is small, many users are connected to the same satellite in order not to handover as much as possible, which will cause a high load variance in the satellite network, and then make the load balance too large, so the two indicators are contradictory.

Table 2 Two metrics changing with δ

δ	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
$E(N)$	19.074 10	2.506 17	2.506 17	2.494 95	2.479 24	2.471 38	2.400 67	2.393 94	2.306 40	2.285 07	2.261 50
$L(N)$	18.110 1	18.110 1	18.110 1	18.113 3	18.122 7	18.128 3	18.216 3	18.229 5	18.524 3	18.642 3	24.089 9

4.3 Comparison of handover strategies

This paper implements the handover strategy based on ILP (HSILP) in Section 2 and HSHA in Section 3. In addition, we add two handover strategies for comparison. One of the algorithms considers the channel gain as its optimization goal (represented by the optimal channel)[23]. The other algorithm is an improved algorithm based on graph theory (represented by the shortest path)[17], which takes the time of satellites covering the ground as nodes. It then uses the Dijkstra algorithm to obtain the shortest path for each terrestrial user.

4.3.1 Number of handovers

For HSILP, we obtain the matrix $\boldsymbol{C}$ by solving the ILP problem, and put $\boldsymbol{C}$ into Eq.(4) to obtain $E(N)$; for HSHA, we obtain *num* by running Algorithm 1, which is $E(N)$. Fig.6 shows that, with the increase in transmission time, the number of handovers under the four strategies increases approximately linearly when $\delta = 1$. In Eq.(11), $\delta = 1$ indicates that only the number of handovers is optimized. It can be observed that the HSILP strategy has the slowest increase in the number of handovers. In contrast, the optimal channel strategy has the fastest increase, and the shortest path strategy and HSHA have a moderate increase rate. These results demonstrate that the HSILP strategy can effectively reduce handover times and provide the best optimization results.

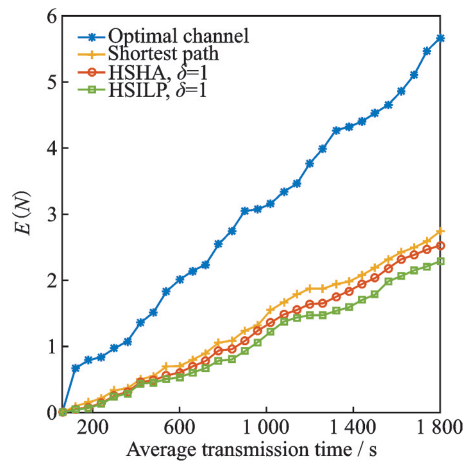

Fig.6 Comparison of cumulative handover times for four different handover strategies when $\delta = 1$

δ can be set according to different optimization needs in the actual scenario. Fig.7 compares the handover times of the proposed strategies with the other two strategies when $\delta = 0.8$ and $\delta = 0.2$. It can be observed that the HSILP strategy has the slowest increase in the number of handovers. Although the curve of HSHA when $\delta = 0.8$ and $\delta = 0.2$ grows faster than the curve of the shortest path, the algorithm computation time of HSHA is much lower. We will conduct experiments to analyze the algorithm complexity later. Therefore, it can be concluded that HSHA can also reduce the handover times in satellites network.

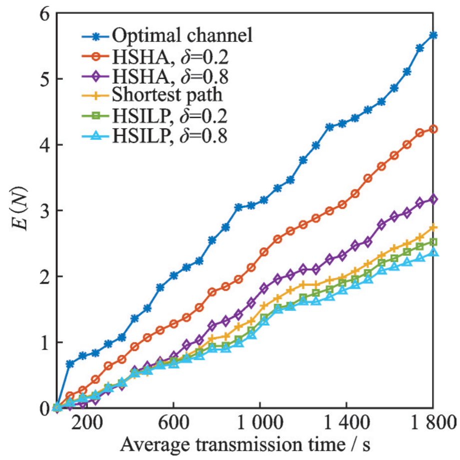

Fig.7 Comparison of cumulative handover times for four different handover strategies when $\delta=0.8$ and $\delta=0.2$

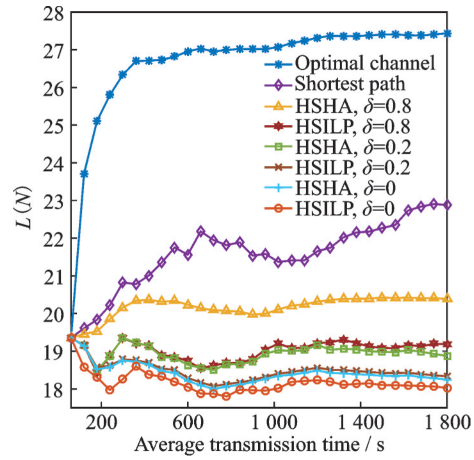

Fig.8 Comparison of load balancing degree for four different handover strategies

4.3.2 Degree of load balancing

For HSILP, we obtain the matrix $\boldsymbol{C}$ by solving the ILP problem, and put $\boldsymbol{C}$ into Eq.(8) to obtain $L(N)$. For HSHA, we obtain L_{num} by running Algorithm 1, which is $L(N)$. Fig.8 presents the changes in the load balancing degree under the four strategies. $\delta=0$ indicates that only load balancing is optimized. $\delta=0.8$ and $\delta=0.2$ refer to different optimization requirements in the scenario. It can be observed that the HSILP strategy results in the lowest load imbalance among the six curves, indicating that the load is relatively evenly distributed among the satellites. On the other hand, the optimal channel strategy has the highest load imbalance, indicating that the load is unevenly distributed among the satellites. Therefore, in a multi-user scenario, the ILP method has excellent load-balancing capabilities. HSHA is guaranteed to obtain suboptimal solutions with very low algorithmic complexity.

4.3.3 Algorithm complexity analysis

An algorithm complexity analysis is performed for a scenario with T time slots, M LEO satellites, and U terrestrial IoT nodes. The algorithm in Ref.[22] is based on the Dijkstra algorithm, whose algorithm complexity is $O(n^2)$[33], so the algorithm complexity of the shortest path is $O(T^2M^2U)$. In contrast, the algorithm complexity of HSHA can be obtained as $O(TMU)$ based on Algorithm 1. It can be found that as the number of LEO satellites and the transmission duration increase, the complexity of HSHA is lower than that of the shortest path algorithm.

To illustrate the disparity in computational time among the three algorithms, we conducted simulations using a continuous 30 min call scenario. The simulations are performed under varying numbers of ground users. As shown in Table 3, the computation time for HSILP significantly exceeds that of HSHA and shortest path algorithms.

Table 3 Differences in computational time among three strategies

Number of users		1 000	2 000	4 000	8 000	16 000	32 000	64 000	128 000
Computation time/ms	HSILP	4 907 389	4 993 927	4 993 927	4 968 896	4 968 896	4 932 813	4 918 525	4 881 186
	Shortest path	13 814	25 255	49 434	93 680	170 440	357 907	713 574	1 422 957
	HSHA	3 577	3 577	10 862	20 321	39 541	39 541	152 493	321 501

Fig.9 shows the simulation time of HSILP, the shortest path strategy, and HSHA. It can be found that the algorithm complexity of HSILP is too high to be used for practical engineering applications. The simulation time of the shortest path strategy and HSHA increases linearly with the number of terrestrial IoT nodes, and the calculation time of HSHA is lower. Therefore, it is proved that HSHA can be effectively applied in satellite networks. HSHA can reduce the number of handovers, reduce computational complexity, and enable quick decision responses.

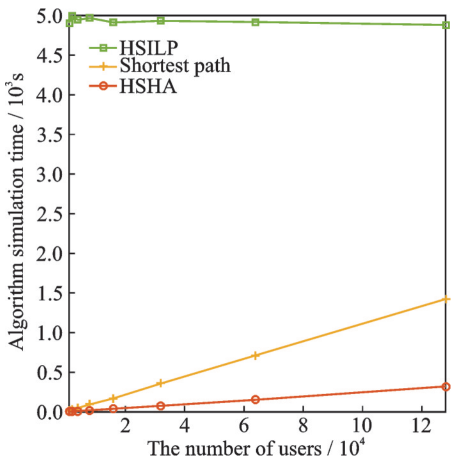

Fig.9 Comparison of computation time for HSILP, HSHA and shortest path strategies

4.3.4 Scenario scalability analysis

We conducted an experimental analysis on handover strategies' scalability. By adjusting the number of orbital planes in Table 1, the orbit density of the satellite network can be modified. More orbital planes translate to higher orbit density, providing a greater number of satellites for ground IoT nodes to connect with. This results in fewer handover numbers for IoT nodes within the same transmission time. Similarly, a denser satellite network also means more LEO satellites involved in the connection switching process, resulting in reduced load balancing. Testing was performed on HSHA, the optimal channel strategy, and the shortest path strategy at different orbit densities, using a 30 min transmission duration as example. As shown in Fig.10, increasing the number of orbital planes elevates the orbit density, leading to a decrease in average handovers across different strategies and reduced load balancing. The optimization results for HSHA in terms of handover times and load balancing were better at different orbit densities. This indicates that HSHA can be better applied to different satellite networks.

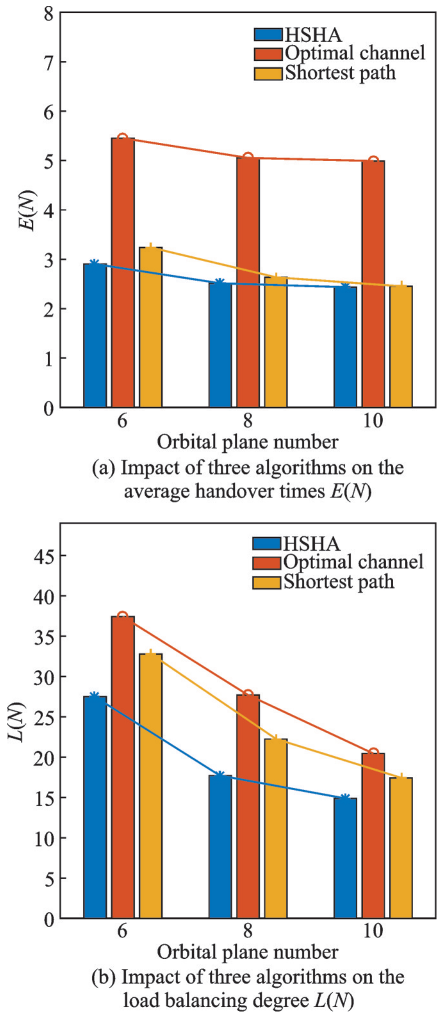

Fig.10 Impact of HSHA, optimal channel, and shortest path strategies on the average handover times and the load balancing degree of a network with varying numbers of orbital planes

5 Conclusions

The satellite handover issues have gained significant attention with the development of SGIN technology. The key to solving the problem is to optimize multiple objectives. This work proposes two multi-objective LEO satellite handover strategies. We transformed the satellite handover problem into an ILP problem through mathematical modeling and obtained the optimal solution using specialized ILP solving tools. But, the computational time required by the HSILP algorithm is impractical for engineering applications. To address this, we developed a heuristic algorithm, HSHA, based on the bipartite graph model. HSHA provides a suboptimal solution that closely approximates the optimal solution achieved by HSILP, while significantly reducing algorithmic complexity. However, there is still room for improvement in this area. Increasing the scale of LEO satellite networks can enable users to select more connectable satellites. Based on the HSILP strategy, training the obtained data as a dataset may lead to optimization results that are very close to the optimal solution.

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Acknowledgements This work was supported by the National Natural Science Foundations of China (Nos. 61961040, 61771089), and the Sichuan Provincial Key Research and Development Program (No.2021YFQ0011).

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guidance on experimental development and thesis writing. Mr. **XIE Xuan** collected experimental data and assisted in designing experimental details. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing inrests.

(Production Editor: ZHANG Huangqun)

天地一体化网络下的多目标切换策略

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摘要: 随着低地球轨道(Low Earth orbit, LEO)卫星的网络结构日益复杂,高效的信息传输对于天地一体化网络(Space-ground integrated network, SGIN)的发展至关重要。本文通过同时考虑切换次数、仰角和可用信道数量等指标来优化多目标切换问题。通过数学建模将地球划分为多个区域,并将优化目标定义为切换次数和负载均衡的加权和,根据不同场景确定加权系数。通过设置表示信息传输质量的阈值,可以优化仰角。本文将天地一体化网络的卫星切换问题转化为整数线性规划(Integer linear programming, ILP)问题,并使用数学工具求解,以提供最优解。同时,由于在实际工程应用中基于ILP的策略具有较高的算法复杂性,本文还提出了一种基于二分图的启发式切换策略。通过对一个实际应用的低轨卫星星座(Globalstar)进行仿真实验,验证了本文所提出的切换策略的有效性。

关键词: 低地球轨道;天地一体化网络;多目标;切换