IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received August 29, 2019, accepted September 5, 2019, date of publication September 13, 2019,
date of current version September 27, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2941217

A Satellite Handover Strategy Based on the Potential Game in LEO Satellite Networks

YANG WU, **GUYU HU**, **FENGLIN JIN**, **AND JIACHEN ZU**
Institute of Command and Control Engineering, Army Engineering University, Nanjing 210007, China
Corresponding author: Guyu Hu (huguyu@189.cn)

ABSTRACT In a low earth orbit (LEO) satellite network, handover management across satellite spot beams needs to be addressed to decrease handover times while using network resources efficiently since the speed of LEO satellites is much higher than that of mobile nodes. In this paper, we propose a novel satellite handover strategy based on the potential game for mobile terminals in a LEO satellite communication network. To continue communication with the counterpart, the user has to switch among the covered LEO satellites. In a software-defined satellite network (SDSN) architecture, the satellite handover can be viewed as a bipartite graph. To balance the satellite network workload, we propose a terminal random-access algorithm based on the target of userspace maximization. The simulated handover conducted on a typical LEO satellite network, Iridium, corroborates the effectiveness of the proposed handover strategy.

INDEX TERMS LEO satellite network, satellite handover, potential game, the bipartite graph, random access.

I. INTRODUCTION

With the steady increase of multimedia business and mobile terminal users' increasingly urgent demand for convenient access, geostationary orbit (GEO) satellites have not satisfied the application requirements of latency and the use of the frequency spectrum. In this case, the constellation network consisting of non-geostationary (NGEO) satellites, especially LEO satellites, has emerged at a historic moment and has good development prospects. The LEO constellation is deployed on the low track at a height of 500-1500 km above the ground. It has the advantages of low propagation delay, low energy consumption and suppression of signaling attenuation, which is conducive to real-time communication and the power reduction of mobile terminals. Therefore, the LEO constellation will be widely applied in the near future.

However, the call duration of a single satellite-ground link only continues for approximately 10 minutes in LEO satellite networks. To maintain the call, the mobile terminals need to disconnect from the currently connected satellite and establish a connection with another satellite. It is necessary to constantly change the connection relationship between satellites and terminals. Nevertheless, the satellite handover can lead to many problems, such as delay, transmission loss and signaling overhead. It is significant to design an intelligent satellite handover strategy to minimize the average satellite handover number, decrease call-dropping probability, improve call quality and balance the constellation network load.

The satellite handover mentioned above is just one of three types of satellite handovers. There are another two satellite handovers, i.e., spotbeam handover and intersatellite link (ISL) handover. Spotbeam handover refers to the satellite handover between multiple beams when the satellite uses multiple beams. The solutions for spotbeam handover are relatively mature [1], [2]. ISL handover refers to the fact that, when a satellite approaches the polar region gradually, it will lose connection with another satellite in adjacent orbit. This is because the relative velocity of satellites in adjacent orbits changes too fast to realize the acquisition, orientation, and tracking of satellites. When it leaves the polar region gradually, it will establish connection with others in an adjacent orbit. ISL handover is related to hardware. Research on the problem of satellite-ground link is relatively rare, which is mainly due to the small number of satellites in the existing satellite networks. For example, in Iridium, users in the middle- and low-latitude region can only select two satellites under normal circumstances, and they have no need to choose when switching. However, when there are a large number

The associate editor coordinating the review of this manuscript and approving it for publication was Nan Wu.

of satellites in the satellite network, it is necessary to study the satellite handover of satellite-ground links to improve the utilization rate of the system and the communication quality. We do not consider the above two types of satellite handovers and only do research on the satellite handover of satellite-ground links. Therefore, the satellite handover mentioned below refers to the handover of a satellite-ground link specifically.

There are three basic criteria for satellite handovers, namely, the remaining visible time, the elevation angle and the number of available satellite channels. The remaining visible time has an impact on the number of satellite handovers. The satellite elevation angle can guarantee the call quality. The number of available satellite channels can affect the load of the satellite constellation network. The other evaluation criteria can be generated by the three evaluation criteria.

The satellite handover problem is a hot issue in academia and industry. Duan *et al.* [3] proposed a handover control strategy combined with multihop routing. Syed Umer Bukhari *et al.* [4] used fuzzy c-mean clustering based on LEO satellite handover. They overlooked the call quality. Hu *et al.* [5] proposed a velocity-aware hand overprediction in LEO satellite communication networks. Gkizeli *et al.* [6] proposed a handover strategy based on hardware to put off the moment of satellite handover as long as possible. Therefore, it can decrease the frequency of satellite handover. On this basis, a hybrid channel adaptive handover scheme was put forward, which realized soft satellite handover. However, the call quality cannot be guaranteed, and the number of satellite handovers can be decreased further. Remmy *et al.* [7] analyzed the performance of correlated handover service in LEO satellite systems. Gervais *et al.* [8] proposed adaptive handoff for multiantenna mobile satellite systems with an ancillary terrestrial component. Liao *et al.* [9] provided analysis of maximum traffic intensity under the preset quality of service requirements for fixed-channel reservation with a queuing handover scheme. Papapetrou *et al.* [10], [11] put forward many satellite handover strategies and tested them with the criteria of maximum service time, maximum elevation angle and most available channels. They made the system have good communication efficiency, but they did not take the Earth's rotation into account. To avoid wasting resources for early resource reservation, Karapantazis and Pavlidou [12] adopted a dynamic Doppler priority handover strategy to decrease the blocking rate. Poethi and Maral [13] chose the visible time, capacity, elevation and overlap time as the criteria for the satellite handover. However, all of the above can be derived from the basic three satellite handover criteria. Seyedi and Safavi [14] worked out the average lower bound of satellite handover and the distribution function of the satellite visible time from the perspective of probability theory in the low-orbit constellation. Younes *et al.* [15] studied a channel model that could calculate the apparent time of a user on a street. Irfan *et al.* [16] calculated the visible time based on many parameters, such as constellation, latitude, longitude and the location of the user. Wu *et al.* [17] studied simple real-time handover management in satellite networks. Wu et al. [18] proposed an architecture called the software-defined satellite network (SDSN) and a seamless handover mechanism based on this architecture. Compared with hard and mixed satellite handovers, the algorithm has greater advantages of delay and throughput. All of the above methods can only minimize the number of satellite handovers. However, the call quality cannot be guaranteed, and the handover time is not considered.

The aim of our works is to improve call quality, balance constellation network load and minimize the number of satellite handovers. Our works are based on an SDSN architecture. In the SDSN architecture, GEO and LEO satellites are respectively used as nodes in the control plane and transport nodes in the data plane, and the network control center serves as a centralized server to control signal transmission. We embarked from the bipartite graph framework for handover and set up the satellite resource sharing game model. The main works are summarized as follows:

- We modeled the handover process for all users and established the framework based on the binary graph. At every moment, the connection relations between LEO satellites and mobile terminals are represented by a bipartite graph. In the bipartite graph, one vertex set shows all LEO satellites, and the other shows all mobile terminal nodes. Moreover, the edges of the bipartite graph show the call between the LEO satellites and the mobile terminal nodes. The ISLs are not considered in this paper.
- Based on an SDSN architecture, we proposed a handover algorithm based on the potential game to gain the maximum benefits of the mobile terminals. At every moment, there are many competitions among the mobile terminals on the ground, and the resources are satellites and available channels. As a result, the system reaches Nash equilibrium, and we have demonstrated it in the appendix.
- A terminal random access algorithm based on the target of userspace maximization is proposed. We set the complexity of the access terminals according to the geographical location and allocate the load by maximizing the feasible area of the subsequent access terminals. Finally, the LEO system can approach the optimal with a balanced workload.

II. A SATELLITE HANDOVER STRATEGY BASED ON THE POTENTIAL GAME

A. SYSTEM MODEL

With the popularization of LEO satellite communication, the number of users and the amount of data in LEO satellite networks have increased rapidly. The number of connection relationships between LEO satellites and mobile terminals is very large. However, the on-board processing and storage capacities of LEO satellites cannot meet the requirements of storing and processing these connection relationships.

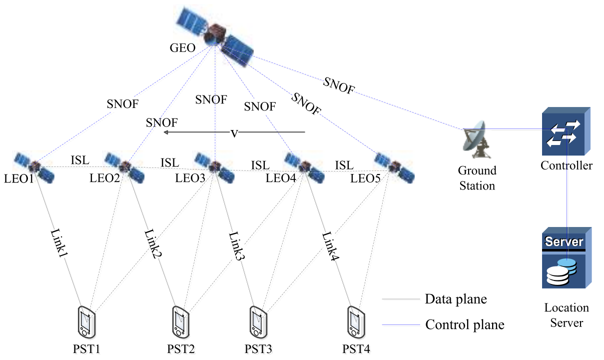


FIGURE 1. A LEO satellite resource-sharing model based on an SDSN architecture.

To manage the connection relationships and establish the framework based on the binary graph, considering the limited processing capacity on the satellite in the classical architecture, we can put the computation and storage into the location servers on the ground. The SDSN architecture proposed in [18] can be used.

As shown in Fig. 1, the data plane consists of LEO satellites and portable satellite terminals (PSTs). The control plane consists of ground stations, controllers and location servers. The controller generates and sends the handover instruction to the LEO satellites via a satellite network OpenFlow (SNOF) channel. The LEO satellites communicate with each other through ISLs. However, the satellite handover strategy proposed in this paper is used to solve the handover problem of satellite-ground link. Therefore, ISLs are not considered in this paper. The solid lines show the satellite-ground links, and the dashed lines show the optional satellites in the data plane.

The control and management planes of the SDSN architecture are not considered in this paper. The data plane is discussed, and a bipartite graph framework for handover is proposed.

In fact, game theory is an excellent tool for calculating both the behavior of individuals and strategic interactions among competitors. We embed game theory into our work. Game theory has the advantage of a rigorous mathematical model. There are several elements of game theory: players, utility functions, actions, strategies, and equilibrium. In the process of the game, each player has a utility function and always chooses the strategy to make his utility optimal. There are two features of the LEO handover problems:

(1) The players are mobile terminals, and they are denumerable.
(2) The resources are LEO satellites and available channels. The set of handover strategies is denumerable.

By using the game theory, we can compute the extremums of the terminal utility functions.

The satellite resource sharing model is defined as a process where multiple mobile terminals compete for satellite resources and available channels. There are two problems in the LEO satellite resource sharing model:

TABLE 1. Symbol definition.

Symbol	Definition
G	The bipartite graph of ISL
m, n	Number of satellites, number of terminals
X	The set of satellites
Y	The set of terminals
S	The set of handover strategies
s_i	The strategies of terminal i
q_i	The number of strategies of terminal i
u_i	The utility function of a terminal
t_{ij}	The remaining service time of satellite j relative to terminal i
θ_{ij}	The elevation angle of satellite j relative to terminal i
$t_{req,ij}$	The handover request time of terminal i relative to satellite j
$t_{res,ij}$	The handover response time of terminal i relative to satellite j

(1) When new mobile terminals randomly access the LEO satellite network, how are the LEO satellite and channel selected?
(2) When mobile terminals need to switch, how are the LEO satellite and channel selected?

To solve the first problem, a handover algorithm to maximize the benefits of mobile terminals is proposed. To solve the second problem, the random access process of new mobile terminals can be regarded as a special satellite handover. A terminal random access algorithm based on the target of userspace maximization is proposed. A bipartite graph framework for handover is proposed in section B, and the two algorithms above are proposed in section C.

B. A BIPARTITE GRAPH FRAMEWORK FOR HANDOVER

The LEO satellites serve as the nodes for data transmission in the SDSN architecture. Because the LEO satellites orbit the Earth at a very fast speed (the speed of subsatellite points of typical LEO satellites is approximately 7 km/s), the call duration between mobile terminals and LEO satellites is very short (usually approximately 9 minutes). As a result, satellite handover is very frequent. The number of mobile terminals on a call is called the satellite payload.

To intuitively express the handover strategy, the symbol definitions are shown in Table 1.
where m = card(X) represents the number of satellites, n = card(Y) represents the number of terminals, and $S = \{s_1, s_2, s_3, \ldots, s_{n-1}, s_n\}$ represents the set of handover strategies in the bipartite graph G = $\langle$X, E, Y$\rangle$. The strategy s_i represents a channel of a LEO satellite.

In a LEO satellite system, a virtual topology strategy is generally adopted to shield the dynamic characteristics of the satellite network topology. The method divides the satellite network topology into $\boldsymbol{n}$ time slots. The time slots

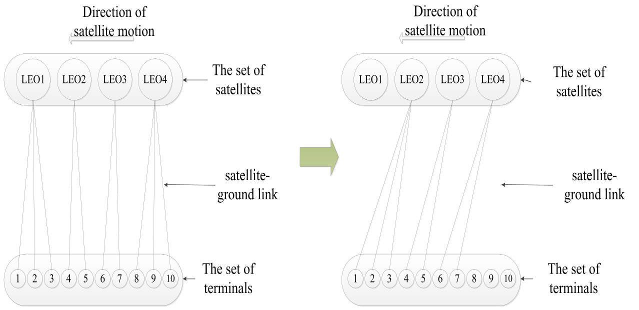


FIGURE 2. **The bipartite graph of the connection relationship between satellites and terminals.**

are $[t_0 = 0, t_1), [t_1, t_2), \ldots [t_{n-1}, t_n]$. The satellite network topology remains unchanged in each time slot. Similarly, we adopt the idea of the virtual topology strategy to divide the satellite-terminal topology into $\boldsymbol{n}$ time slots. The connection relationship between satellites and terminals in each time slot can be represented by a bipartite graph. There are different connection relations in different time slots. Thus, the corresponding bipartite graph is different. On the one hand, the change of the connection relationship can be expressed more clearly by using the bipartite graph. On the other hand, it is convenient for the management and storage of the connection relationship. The set of all LEO satellites is named X, and the set of all mobile terminals is named Y. For example, the connection relationship between satellites and terminals is represented by a bipartite graph $\mathrm{G} = \langle \mathrm{X, E, Y} \rangle$ in a time slot and E represents the edge set between the vertex sets X and Y. When satellite handover occurs, elements in the edge set E are changed. The bipartite graph changes from $\mathrm{G} = \langle \mathrm{X, E, Y} \rangle$ to $\mathrm{G}' = \langle \mathrm{X, E', Y} \rangle$. When mobile terminals access the LEO satellite network or shut down, Y and E change. The bipartite graph changes from $\mathrm{G} = \langle \mathrm{X, E, Y} \rangle$ to $\mathrm{G}' = \langle \mathrm{X, E', Y'} \rangle$. The call duration between mobile terminals and LEO satellites is far longer than the propagation delay in ISLs. We assume equivalence between the adjacent LEOs as regards the call source and its destination in the adjacent time slots.

The satellite node set serves as a vertex set, the mobile terminal set serves as the other vertex set, and the edges between the two vertex sets represent the connection relationship between satellites and terminals in the bipartite graph proposed in this paper. Fig. 2 shows the bipartite graph.

For example, the mobile terminals 1, 2 and 3 communicate by satellite LEO1. The mobile terminals 4 and 5 communicate by satellite LEO2. The mobile terminals 6 and 7 communicate by satellite LEO3. The mobile terminals 8, 9 and 10 communicate by satellite LEO4. When the LEO satellites move around the Earth for some time or the mobile terminals move away from the coverage of a satellite, there must be satellite handover. Specifically, when mobile terminal 1 moves away from the coverage of satellite LEO1, it needs to select a satellite that covers it to continue its call. In the bipartite graph, the edge between node LEO1 and node 1 is disconnected, and an edge between node 1 and node LEO2 is established when node 1 selects LEO2. The rest can be done in the same manner. When mobile terminals want to release the connection, the edge directly disappears. When new mobile terminals want to access the LEO satellite network, the terminal random access algorithm based on the target of userspace maximization proposed in section C is used.

C. HANDOVER ALGORITHM BASED ON THE POTENTIAL GAME TO MAXIMIZE THE BENEFITS OF MOBILE TERMINALS

The satellite handover can be regarded as a procedure in which multiple mobile terminals compete for satellite resources. It is a potential game. In the following part, we put forward the utility function expressed by symbols in Table 1 and prove Nash equilibrium. Finally, we give the satellite handover strategy.

Generally, different mobile terminals cannot select the same channel of the same satellite. Hypothetically, when mobile terminal i selects a channel of a satellite and all channels of that satellite are used by other mobile terminals, this mobile terminal will be unable to communicate with others. At this time, the utility function $u_i = 0$.

There are three basic criteria for the satellite handover for a single mobile terminal, namely, the remaining visible time t_{ij}, the satellite elevation angle θ_{ij} for terminals, and the number φ of available satellite channels.

The following is a global consideration. To make all mobile terminals obtain as much remaining visible time as possible, reduce the number of handovers and ensure the call quality of all mobile terminals at the same time, the utility function selected consists of two parts, namely, a gain function and loss function. The gain function $g_i(\mathrm{S})$ is composed of two handover criteria, remaining visible time and the satellite elevation angle. The constant coefficients α, β are used to adjust the proportion of the two handover criteria according to different applications. The loss function $l_i(\mathrm{S})$ is composed of the handover request time and response time. The longer the time is, the worse the time benefit is. The handover request time and the handover response time have little influence on the utility function. $t_{req,ij}$ and $t_{res,ij}$ used to abstractly express the delay costs. The utility function of mobile terminals selected by us are:

$$u_i(\mathrm{S}) = g_i(\mathrm{S}) - l_i(\mathrm{S}) \tag{1}$$

$$g_i(\mathrm{S}) = \alpha t_{ij}^{*} + \beta \theta_{ij}^{*} \tag{2}$$

$$l_i(\mathrm{S}) = w_{req} t_{req,ij}^{*} + w_{res} t_{res,ij}^{*} \tag{3}$$

α, β are constant coefficients, and $\alpha + \beta = 1$ in formula (2). α, β are selected according to different applications. t_{ij}^{*} can be obtained by using Z - score standardized methods for t_{ij}. θ_{ij}^{*} can be obtained by using Z - score standardized methods for θ_{ij}. The data processed conforms to the standard normal distribution. That is, the mean value is 0, and the standard deviation is 1. The conversion functions are:

$$t_{ij}^{*} = \frac{t_{ij} - \mu_t}{\sigma_t} \tag{4}$$

$$\theta_{ij}^{*} = \frac{\theta_{ij} - \mu_{\theta}}{\sigma_{\theta}} \tag{5}$$

μ_t is the mean of all the remaining service time, and σ_t is the standard deviation of all the remaining service time at the current moment. μ_θ is the average elevation angle, and σ_θ is the standard deviation of the elevation angle at the current moment:

$$\mu_t = \frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i} t_{ij}}{\sum_{i=1}^{n} q_i} \tag{6}$$

$$\sigma_t = \sqrt{\frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i} (t_{ij} - \mu_t)^2}{\sum_{i=1}^{n} q_i - 1}} \tag{7}$$

$$\mu_\theta = \frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i} \theta_{ij}}{\sum_{i=1}^{n} q_i} \tag{8}$$

$$\sigma_\theta = \sqrt{\frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i} (\theta_{ij} - \mu_\theta)^2}{\sum_{i=1}^{n} q_i - 1}} \tag{9}$$

Accordingly, w_{req} ($w_{req} > 0$) indicates the urgency of the handover request in formula (3). Similarly, $t_{req,ij}^{*}$ can be obtained by using Z - score standardized methods for $t_{req,ij}$. The data processed conforms to the standard normal distribution. That is, the mean value is 0, and the standard deviation is 1. The conversion functions are:

$$t_{req,ij}^{*} = \frac{t_{req,ij} - \mu_{t_{req}}}{\sigma_{t_{req}}} \tag{10}$$

$$t_{res,ij}^{*} = \frac{t_{res,ij} - \mu_{t_{res}}}{\sigma_{t_{res}}} \tag{11}$$

$\mu_{t_{req}}$ is the mean of the handover request time, and $\sigma_{t_{req}}$ is the standard deviation of all the handover request times at the current moment. $\mu_{t_{res}}$ is the mean of the handover response time and $\sigma_{t_{res}}$ is the standard deviation of all the handover response time at the current moment:

$$\mu_{t_{req}} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i} t_{req,ij}}{\sum_{i=1}^{n} q_i} \tag{12}$$

$$\sigma_{t_{req}} = \sqrt{\frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i} (t_{req,ij} - \mu_{t_{req}})^2}{\sum_{i=1}^{n} q_i - 1}} \tag{13}$$

$$\mu_{t_{res}} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i} t_{res,ij}}{\sum_{i=1}^{n} q_i} \tag{14}$$

$$\sigma_{t_{res}} = \sqrt{\frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i} (t_{res,ij} - \mu_{t_{res}})^2}{\sum_{i=1}^{n} q_i - 1}} \tag{15}$$

$u_i(\mathrm{S})$ is the utility function of each player, and it is obtained by subtracting the loss function from the gain function in the satellite resource sharing model. The handover strategy that makes $u_i(\mathrm{S})$ maximum needs to be selected.

The reason for selecting the utility function is to integrate two satellite handover criteria. As a result, it can not only ensure the call duration and reduce the number of handovers but also ensure the call quality and balance the satellite load. At the same time, considering the time efficiency: the longer the waiting time is, the worse the time benefit is. According to the utility function proposed, $s_i \in \{1, 2, 3, \ldots, m\}$ are the labels that mobile terminal i establishes a connection with. In our framework, the best response strategy of a terminal i with respect to strategies s_{-i} of other terminals is calculated by:

$$\mathop{\arg\max}_{s_i \in \{1,2,3,\ldots,m\}} u_i(\mathrm{S}_{-i}, \mathrm{s}_i) = \mathop{\arg\max}_{s_i \in \{1,2,3,\ldots,m\}} g_i(\mathrm{S}_{-i}, \mathrm{s}_i) - l_i(\mathrm{S}_{-i}, \mathrm{s}_i) \tag{16}$$

If all terminals play their best strategies, the strategy profile S forms a pure Nash equilibrium of the satellite resource-sharing game. In other words, no terminal can improve its own utility by changing its strategy. That is, every terminal is satisfied with its current utility:

$$\forall i,\ \mathrm{s}_i' \neq \mathrm{s}_i, \quad u_i(\mathrm{S}_{-i}, \mathrm{s}_i') \leq u_i(\mathrm{S}_{-i}, \mathrm{s}_i) \tag{17}$$

Because reaching a global one is not feasible, we use the local Nash equilibrium [3], [10] in this game. In other words, if all terminals play their local optimal strategies, the strategy profile S forms a local equilibrium.

$$\forall i,\ \mathrm{s}_i' \in ls(\mathrm{s}_i), \quad u_i(\mathrm{S}_{-i}, \mathrm{s}_i') \leq u_i(\mathrm{S}_{-i}, \mathrm{s}_i) \tag{18}$$

Here, $ls(\mathrm{s}_i)$ refers to the local strategy space of terminal i, which is the set of possible label sets. The strategy space includes the satellites and their available channels by subtracting the channels occupied by other mobile terminals from all satellites and their channels.

When the bipartite graph changes from one time slot to another, the users who need to switch compete for the available satellites and channels at the same time. By using the proposed algorithm, the local Nash equilibrium can be reached.

Algorithm 1 shows the handover algorithm that maximizes the benefits of mobile terminals. It consists of two phases: the personal phase and system phase. In the personal phase,

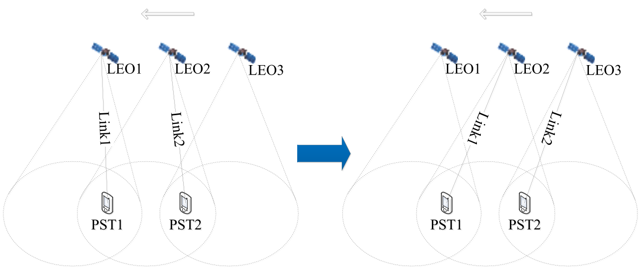


FIGURE 3. The situation in the system phase.

when LEO satellites orbit around the Earth or mobile terminals move, mobile terminals select the satellite with the maximum benefits to switch according to their own utility functions. In the system phase, there may not be any available channels or available satellites for some mobile terminals. The corresponding satellites and channels shall be vacated for them. Then, the disconnected mobile terminals switch again according to algorithm 1. To ensure sufficient computing speed and capability, all algorithms are based on an SDSN architecture.

1) PERSONAL PHASE

In the personal phase, all mobile terminals that need to switch calculate their own utility functions for every satellite that covers the terminals and every channel. They are compared by bubble sort to obtain the max to select the corresponding optimal strategy.

If there are no available channels or satellites for some mobile terminals, null is assigned to the strategy s_i. If there is only one strategy for some mobile terminals, we mark the terminals with a different label to be handled in the system phase.

2) SYSTEM PHASE

The system phase of algorithm 1 applies to the situation shown in Fig. 3. When PST1 wants to switch and establish a connection by LEO2 and there is no available channel (LEO2 is the only choice), PST2 will disconnect from LEO2 and establish a connection by LEO3. As a result, PST1 can execute the handover.

In the system phase, an SDSN architecture is adopted to gain information about the entire LEO satellite network. First, we look up all the edges whose values are null to find the corresponding free mobile terminal vertices. Second, we randomly find mobile terminal vertices nearby that can provide available channels and satellites for free vertices. The terminal vertices nearby meet the following conditions:

(1) They share one or more coverage satellites and available channels with the free vertices.
(2) The optimal strategy is in the sharing channels and satellites. That is, they are calling by using the channels and satellites.
(3) There are other optional strategies (available satellites and available channels). That is, the terminal vertices nearby should be from unmarked vertices whose edges are not null in the personal phase.

Algorithm 1 Handover Algorithm to Maximize the Benefits of Mobile Terminals

```
input: A bipartite graph framework before handover G = ⟨X, E, Y⟩
output: A bipartite graph framework after handover G = ⟨X, $E'$, Y⟩
$E' = \{\}$. $u_i = u_j = 0$. Initialization.
\*Personal Phase*\
if terminal i needs handover then
    find an available satellite and channel $x_j$; if cannot find $x_j$, $x_j$ = null; if the handover strategy is unique, mark i
    if $x_j != $ null then
        while there are available channels and satellites do
            find an available satellite and channel and calculate the utility function $u'_i$.
            if $u'_i > u_i$ then
                $u_i \rightarrow u'_i$.
                update handover strategy $s_i$.
            else
                no operation
            end if
        end while
    else
        $s_i \rightarrow$ null.
    end if
    add $s_i$ into $E'$
else
    no operation
end if
\*System Phase*\
while there is $s_i$ that is null do
    find terminal j and $s_j$ (j is unmarked) randomly that terminal i can switch
    $s_i \rightarrow s_j$.
    while there are available channels and satellites do
        find another available satellite and channel and calculate the utility function $u'_j$.
        if $u'_j > u_j$ then
            $u_j \rightarrow u'_j$.
            update handover strategy $s_j$.
        else
            no operation
        end if
    end while
end while
output G = ⟨X, $E'$, Y⟩.
```

Actually, the remaining visible time and the elevation angle are considered in the personal phase, and the number of available satellite channels is considered in the system phase.

Algorithm 2 Terminal Random Access Algorithm Based on the Target of Userspace Maximization

```
input: A bipartite graph framework before random access
    G = ⟨X, E, Y⟩
output: A bipartite graph framework after random access
    G = ⟨X, $E'$, $Y'$⟩
$s_i$ = null. $u_i = 0$. The number of available channels of
    satellite k is |k| = 0. Initialization.
find an available satellite and channel $x_j$; if cannot find
    $x_j$, return an error.
if the location of new terminal i is ocean surface or
    sparsely populated area then
    while there are available channels and satellites do
        find an available satellite and channel and calculate
        the utility function $u_t'$.
        if $u_t' > u_i$ then
            $u_i \rightarrow u_i'$.
            update handover strategy $s_i$.
        else
            no operation
        end if
    end while
else
    while there are available channels and satellites do
        find an available satellite $y$
        if |y| > |k| then
            k = y. update strategy $s_i$.
        else
            no operation.
        end if
    end while
end if
add $s_i$ into $E'$ and add i into $Y'$
output G = ⟨X, $E'$, $Y'$⟩
```

D. TERMINAL RANDOM ACCESS ALGORITHM BASED ON THE TARGET OF USERSPACE MAXIMIZATION

When the mobile terminals need to switch, the handover algorithm based on the potential game to maximize the benefits of mobile terminals is used. In fact, the random access of the new mobile terminals to the satellite network can also be regarded as a special satellite handover. To balance the constellation network load, a terminal random access algorithm based on the target of userspace maximization is proposed.

When mobile terminal i wants to access the LEO satellite network, algorithm 2 is used. The random access strategy of the new terminal is set according to its location. This is because the complexities of the land surface terminals are higher than those of the ocean surface terminals and the complexity of the densely populated land area is higher than that of the sparsely populated area. On the one hand, if the new terminal is located in a region with low complexity, algorithm 1 is directly used. On the other hand, if it is located in a region with high complexity, it will select the satellite and channel that maximizes the user space for other new terminals. That is, the satellites with the most available channels are selected for communication.

In the process of random access, when a new terminal is located in an area with low complexity, the use of algorithm 1 can ensure the greatest possible benefits and call quality. When the new terminal is located in an area with high complexity, use of the algorithm can maximize the user space of mobile terminals that need random access later (that is, the maximum feasible region) to approach the optimum.

TABLE 2. **The detailed parameters of Iridium [14].**

	Iridium
Altitude	780 km
Planes	6
Satellites per plane	11
Inclination (deg)	86.4
Interplane separation (deg)	31.6
Seam separation (deg)	22
Intraplane phasing	Yes
Interplane phasing	Yes
ISLs per satellite	4
ISL bandwidth	25 Mb/s
Link bandwidth	1.5 Mb/s
Cross-seam ISLs	No
ISL latitude threshold (deg)	60

III. PERFORMANCE EVALUATION

A. SIMULATION SETUP

We assume that all mobile terminals want maximum SNR (signal-to-noise ratio) and the least handovers to reduce the call drop probability. The link weight of the bipartite graph is simply set to 1. All simulations have been carried out on a typical LEO satellite constellation named Iridium. The operational constellation represents the main networking topology of satellite networks. By using Iridium to demonstrate the algorithm, we can confirm the effectiveness of the algorithm in the networking topology of satellite networks. The detailed parameters of the constellation are shown in Table 2.

The Iridium satellite network is simulated with STK9, and 30 stations are randomly distributed on the Earth. The longitude and latitude range of the stations are $[-180°, 180°]$ and $[0°, 90°]$, respectively.

The call duration X follows the exponential distribution, and the cumulative distribution function of X is $P\{X < x\} = F(x) = 1 - e^{-(x/\lambda)}$ with λ as its mathematical expectation. The value of p is set at 95%. On the one hand, we use STK9 for simulating Iridium and get the satellite ephemeris. On the other hand, the outputs of the simulation are used to calculate the average number of satellite handover and the signal-to-noise ratios of different handover strategies.

B. SIMULATION RESULTS

1) SNR (SIGNAL TO NOISE RATIO)

As we can see from Fig. 4, we assume that the beam coverage of a LEO satellite is circular and that, the smaller the elevation

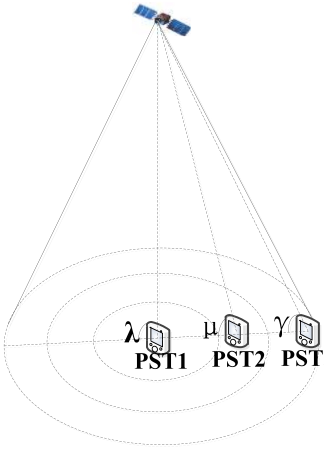


FIGURE 4. The relationship between SNR and elevation angle.

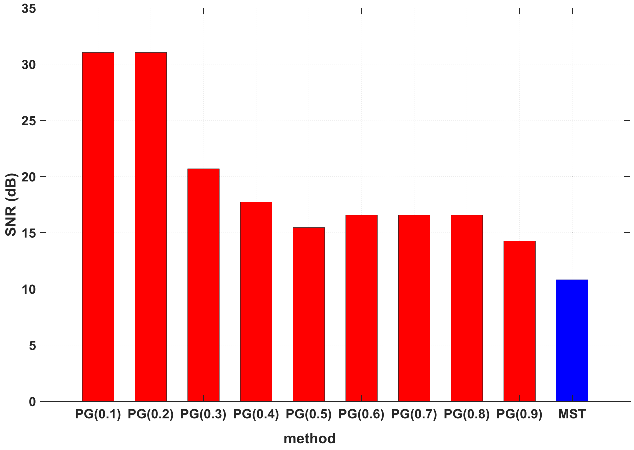


FIGURE 5. Comparison of the simulation results with the maximum service time strategy of the signal-to-noise ratio in the Iridium satellite network.

angle is, the smaller the signal-to-noise ratio is. For example, $\lambda > \mu > \gamma$, and then PST1 > PST2 > PST3 (SNR). Therefore, elevation angle can directly affect communication quality. The switching time can be decided by the elevation angle. We adopt SNR to evaluate the strategies proposed in this paper. the experimental results are shown below.

Fig. 5 displays the two methods, including the satellite handover strategy based on the potential game proposed (PG) and the maximum service time strategy proposed in [19] (MST) on the horizontal axis and the signal-to-noise ratio of the call on the vertical axis. There are different values of α in the satellite handover strategy proposed. The range of α is from 0.1 to 0.9. As seen from Fig. 5, with the increase of α, the signal-to-noise ratio of the communication decreases roughly, and the call quality decreases. If the maximum service time strategy is selected, the signal-to-noise ratio is the lowest. As a result, the call quality is the worst. It is suggested that the satellite handover strategy based on the potential game can increase the signal-to-noise ratio and improve the call quality greatly. When the value of α is 0.1, the elevation angle accounts for the largest proportion of the utility function, and the elevation angle at the beginning of the connection is the largest. As a result, the SNR of the call is the largest, and the average call quality is the best. Fig. 5 shows the effectiveness of the strategy proposed.

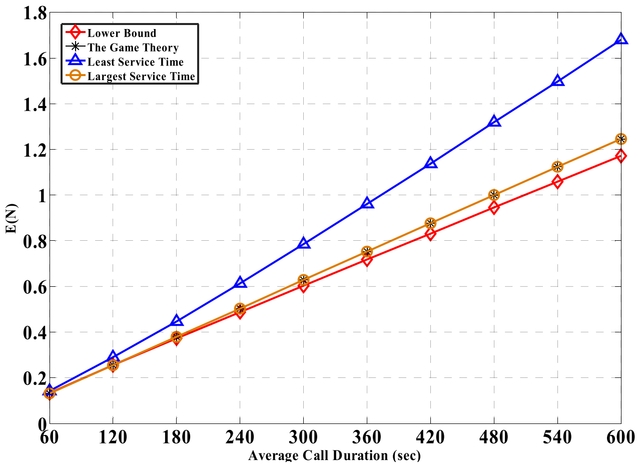


FIGURE 6. Comparison of the simulation results of the average handover number in the Iridium satellite network targeting the lower bound, largest service time and lowest service time, respectively.

2) THE AVERAGE HANDOVER TIMES

To maintain and determine the proportion of remaining visible time and elevation angle, the value of α is set to 0.5. Fig. 6 displays the average call duration on the horizontal axis and the average handover number of the call on the vertical axis. The step size of the average call duration is 60, and the range is from 60 to 600. The satellite handover strategy based on the potential game proposed is compared with the lowest service time strategy, the largest service time strategy proposed in [19] and the derived lower bound in [14]. As seen from Fig. 6, first the average handover number based on the lowest service time strategy is expected to be the maximum. Second, the average handover number based on the largest service time strategy is the closest to the lower bound. Finally, the satellite handover strategy proposed is relatively close to the largest service time strategy. From Fig. 5 and Fig. 6, we can conclude the major result that selecting the best elevation angle (the lowest α) yields better results (the highest SNR) than maximizing service time (and hence decreasing the number of handovers). The experiment proves that the satellite handover strategy based on the potential game can greatly improve the signal-to-noise ratio and call quality under the condition of reducing the average number of times of satellite handover. The experiment clearly confirms the effectiveness of the proposed satellite handover strategy based on the potential game.

3) DISCUSSION REGARDING α

The influence of α on the average handover number is discussed in this section. Fig. 7 displays the value of α on the horizontal axis and the average handover number of the call on the vertical axis. The range of α is from 0.1 to 0.9.

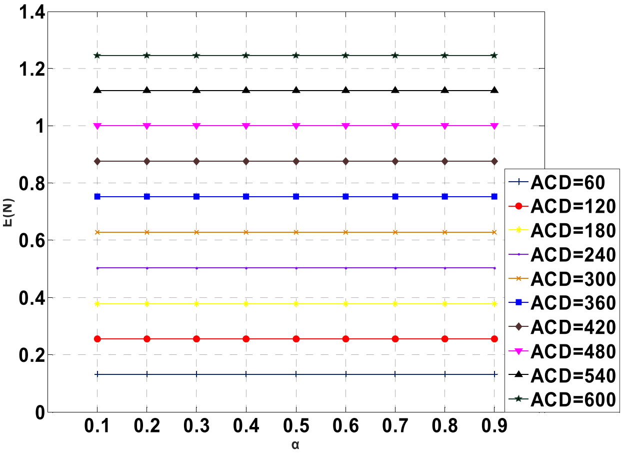


FIGURE 7. **Comparison of the simulation results with different values of α of the average handover number in the Iridium satellite network.**

The step size of the average call duration is 60, and the range is from 60 to 600. "ACD" means the "average call duration" in Fig. 7. As shown in Fig. 7, under the condition of the same average call duration, the value of α has little influence on the average satellite handover number. With the increase of the average call duration, the average handover number increase linearly. It is shown in Fig. 7 that the satellite handover strategy based on the potential game can improve the call quality and ensure reduction of the average handover number as much as possible, and parameter α has little influence on the result.

IV. CONCLUSION

The construction and development of the integrated space-air-ground network support the continuous progress of the satellite network to realize global coverage and mobility. Low-orbit satellite networks exhibit the advantages of low delay and low terminal power. However, in low-orbit satellite constellation communication, the connection time is very short since it requires frequent satellite handovers.

We provide the bipartite graph framework for handover on the basis of an SDSN architecture. A handover algorithm based on the potential game to maximize the benefits of mobile terminals and a terminal random access algorithm based on the target of userspace maximization are proposed to solve the two problems in the LEO satellite resource-sharing model.

Both theory and experiment prove that our proposed methods can greatly reduce the average number of handovers and improve the call quality. The constellation network load can maintain balance.

There remain many interesting open problems under this problem. One of the directions is to find more appropriate gain and loss functions. Though the proposed functions are simple and effective, they are not the best choices for the satellite handover game. In particular, better gain and loss functions can be obtained by a deeper understanding of satellite handover in the real world.

APPENDIX

In the section, the existence of Nash equilibrium is strictly proved by using existing definitions, theories, and proofs. Some games do not have Nash Equilibrium. To see when a certain game has Nash equilibrium, recall that potential games are a general class of games that permit pure Nash equilibrium [29]. Indeed, there is a potential function $\phi(*)$ defined on the strategy profile S of the terminals that maps this profile to some real values for any finite game. Moreover, the function needs to validate the following condition:

$$\forall i, \phi(\mathrm{S}) - \phi(\mathrm{S}_{-i}, \mathrm{s}'_i) = u_i(\mathrm{S}_{-i}, \mathrm{s}'_i) - u_i(\mathrm{S}) \tag{19}$$

The satellite handover game we proposed is a potential game. In other words, if any mobile terminal i increases its benefit by changing its strategy, the potential function also strictly reduces the corresponding value. Because the strategy profile set S of the potential game is finite, Nash equilibrium must exist. Moreover, to obtain a better benefit, terminals change their strategy and eventually converge to the Nash equilibrium.

A sufficient condition is proposed below to make the satellite handover game be a potential game to prove the existence of Nash equilibrium.

Definition 1 (Locally Linear Function): A set of functions $\{f_i(*) : 1 \leq \mathrm{i} \leq n\}$ is locally linear if, for every strategy profile S, the following condition holds:

$$\forall i \in [n], f_i(\mathrm{S}_{-i}, \mathrm{s}'_i) - f_i(\mathrm{S}) = \rho(f(\mathrm{S}_{-i}, \mathrm{s}'_i) - f(\mathrm{S})) \tag{20}$$

where ρ is a linear function parameter and $f(*) = \sum_{i\in[n]} f_i(*)$.

If the gain function and loss function are both local linear functions, the satellite handover game is a potential game.

Theorem 1: $\{g_i(*) : \mathrm{i} \in [n]\}$ and $\{l_i(*) : \mathrm{i} \in [n]\}$ are the sets of gain and loss functions in a satellite handover game. If the sets are locally linear functions with linear factors ρ_g and ρ_l, the satellite handover game is a potential game [29].

Proof: We define a potential function as $\phi(\mathrm{S}) = \rho_l \cdot l(\mathrm{S}) - \rho_g \cdot g(\mathrm{S})$ and assume that terminal i changes its strategy from s_i to s'_i. Based on the definitions of locally linear functions and the utility functions $u_i(*)$, we have $\phi(\mathrm{S}) - \phi(S_{-i}, \mathrm{s}'_i) = u_i(S_{-i}, s'_i) - u_i(\mathrm{S})$. Therefore, the satellite handover game is a potential game [9].

Now, we prove that the gain and loss functions that we have chosen are locally linear functions. First, suppose that the mobile terminal 'a' wants to handover and change the strategy from s_a to s'_a, i.e., from satellite 'b' to satellite 'b'.' Then, from the left-hand side of (20), we have:

$$\begin{aligned} & g_a(\mathrm{S}_{-a}, \mathrm{s}'_a) - g_a(\mathrm{S}) \\ & = (\alpha t^*_{ab'} + \beta\theta^*_{ab'}) - (\alpha t^*_{ab} + \beta\theta^*_{ab}) \\ & = = \alpha(t^*_{ab'} - t^*_{ab}) + \beta(\theta^*_{ab'} - \theta^*_{ab}) \end{aligned}$$

$$
\begin{aligned}
&= \alpha \frac{\left(t_{ab'} - \frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i} t_{ij}}{\sum_{i=1}^{n} q_i}\right) - \left(t_{ab} - \frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i} t_{ij}}{\sum_{i=1}^{n} q_i}\right)}{\sqrt{\frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i}\left(t_{ij}-\frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i} t_{ij}}{\sum_{i=1}^{n} q_i}\right)^2}{\sum_{i=1}^{n} q_i-1}}} \\
&\quad + \beta \frac{\left(\theta_{ab'} - \frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i} \theta_{ij}}{\sum_{i=1}^{n} q_i}\right) - \left(\theta_{ab} - \frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i} \theta_{ij}}{\sum_{i=1}^{n} q_i}\right)}{\sqrt{\frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i}\left(\theta_{ij}-\frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i} \theta_{ij}}{\sum_{i=1}^{n} q_i}\right)^2}{\sum_{i=1}^{n} q_i-1}}} \\
&= \alpha \frac{t_{ab'} - t_{ab}}{\sqrt{\frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i}\left(t_{ij}-\frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i} t_{ij}}{\sum_{i=1}^{n} q_i}\right)^2}{\sum_{i=1}^{n} q_i-1}}} + \beta \frac{\theta_{ab'} - \theta_{ab}}{\sqrt{\frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i}\left(\theta_{ij}-\frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i} \theta_{ij}}{\sum_{i=1}^{n} q_i}\right)^2}{\sum_{i=1}^{n} q_i-1}}} \\
&= \alpha \sum_{i=1}^{n} q_i \sqrt{\sum_{i=1}^{n} q_i - 1}\, \frac{t_{ab'} - t_{ab}}{\sqrt{\sum_{i=1}^{n}\sum_{j=1}^{q_i}\left(t_{ij}\sum_{i=1}^{n} q_i - \sum_{i=1}^{n}\sum_{j=1}^{q_i} t_{ij}\right)^2}} \\
&\quad + \beta \sum_{i=1}^{n} q_i \sqrt{\sum_{i=1}^{n} q_i - 1}\, \frac{\theta_{ab'} - \theta_{ab}}{\sqrt{\sum_{i=1}^{n}\sum_{j=1}^{q_i}\left(\theta_{ij}\sum_{i=1}^{n} q_i - \sum_{i=1}^{n}\sum_{j=1}^{q_i} \theta_{ij}\right)^2}}
\end{aligned} \tag{21}
$$

There is an objective fact: when the mobile terminal 'a'' switches, it has no influence on the remaining service time and elevation angle of other mobile terminals. Therefore, from the right-hand side of (20), we have:

$$
\begin{aligned}
&g(\mathrm{S}_{-i}, \mathrm{s}'_i) - g(\mathrm{S}) \\
&\quad = \sum_{i\in[n]} g_i(\mathrm{S}_{-i}, \mathrm{s}'_i) - \sum_{i\in[n]} g_i(\mathrm{S}) \\
&\quad = \sum_{i\in[n-1], i\neq a} g_i(\mathrm{S}_{-i}, \mathrm{s}'_i) + g_a(\mathrm{S}_{-a}, \mathrm{s}'_a) \\
&\qquad - \sum_{i\in[n-1], i\neq a} g_i(\mathrm{S}) - g_a(\mathrm{S}) \\
&\quad = \sum_{i\in[n-1], i\neq a} g_i(\mathrm{S}) + g_a(\mathrm{S}_{-a}, \mathrm{s}'_a) \\
&\qquad - \sum_{i\in[n-1], i\neq a} g_i(\mathrm{S}) - g_a(\mathrm{S}) \\
&\quad = \alpha \sum_{i=1}^{n} q_i \sqrt{\sum_{i=1}^{n} q_i - 1}\, \frac{t_{ab'} - t_{ab}}{\sqrt{\sum_{i=1}^{n}\sum_{j=1}^{q_i}\left(t_{ij}\sum_{i=1}^{n} q_i - \sum_{i=1}^{n}\sum_{j=1}^{q_i} t_{ij}\right)^2}} \\
&\qquad + \beta \sum_{i=1}^{n} q_i \sqrt{\sum_{i=1}^{n} q_i - 1}\, \frac{\theta_{ab'} - \theta_{ab}}{\sqrt{\sum_{i=1}^{n}\sum_{j=1}^{q_i}\left(\theta_{ij}\sum_{i=1}^{n} q_i - \sum_{i=1}^{n}\sum_{j=1}^{q_i} \theta_{ij}\right)^2}}
\end{aligned} \tag{22}
$$

Comparing formulas (21) and (22), we only need to set $\rho_g = 1$ to reach the following equation and thereby prove (20).

$$
g_a(\mathrm{S}_{-a}, \mathrm{s}'_a) - g_a(\mathrm{S}) = g(\mathrm{S}_{-i}, \mathrm{s}'_i) - g(\mathrm{S}) \tag{23}
$$

We have proved that the gain function is a locally linear function. Accordingly, we prove the local linearity of the loss function. Then, from the left-hand side of (20), we have:

$$
\begin{aligned}
&l_a(\mathrm{S}_{-a}, \mathrm{s}'_a) - l_a(\mathrm{S}) \\
&\quad = w_{req}(t^*_{req,ij'} - t^*_{req,ij}) + w_{res}(t^*_{res,ij'} - t^*_{res,ij}) \\
&\quad = w_{req} \frac{t_{req,ab'} - t_{req,ab}}{\sqrt{\frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i}\left(t_{req,ij}-\frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i} t_{req,ij}}{\sum_{i=1}^{n} q_i}\right)^2}{\sum_{i=1}^{n} q_i-1}}} \\
&\qquad + w_{res} \frac{t_{res,ab'} - t_{res,ab}}{\sqrt{\frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i}\left(t_{res,ij}-\frac{\sum_{i=1}^{n}\sum_{j=1}^{q_i} t_{res,ij}}{\sum_{i=1}^{n} q_i}\right)^2}{\sum_{i=1}^{n} q_i-1}}} \\
&\quad = w_{req} \sum_{i=1}^{n} q_i \sqrt{\sum_{i=1}^{n} q_i - 1} \\
&\qquad \times \frac{t_{req,ab'} - t_{req,ab}}{\sqrt{\sum_{i=1}^{n}\sum_{j=1}^{q_i}\left(t_{req,ij}\sum_{i=1}^{n} q_i - \sum_{i=1}^{n}\sum_{j=1}^{q_i} t_{req,ij}\right)^2}} \\
&\qquad + w_{res} \sum_{i=1}^{n} q_i \sqrt{\sum_{i=1}^{n} q_i - 1} \\
&\qquad \times \frac{t_{res,ab'} - t_{res,ab}}{\sqrt{\sum_{i=1}^{n}\sum_{j=1}^{q_i}\left(t_{res,ij}\sum_{i=1}^{n} q_i - \sum_{i=1}^{n}\sum_{j=1}^{q_i} t_{res,ij}\right)^2}}
\end{aligned} \tag{24}
$$

There is an objective fact: when the mobile terminal 'a' switches, it has no influence on the handover request time and the handover response time of other mobile terminals. Therefore, from the right-hand side of (20), we have:

$$
\begin{aligned}
&l(\mathrm{S}_{-i}, \mathrm{s}'_i) - l(\mathrm{S}) \\
&\quad = \sum_{i\in[n]} l_i(\mathrm{S}_{-i}, \mathrm{s}'_i) - \sum_{i\in[n]} l_i(\mathrm{S}) \\
&\quad = \sum_{i\in[n-1], i\neq a} l_i(\mathrm{S}_{-i}, \mathrm{s}'_i) + l_a(\mathrm{S}_{-a}, \mathrm{s}'_a) \\
&\qquad - \sum_{i\in[n-1], i\neq a} l_i(\mathrm{S}) - l_a(\mathrm{S})
\end{aligned}
$$

$$
\begin{aligned}
&= \sum_{i\in[n-1],i\neq a} l_i(\mathrm{S}) + l_a(\mathrm{S}_{-a}, \mathrm{s}'_a) \\
&\quad - \sum_{i\in[n-1],i\neq a} l_i(\mathrm{S}) - l_a(\mathrm{S}) \\
&= w_{req}\sum_{i=1}^{n} q_i \sqrt{\sum_{i=1}^{n} q_i - 1} \\
&\quad \times \frac{t_{req,ab'} - t_{req,ab}}{\sqrt{\sum_{i=1}^{n}\sum_{j=1}^{q_i}\left(t_{req,ij}\sum_{i=1}^{n} q_i - \sum_{i=1}^{n}\sum_{j=1}^{q_i} t_{req,ij}\right)^2}} \\
&\quad + w_{res}\sum_{i=1}^{n} q_i \sqrt{\sum_{i=1}^{n} q_i - 1} \\
&\quad \times \frac{t_{res,ab'} - t_{res,ab}}{\sqrt{\sum_{i=1}^{n}\sum_{j=1}^{q_i}\left(t_{res,ij}\sum_{i=1}^{n} q_i - \sum_{i=1}^{n}\sum_{j=1}^{q_i} t_{res,ij}\right)^2}}
\end{aligned}
\tag{25}
$$

Comparing formulas (21) and (22), we only need to set $\rho_g = 1$ to reach the following equation and thereby prove (20).

$$
l_a(\mathrm{S}_{-a}, \mathrm{s}'_a) - l_a(\mathrm{S}) = l(\mathrm{S}_{-i}, \mathrm{s}'_i) - l(\mathrm{S}) \tag{26}
$$

Thus, the gain function is a locally linear function.

At present, we have proved that our gain and loss functions are both locally linear with $\rho_g = \rho_l = 1$. Therefore, we find that our utility function is a potential function. Based on Theorem 1, the satellite handover game is a potential game. Consequently, we conclude that the proposed model has a Nash equilibrium. Because the satellites, channels, and users who need to switch are all limited, we can calculate all of the Nash equilibrium directly. Moreover, every user only has an optimal strategy, so the proposed algorithm can reach the equilibrium.

REFERENCES

[1] Z. Wang and P. T. Mathiopoulos, "On the performance analysis of dynamic channel allocation with FIFO handover queuing in LEO-MSS," *IEEE Trans. Commun.*, vol. 53, no. 9, pp. 1443–1446, Sep. 2005.

[2] Z. Wang, P. T. Mathiopoulos, and R. Schober, "Performance analysis and improvement methods for channel resource management strategies of LEO–MSS with multiparty traffic," *IEEE Trans. Veh. Technol.*, vol. 57, no. 6, pp. 3832–3842, Nov. 2008.

[3] C. Duan, J. Feng, H. Chang, B. Song, and Z. Xu, "A novel handover control strategy combined with multi-hop routing in LEO satellite networks," in *Proc. IEEE Int. Parallel Distrib. Process. Symp. Workshops (IPDPSW)*, May 2018, pp. 845–851.

[4] S. U. Bukhari, L. Yu, X. Q. Di, C. Chen, and X. Liu, "Fuzzy C-mean clustering based: LEO satellite handover," in *Proc. ICPCSEE*, vol. 901, Sep. 2018, pp. 347–358.

[5] X. Hu, H. Song, S. Liu, and W. Wang, "Velocity-aware handover prediction in LEO satellite communication networks," *Int. J. Satell. Commun. Netw.*, vol. 36, no. 6, pp. 451–459, 2018.

[6] M. Gkizeli, R. Tafazolli, and B. Evans, "Modeling handover in mobile satellite diversity based systems," in *Proc. IEEE 54th Veh. Technol. Conf.*, Atlantic City, NJ, USA, Oct. 2001, pp. 131–135.

[7] R. Musumpuka, T. M. Walingo, and J. M. Smith, "Performance analysis of correlated handover service in LEO mobile satellite systems," *IEEE Commun. Lett.*, vol. 20, no. 11, pp. 2213–2216, Nov. 2016.

[8] G. N. Kamga, M. Sadek, and S. Aïssa, "Adaptive handoff for multi-antenna mobile satellite systems with ancillary terrestrial component," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2016, pp. 1–6.

[9] M. Liao, Y. Liu, H. Hu, and D. Yuan, "Analysis of maximum traffic intensity under pre-set quality of service requirements in low earth orbit mobile satellite system for fix channel reservation with queueing handover scheme," *IET Commun.*, vol. 9, no. 13, pp. 1575–1582, Sep. 2015.

[10] E. Papapetrou, S. Karapantazis, G. Dimitriadis, and F.-N. Pavlidou, "Satellite handover techniques for LEO networks," *Int. J. Satell. Commun. Netw.*, vol. 22, pp. 231–245, Mar. 2004.

[11] E. Papapetrou and F.-N. Pavlidou, "Analytic study of Doppler-based handover management in LEO satellite systems," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 41, no. 3, pp. 830–839, Jul. 2005.

[12] S. Karapantazis and F.-N. Pavlidou, "Dynamic time-based handover management in LEO satellite systems," *Electron. Lett.*, vol. 43, no. 5, pp. 57–58, Mar. 2007.

[13] P. Boedhihartono and G. Maral, "Evaluation of the guaranteed handover algorithm in satellite constellations requiring mutual visibility," *Int. J. Satell. Commun. Netw.*, vol. 21, no. 2, pp. 163–182, 2003.

[14] Y. Seyedi and S. M. Safavi, "On the analysis of random coverage time in mobile LEO satellite communications," *IEEE Commun. Lett.*, vol. 16, no. 5, pp. 612–615, May 2012.

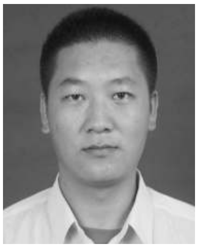
[15] Y. Seyedi, A. Moharrer, S. M. Safavi, and H. Amindavar, "Use of shadowing moments to statistically model mobile satellite channels in urban environments," *IEEE Trans. Wireless Commun.*, vol. 12, no. 8, pp. 3760–3769, Aug. 2013.

[16] I. Ali, N. Al-Dhahir, and J. E. Hershey, "Predicting the visibility of LEO satellites," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 35, no. 4, pp. 1183–1190, Oct. 1999.

[17] W. Zhaofeng, H. Guyu, Y. Seyedi, and J. Fenglin, "A simple real-time handover management in the mobile satellite communication networks," in *Proc. APNOMS*, Aug. 2015, pp. 175–179.

[18] B. Yang, Y. Wu, X. Chu, and G. Song, "Seamless handover in software-defined satellite networking," *IEEE Commun. Lett.*, vol. 2, no. 93, pp. 1768–1771, Sep. 2016.

[19] Z. Wu, F. Jin, J. Luo, Y. Fu, J. Shan, and G. Hu, "A graph-based satellite handover framework for LEO satellite communication networks," *IEEE Commun. Lett.*, vol. 20, no. 8, pp. 1547–1550, Aug. 2016.



YANG WU received the B.S. and M.Sc. degrees in computer science and technology from Army Engineering University, Nanjing, China, in 2015 and 2017, respectively, where he is currently pursuing the Ph.D. degree with the Department of Network Engineering. His research interests include satellite networks and computer networks.

GUYU HU received the B.S. degree in radio communication from Zhejiang University, Hangzhou, China, in 1983, the M.Sc. degree in computer application technology from the Nanjing Institute of Communications, Nanjing, China, in 1989, and the Ph.D. degree in communications and information systems from the Nanjing Institute of Communications, in 1992. Since 1997, he has been a Full Professor with the Army Engineering University, Nanjing. Since 1990, he devotes to the research on network management. His research interests include computer networks, maintenance and administration of the satellite networks, and intelligent network management.

FENGLIN JIN received the B.S. degree in electronics and information systems from the Institute of communication engineering, the M.Sc. degree in computer application from the Army Engineering University, Nanjing, China, in 1996 and 2001, respectively, and the Ph.D. degree in computer science and technology from Nanjing University, Nanjing, in 2012. His current research interests include computer networks, broadband satellite networking, and satellite system operating and administration.

JIACHEN ZU received the B.S. degree in electronic science and technology from Shanghai Jiao Tong University, in 2017. He is currently pursuing the Ph.D. degree with the Department of Network Engineering, Army Engineering University, Nanjing, China. His research interests include satellite networks and NFV.

• • •