# QoE-Driven Intelligent Handover for User-Centric Mobile Satellite Networks

Huihui Xu, Deshi Li, Mingliu Liu, *Member, IEEE*, Guangjie Han, *Senior Member, IEEE*, Wei Huang, and Chan Xu

***Abstract*—Recently, many satellites are being launched for providing global internet broadband service to individual consumers. Since satellites and users could move separately, providing seamless connectivity has become one of the most important tasks for mobile satellite networks. Current handover methods are based on either signal strength or service time, however, due to the randomness of user terminal (UT) arrivals and the unbalanced traffic distribution for high-mobility satellite networks, the success rate can hardly be guaranteed. To this end, we propose a QoE-driven intelligent handover mechanism for user-centric mobile satellite networks, through which the access satellites can be selected by predicted service time and communication channel resources. Accordingly, to ensure the service duration, a spatial relationship coupling model is proposed to predict relative motion pattern between UT and satellites; To improve the effectiveness of handover, an available channel estimation model is then developed based on the mobility pattern of adjacent satellites. Finally, reinforcement learning is adopted to maximize the UT′s Quality of Experience (QoE) through predicted handover factors. Simulation results show that the proposed handover mechanism offers good performance in terms of handover times, handover success rate and end-to-end delay.**

***Index Terms*—Handover, mobile satellite networks, qoe, reinforcement learning, space-time, user-centric.**

## I. Introduction

In THE past few decades, the rapid development of terrestrial wireless communications has triggered the increased demand for high-data-rate applications, which in turn raised emergence requirements on achieving massive connectivity and high capacity in future communication systems. To meet such demands, the 5G network has been considered as a well-accepted architecture due to its high broadband, low latency and massive connectivity. However, limited by the coverage of small cells in 5G networks, mobile satellite networks (MSNs) have attracted many attentions from academia to industry, which can guarantee wireless access services with reliability at any place on the earth, especially for harsh environment such as ocean and mountains [1]–[3]. Ten years ago, Iridium system begins to provide internet service, however, the limited bandwidth and expensive operation cost restrict the expansion of consumer groups. Recently, several companies and organizations announce to launch Low Earth Orbit (LEO) communication satellites for constructing MSNs, for example, SpaceX has presented the explicit goal to provide broadband internet connectivity for global users, as well as provides communication service with competitive price to users. 12,000 satellites would be deployed in three orbital shells according to the US governments approval [4]. Similarly, aiming to provide global satellite internet broadband service, OneWeb successfully launched the first 6 of the 648 planned satellites during 2019 [5].

In terrestrial networks, for high-speed UTs, such as intercontinental aircraft and military aircraft, the high-speed mobility will cause the frequent handovers of UTs. Especially, for 5G small cells, handovers will occur more frequently, with the increasing of UTs′ speed, there is not enough time to make handover decisions before UT leaves the overlap area. Once handovers are triggered but interrupted, the failed handover process would result in call drops. Owing to wide coverage and broad operating spectrum, MSNs have been identified as the most cost-affordable technology to meet the high-mobility UT requirements. However, for high-speed UTs and satellites, the handover factors in candidate satellites would change rapidly. Therefore, it is extremely challenging to develop handover methods for MSNs [6], [7]. First, the dynamic topology in MSNs would lead to frequent change of links [8], [9], [11], thus the handover times would increase greatly due to the randomness of UT arrivals. Second, for high-mobility UTs and satellites, there is not enough time to calculate uncertain handover factors before UT leaves the overlap area. As a result, it becomes difficult to finish the handover process at satellite cell edge, which could finally lead to high handover failure rate. In particular, due to the unbalanced traffic distribution in satellite cells [10], congestion may also cause handover failures. Finally, since the selection of handover factors for MSNs is affected by many criteria, the method should be designed comprehensively to minimize the failure rate and handover times.

In order to provide seamless communication service for UTs, the satellite handover strategy has gained increasing attention in recent years. For ultra-dense MSN, such as OneWeb [14],

Manuscript received January 20, 2020; revised April 27, 2020; accepted June 4, 2020. Date of publication June 30, 2020; date of current version October 13, 2020. This work was supported in part by the National Natural Science Foundation of China under Grant 61571334 and in part by the National High Technology Research and Development Program (863 Program) under Grant 2014AA09A512. The review of this article was coordinated by Dr. P. Lin. *(Corresponding author: Deshi Li.)*

Huihui Xu, Deshi Li, Mingliu Liu, Wei Huang, and Chan Xu are with the School of Electronic Information, Wuhan University, Wuhan 430072, China (e-mail: xuhuihui@whu.edu.cn; dsli@whu.edu.cn; liumingliu@whu.edu.cn; whuwsnhw@whu.edu.cn; xuchan@whu.edu.cn).

Guangjie Han is with the Key Laboratory for Ubiquitous Network and Service Software of Liaoning Province, School of Software, Dalian University of Technology, Dalian 116024, China, and also with the Department of Information and Communication Systems, Hohai University, Changzhou 213022, China (e-mail: hanguangjie@gmail.com).

Digital Object Identifier 10.1109/TVT.2020.3000908

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SpaceX [15], since the communication distances and elevation angles [12], [13] between UT and satellite in the same cell are quite close, their signal quality has no significant difference, but the service time and available channel resources can be quite different for the candidate satellites. Basically, the handover strategies in MSNs are either based on single criterion or multiple criteria. There are three types of typical handover factors in the literature, namely the maximum service time [18], [20], maximum available channels [19] and minimum distance [21]. In some specific scenarios, multiple criteria have been combined together to make handover decisions, such as received signal strength (RSS), available channel, service time and transmission distance in [16], [22], [23]. However, most of these studies are only suitable for low-speed UTs. In particular, available channels are obtained by pre-calculated topology, which can hardly reflect real-time traffic situations in MSNs. Therefore, for the highly moving UTs and satellites, the problem of frequent satellite handover should be carefully addressed.

To cope with these issues, we propose a QoE-driven Intelligent Handover (QIH) algorithm. The selection of handover factors is crucial for making the handover decision, especially in ultra-dense MSNs. The service time, communication channel resources and relay overhead are selected as handover criterions in our proposed QIH algorithm, the reasons can be explained as follows:

- *Service time:* since the short association between UT and satellite can increase the number of handovers, to ensure the service duration, satellites that offer maximum service time tends to be selected. This will eventually improve the service experienced of UT.
- *Communication channel resources:* due to the non-uniform and dynamic traffic distribution in satellite cell, some candidate satellites are congested while others remain underutilized. To avoid being switched to overload satellites, the communication channel resources is adopted as a decision criterion.
- *Relay overhead:* As data transmission path changes when the UTs access satellite changes in MSNs, satellite handover inevitably affect the end-to-end delay. To guarantee UTs QoE, relay delay need to be considered as a selection criterion.

Due to the periodical motion of LEO satellite system, handover factors could be predicted in advance, thus the handover failure caused by dynamic topologies can be effectively prevented. In particular, the service time is defined as the duration when UT is covered by a satellite, thus it can be inferred from the spatial relationship between UT and satellite. To guarantee the success of handover decisions, the available channel resource of candidate satellites should be carefully analyzed. As satellites are moving in periodical trajectories, the time-varying communication resources of adjacent satellites can be used to predict the resource factor of candidate satellites. In addition, with the increasing number of satellites in outer space, only depending on the ground stations to make handover decisions will increase the signal overhead and operation expenditure at the same time, thus UT can make handover decisions directly. In this way, the message forwarding delay caused by ground stations can be avoided, and we name it as user-centric MSNs in this paper. Due to the benefit of providing an overall evaluation for complex input conditions, artificial intelligence technology is introduced to solve the multi-criteria problem. However, as the traffic distribution in satellite cells is dynamic and UTs mobility is random, the learning experience in a certain communication session could not ensure best service in the next session. Meanwhile, the neural networks need to store handover information of all UTs and satellites, which would take a lot of memory. In contrast, since Reinforcement Learning (RL) can perform online learning with limited information, and training results can be used in periodical motion behavior, it is applicable for satellite handover in the repeatable path for a certain area. Therefore, based on the predicted handover factors, we adopt RL to solve the multi-criteria optimization problem with the goal of maximizing UTs QoE, which represents the experience of mobile UT during data delivery, including available channels, service time, relay overhead and handover payoff. The contributions of this paper are summarized as below:

- To maximize the UT′s QoE, we propose a QoE-driven Intelligent Handover (QIH) algorithm. The handover factors are first predicted according to the periodic motion of satellites. Then to make optimal handover decisions and achieve best QoE for candidate satellite, RL is adopted to solve the multi-criteria optimization problem.
- To avoid frequent satellite handover, we propose a spatial relationship coupling model to predict relative motion patterns between UTs and satellites. The relative azimuth and distance are quantified, and the longest service time of candidate satellites can be derived in advance.
- To improve the handover success rate, we develop an available channel estimation model. Taking advantage of the periodic movement of adjacent satellites, future available communication resources can be predicted to decrease the handover failure.

The remainder of this paper is organized as follows. Section II gives the review of related works, an overview of system architecture is analyzed in Section III, and Section IV introduces the handover factors modeling. In Section V, the QIH mechanism is detailly presented. Then, simulation results are analyzed in Section VI. Finally, we conclude the paper and present our future research in Section VII.

## II. Related Work

In this section, recent studies on satellite handover are reviewed for their handover metrics and handover mechanisms.

### A. *Metrics for Handover Decision*

In the literature, many satellite handover methods have been proposed based on various decision metrics, including RSS, service time, the shortest distance and number of communication channels. As one of the most common metrics, RSS has been widely used [16], [17]. However, due to the large variation of path loss, it could not reflect the distance relationship between UT and satellite accurately. Another metric is service time based on the ephemeris data [24], [30], which aims to reduce

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the handover times. For example, according to the predicted UT's trajectory and ephemeris data, Hu *et al.* [18] proposed a velocity-aware handover prediction method to find candidate satellite with the longest service time. However, ephemeris data is not always available, e.g. during or after the disasters. In most point-to-point scenarios, which aim to shrink the link delay between ground station and UT, the shortest distance is commonly used [21], [31]. For example, according to the periodic movement of satellites, Wu *et al.* [31] proposed a graph-based handover method to find accessible satellite with the shortest path. One of the most important reasons for the drop/block of an ongoing call is multi-user competition, which would cause the congestion and lead to terrible communication performance. To this end, some studies reserved fixed channels for the switching UTs, and the number of communication channels is adopted as a handover metric [16], [19]. However, the new call blocked probability is increasing at the same time as fewer channels are available for them. Papapetrou *et al.* used the UT location to estimate required channels in [20], but with the increasing number of UTs, it will consume a lot of computing resources on the satellites. As a result, to provide seamless communication service and maximize the UT′s QoE, the metrics should be carefully designed according to the dynamic user-centric MSNs.

### *B. Handover Mechanisms*

In the literatures shown above, each handover metric is adopted to solve a special problem, thus the corresponding handover mechanism is hard to provide an overall solution. To this end, many researchers tend to provide multi criteria decision making (MCDM) mechanisms. For example, to avoid unnecessary handover and decrease the failure rate, Huang *et al.* [22] proposed a handover decision method based on the combination of service time and available communication channels. However, how to assign the weight of handover parameters needs to be well accounted. To solve this issue, the MCDM is formulated as a Linear Programming (LP) optimization problem in [25], which assumes that handover parameters would not change over time. In order to balance the tradeoff between the network resources and communication quality, network selection algorithms based on fuzzy order are proposed in [28], [29]. However, since the scheme adopted the predefined linguistic rules to obtain current handover conditions, it can hardly reflect the non-linear relationship between handover conditions and decision. As a classic technology to provide overall evaluation for complex input conditions, RL is adopted to solve the multi-criteria problem recently in the field of terrestrial mobile communication networks. For example, to improve the handover success rate, Saptarshi *et al.* [26] proposed a reinforcement learning method to build the handover decision matrix based on received signal strength indicator (RSSI), handover event and trigger time. Similarly, RSSI, movement speed and transmission delay are utilized in the RL reward function designed in [27].

Existing satellite handover schemes are mostly suitable for static or low-speed UTs, but dynamic traffic characteristics and handover decision time for high-speed orbiting satellites have rarely been discussed. For high-speed UTs, such as train and plane, the handover factors in candidate satellite would change rapidly, and UTs may often fail to choose the correct satellite. Therefore, it is pivotal to consider both the movements of UTs and satellites.

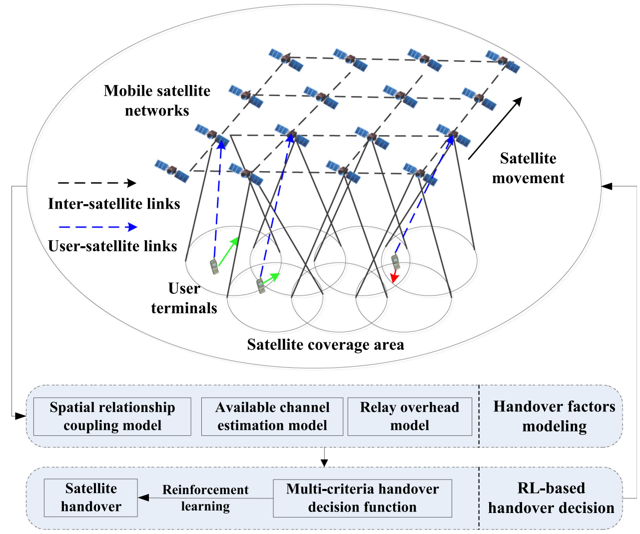


Fig. 1. User-centric MSNs scenario.

## III. System Architecture

A typical MSNs is presented in Fig. 1, which consists of low earth orbit satellites and user terminals. Mobile UTs are assumed to be randomly distributed, and the mission data can be transmitted from ground to space only when they are covered by specific satellites. In a session duration, the data would go through both inter-satellite links and satellite to ground links. The continuous movement of satellites and UTs would lead to a dynamic spatial coverage relation, thus a UT may need to be served by several satellites during a communication session. In specific, the transfer of an ongoing connection from one satellite to another is referred to as handover, which is essential to provide seamless communication service for UTs in MSNs.

To ensure the QoE of handover decision in MSNs, we propose a QoE-driven Intelligent Handover (QIH) algorithm. As shown in Fig. 1, there are two modules in QIH, including handover factors modeling and RL-based handover decision. Handover factors modeling aims to obtain handover factors in advance. Then through RL-based handover decision, an optimal access satellite can be found by the predicted handover factors. The selection and prediction of handover factors are crucial for making the handover decision, especially in dynamic MSNs environment. To ensure the service duration, the relative motion pattern between UTs and satellites is predicted by the proposed spatial relationship coupling model. Available communication resource is predicted by the proposed channel estimation model, so that candidate satellite with enough communication resource could be selected. Meanwhile, relay overhead is adopted as a handover metric to improve the transmission delay. Finally, to solve the multi-criteria problem, RL is introduced to determine the accessible satellite by maximizing the QoE.

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## IV. Handover Factors Modeling

The handover factors modeling includes spatial relationship coupling model, available channel estimation model and relay overhead model. Due to the random movement of UTs, an UT and candidate satellites may move in an opposite direction; With the increasing of UT′s speed, there is not enough time to judge whether the UT will leave and calculate handover factors before UT leaves the overlap area. As a result, the frequent handover will be triggered but interrupted, which would finally lead to high handover failure rate. To this end, the handover factors are predicted to make decision in advance in this paper, thus the handover failure caused by high-speed movement can be effectively prevented. Accordingly, to reduce the handover times, the spatial relationship coupling model is used to predict the relative motion pattern between UTs and satellites, through which the longest service time of candidate satellites can be derived. To avoid the handover failure caused by congestion, future available communication resource of candidate satellites can be predicted by available channel estimation model. Accordingly, the handover factors modeling calculates the relay overhead to estimate propagation delay between the source UT and the destination UT.

### A. Spatial Relationship Coupling Model

A UT should be covered by the satellites during the whole communication session. Hence, to minimize the handover times, satellites that offer maximum service time would tend to be selected. It is straightforward for UT to obtain the satellites′ service time based on the satellites ephemeris data along with the UTs exact location. The UT has to update the ephemeris data periodically via the Internet or other ways. Yet there exist some scenarios where the UT could not access the ephemeris data easily, e.g. during or after the disasters. In particular, for the UTs with greater speed, such as train and plane, both the movements of UTs and satellites should be considered.

By analyzing the spatial relationship between UT and candidate satellites, whether they are moving in the same direction or not can be naturally judged. If the candidate satellite moves in the opposite direction of the UT's movement, the service time of candidate satellite would be short and vice versa. To this end, we use the spatial relationship value as one of the decision criteria to guarantee service time and reduce handover times. To better describe the relative motion between UT and satellites, a spatial relationship coupling model is proposed based on the periodical movement of satellites. In this model, by the current movement direction and speed of candidate satellites and UT, the spatial relationship value between UT and candidate satellites at the next moment can be calculated. The detailed notations and definitions used in this paper are summarized in Table I.

According to the satellite constellation design, the relationship of satellite cells is shown in Fig. 2. Each satellite covers a circle service area on the earth's surface. The relative azimuth value $P_a$ and relative distance change value $P_d$ between UT $u$ and candidate satellite $s$ are adopted to describe the spatial relationship. Denoting $L_{us}$ as the connecting line between $u$ and $s$. Then we denote $\phi$ and $\theta$ as the position angle and approaching angle respectively, where $0 \leq |\phi| \leq \pi$ and $0 \leq |\theta| \leq \pi$. Denoting that the clockwise direction is positive, otherwise, it is negative.

TABLE I
Notations and Definitions

| Notations | Definitions |
|---|---|
| $u$ | A UT |
| $s$ | A candidate satellite |
| $\phi$ | Position angle |
| $\theta$ | Approaching angle |
| $P_\phi$ | The normalized $\phi$ |
| $P_\theta$ | The normalized $\theta$ |
| $P_a$ | The relative azimuth value |
| $P_d$ | The relative distance change value |
| $P_{\triangle D}$ | The distance variation value |
| $P_D$ | The normalized effective relative distance |
| $L_{us}$ | The connecting line between $u$ and $s$ |
| $v_{us}$ | The speed projection difference in direction of $L_{us}$ |
| $v_u$ | The speed of UT $u$ |
| $v_s$ | The speed of candidate satellite $s$ |
| $P_{us}$ | The spatial relationship value |
| $d_{us}$ | The distance between $u$ and $s$ |

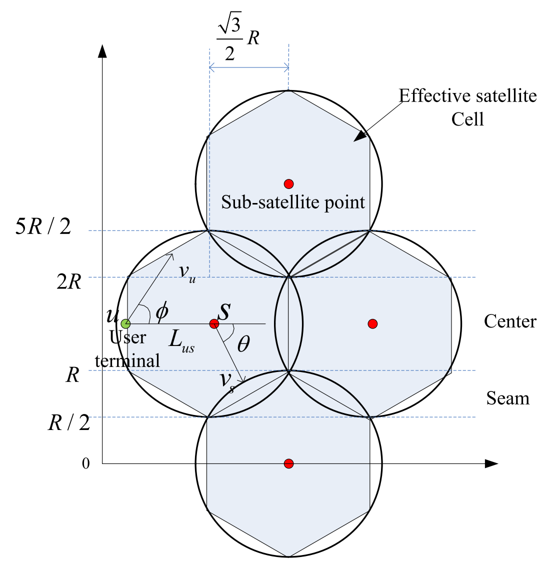


Fig. 2. Relative motion relationship between UT and satellites.

Normalizing $\phi$ and $\theta$ to [−1,1], $P_\phi$ and $P_\theta$ can be obtained as

$$P_\phi = 1 - \frac{2\,|\phi|}{\pi}, \tag{1}$$

$$P_\theta = \frac{2\,|\theta|}{\pi} - 1, \tag{2}$$

when $|\phi| = 0$, $u$ is approaching $s$, so the UT's position angle factor $P_\phi = 1$. When $|\phi| = \pi$, $u$ is moving away from $s$, so $P_\phi = -1$. The approaching angle factor $P_\theta$ of the satellite is the same as $P_\phi$. Then, $P_a$ can be expressed as

$$P_a = 2 + \frac{p_\phi + p_\theta}{2}. \tag{3}$$

The speed projection difference in the direction of $L_{us}$ is $v_{us}$, which can be calculated as

$$v_{us} = v_s \cos\theta - v_u \cos\phi. \tag{4}$$

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When $v_{us} < 0$, it indicates that $u$ is close to $s$, and the service time will be extended, and vice versa. To transform $v_{us}$ into a positive value, we define that the distance variation value is $P_{\Delta D}$, and it can be expressed as

$$P_{\Delta D} = 2 - \frac{v_{us} d_{us}}{R(v_s + v_u)}, \qquad -v_s - v_u \leq v_{us} \leq v_s + v_u, \tag{5}$$

where $d_{us}$ is the distance between $u$ and $s$, $R$ is the radius of the satellite coverage. The communication coverage cell of a single satellite can be assumed as a circular area on the earths surface, to satisfy full coverage of the earths surface, according to the designed constellation orbit, some overlapping between the cells of the adjacent satellites is necessary. Due to the different satellite densities in constellation orbit, the effective cell may have different shapes, such as quadrilateral, hexagon and octagon. Specifically, for ultra-dense constellation with phasing factor, the effective cell is hexagon. In addition, due to the minimum ratio of perimeter to area in regular hexagonal, [32] has proved that the regular hexagonal coverage has the minimum handover rate. Based on the above analysis and future ultra-dense constellation requirement, we assume the largest possible effective cell of a satellite is equivalent to regular hexagon [33]. Thus, the maximum effective radius is $\frac{\sqrt{3}R}{2}$. Accordingly, the normalized effective relative distance $P_D$ can be expressed as

$$P_D = \begin{cases} 1, & d_{us} \leq \frac{\sqrt{3}R}{2}, \\ \frac{R - d_{us}}{R}, & d_{us} > \frac{\sqrt{3}R}{2}. \end{cases} \tag{6}$$

Then, relative distance change value $P_d$ is calculated as

$$P_d = P_D P_{\Delta D}. \tag{7}$$

To give an overall assessment for spatial relations, we define $P_{us}$ as the spatial relationship value which combines the orientation and distance change value between UT and satellite. When $d_{us} \leq \frac{\sqrt{3}R}{2}$, $P_{us}$ can be expressed as

$$\begin{aligned} P_{us}(\phi, v_u) &= P_a P_d \\ &= \left(2 + \frac{|\theta| - |\phi|}{\pi}\right)\left(2 - \frac{(v_s \cos\theta - v_u \cos\phi) d_{us}}{R(v_s + v_u)}\right). \end{aligned} \tag{8}$$

Obviously, the greater the spatial relationship value, the longer the service time for candidate satellite.

As shown in Fig. 3, according to satellite orbit parameters, the effects of velocity and angle of UT on $P_{us}$ can be derived. When the satellite′s approaching angle is zero, the spatial relationship value increases with the increasing of UT velocity and the decreasing of UT′s position angle. In other words, when the satellite moves in the same direction to the connected UT, with the increasing of UT velocity and the decreasing of UT's position angle, the service time will be prolong.

To derive the accurate service time of candidate satellites, as shown in Fig. 4, we took real-world candidate satellites motion parameters supplied from the Satellite Tool Kit (STK) [39]. Then, to verify the accuracy of our model, as shown in Table II, $P_{us}$ in spatial relationship coupling model and service time using ephemeris data in STK are compared. The table shows that the candidate satellite with the largest spatial relationship value has the longest service time. When the UTs velocity is 500 m/s, the spatial relationship coupling model would also predicate the candidate satellites with the longest service time.

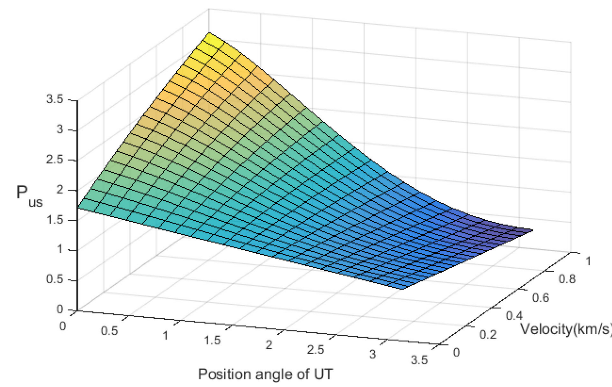


Fig. 3. $P_{us}$ with velocity and angle of UT.

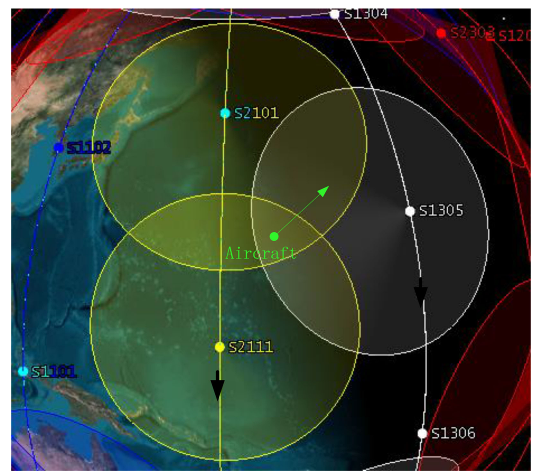


Fig. 4. UT and candidate satellites motion scenario in STK.

TABLE II
A COMPARISON OF SPATIAL RELATIONSHIP COUPLING MODEL VS. EPHEMERIS DATA

| Aircraft-To-Candidae satellite | $v_u$=0m/s $P_{us}$ | $v_u$=0m/s service time | $v_u$=500m/s $P_{us}$ | $v_u$=500m/s service time |
|---|---|---|---|---|
| Aircraft-To-S2101 | 3.63 | 558.127s | 3.51 | 546.184s |
| Aircraft-To-S2111 | 2.12 | 130.388s | 2.04 | 120.219s |
| Aircraft-To-S1305 | 2.59 | 288.329s | 2.68 | 301.599s |

## B. Available Channel Estimation Model

The traffic distribution in satellite cell is non-uniform and dynamic, i.e, some candidate satellites are congested while others remain underutilized. To avoid being switched to overload satellites, an available channel estimation model is proposed to predict the available communication resources of candidate satellites. As shown in Fig. 5, we assume that each beam distribution is a regular honeycomb cellular network. $r$ denotes the coverage radius of the satellite beam, thus $d_{OA} = \sqrt{3}r$. When given the satellite coordinates $S(x_{i,j}, y_{i,j})$, center coordinates $O(x_{i,j}^k, y_{i,j}^k)$ of each beam can be naturally obtained.

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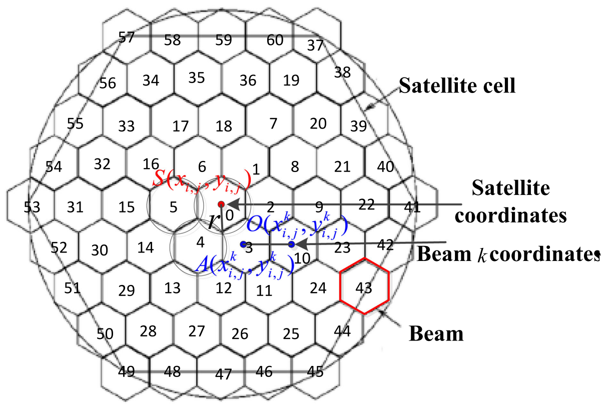


Fig. 5. Beam distribution of satellite.

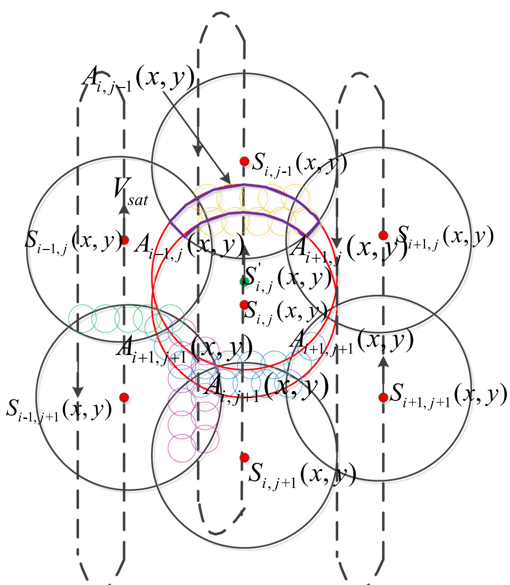

Fig. 6. Illustration of adjacent satellite channel resource occupancy.

The channel occupied by satellites $S_{i,j}$ at time $t$ is $C_{i,j}$, in specific, the channel occupied of the $k$th beam is $C_{i,j}^k$. We assume that the traffic in satellite $j$ of the $ith$ orbit is non-uniform and the traffic in each beam $k$ is evenly distributed. As shown in Fig. 6, let $R$ denotes the coverage radius of each satellite, and $S_{i,j}'$ is the position of satellite $S_{i,j}$ after time duration $\Delta t$. $S_{m,n}$ is the adjacent satellite of satellite $S_{i,j}$, $A_{m,n}(x,y)$ are the intersection of satellite $S_{i,j}'$, $S_{i,j}$ and $S_{m,n}$, where $m = (i-1, i, i+1), n = (j-1, j, j+1)$. $A_{m,n}^k(x,y), k \in A_{m,n}(x,y)$ are the intersection of $A_{m,n}(x,y)$ and the $k^{th}$ beam of adjacent satellite, respectively. Denoting the velocity of satellite as $V_{sat}$. Thus, $A_{m,n}^k(x,y)$ can be calculated as

$$\begin{cases} (x - x_{i,j})^2 + (y - y_{i,j})^2 \geq R^2, \\ (x - x_{i,j})^2 + (y - (y_{i,j} + \Delta t V_{sat}))^2 \leq R^2, \\ (x - x_{m,n})^2 + (y - y_{m,n})^2 \leq R^2, \\ (x - x_{m,n}^k)^2 + (y - y_{m,n}^k)^2 \leq r^2, \end{cases} \tag{9}$$

where $m = (i-1, i, i+1), n = (j-1, j, j+1), k \in A_{m,n}(x,y)$.

Let $T_m$ denotes the average session duration. Since the user communication flows usually constitute a Poisson process, and negative exponential distribution (also called exponential distribution) is a probability distribution which describes the time between events in the Poisson process, we assume communication time $t_d$ follows negative exponential distribution with a mean $T_m$. User handover time $t_h$ represents the time interval from session initialization to handover. As the movement distance $d_h$ of satellite during $t_h$ is monotonous and continuous, $d_h$ follows uniformly distributed between zero and $\Delta t V_{sat}$, thus $t_h \sim U(0, \Delta t)$. Denoting the probability density function of $t_h$ as $p_{th}(t)$. Therefore, the UT handover probability $p_h$ can be derived as

$$\begin{aligned} p_h &= p\{t_d > t_h\} \\ &= \int_0^\infty p[t_d > t | t = t_h] p_{th}(t)\, dt \\ &= \int_0^\infty e^{-\frac{t}{T_m}} p_{th}(t)\, dt \\ &= \frac{T_m(1 - e^{-\frac{\Delta t}{T_m}})}{\Delta t}. \end{aligned} \tag{10}$$

Let $S_{A_{m,n}^k}, m = (i-1, i, i+1), n = (j-1, j, j+1)$ denotes the area of $A_{m,n}^k(x,y)$. Thus, the demanded link resource of satellite $S_{i,j}'$ at time $t + \Delta t$ is

$$\left( \sum_{k \in A_{i-1,j}(x,y)} \frac{S_{A_{i-1,j}^k}}{\pi r^2} C_{i-1,j}^k + \sum_{k \in A_{i,j-1}(x,y)} \frac{S_{A_{i,j-1}^k}}{\pi r^2} C_{i,j-1}^k + \sum_{k \in A_{i+1,j}(x,y)} \frac{S_{A_{i+1,j}^k}}{\pi r^2} C_{i+1,j}^k \right) P_h.$$

Similarly, the channel released by satellite $S_{i,j}'$ at time $t + \Delta t$ is

$$\left( \sum_{k \in A_{i-1,j}(x,y)} \frac{S_{A_{i-1,j}^k}}{\pi r^2} C_{i-1,j}^k + \sum_{k \in A_{i,j-1}(x,y)} \frac{S_{A_{i,j-1}^k}}{\pi r^2} C_{i,j-1}^k + \sum_{k \in A_{i+1,j}(x,y)} \frac{S_{A_{i+1,j}^k}}{\pi r^2} C_{i+1,j}^k \right) P_h.$$

Therefore, the occupied channels of $S_{i,j}'$ at time $t + \Delta t$ can be calculated as

$$\begin{aligned} C_{i,j}' = C_{i,j} &+ \left( \sum_{k \in A_{i-1,j}(x,y)} \frac{S_{A_{i-1,j}^k}}{\pi r^2} C_{i-1,j}^k \right. \\ &\left. + \sum_{k \in A_{i,j-1}(x,y)} \frac{S_{A_{i,j-1}^k}}{\pi r^2} C_{i,j-1}^k + \sum_{k \in A_{i+1,j}(x,y)} \frac{S_{A_{i+1,j}^k}}{\pi r^2} C_{i+1,j}^k \right) P_h \\ &- \left( \sum_{k \in A_{i-1,j+1}(x,y)} \frac{S_{A_{i-1,j+1}^k}}{\pi r^2} C_{i-1,j+1}^k \right. \end{aligned}$$

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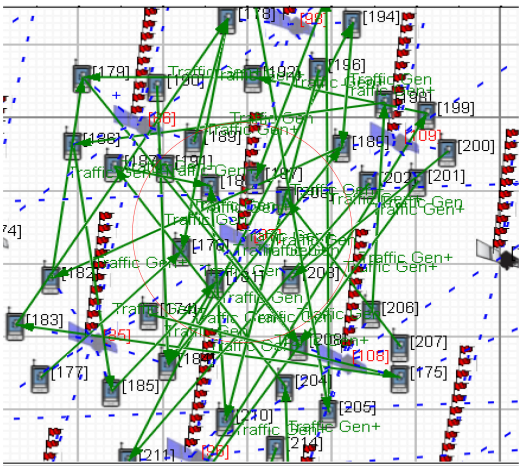

Fig. 7. Simulation scenario of available channels.

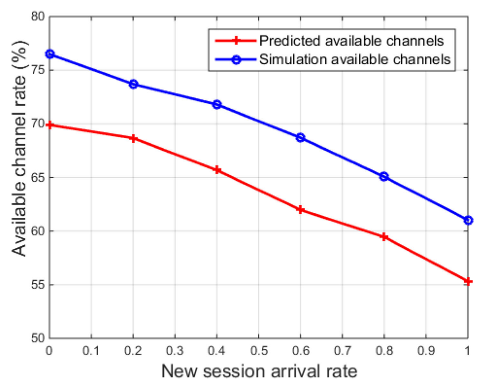


Fig. 8. Comparison of predicted available channels vs. simulation available channels.

$$+\sum_{k\in A_{i,j+1}(x,y)}\frac{S_{A^k_{i,j+1}}}{\pi r^5}C^k_{i,j+1}$$
$$\left.+\sum_{k\in A_{i+1,j+1}(x,y)}\frac{S_{A^k_{i+1,j+1}}}{\pi r^2}C^k_{i+1,j+1}\right)P_h. \tag{11}$$

Denoting the capacity of a satellite communication channel as constant $C$, then based on the above analysis, the available channels of $S'_{i,j}$ at time $t+\Delta t$ can be predicted as

$$C''_{i,j}=C-C'_{i,j}. \tag{12}$$

To verify the accuracy of our model, we first create a constellation model in STK, in which each satellite includes 61 beams. Then, through the QualNet interface of STK, we conduct a experiment on polar orbit constellation by QualNet simulator. As shown in Fig. 7, to simulate realistic data traffic, we set 600 data flows, in which the source and destination UTs are randomly dispersed all over satellites [34]. The communication session follows exponential distribution with a mean 180 s. $\Delta t$ is set to 120 s, and the channel number of each beam is set to 8. As shown in Fig. 8, the predicted available channels and simulation available channels are compared, and the mean square error between the predicted number of available channels and actual value is less than 6.15.

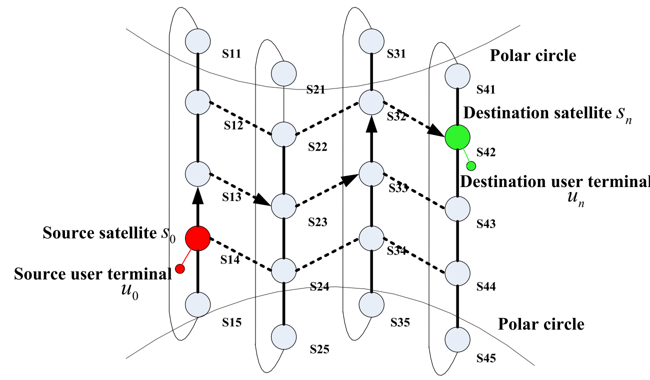


Fig. 9. Relay overhead.

## C. Relay Overhead Model

Switching to a candidate satellite with enough communication channels would ensure a successful handover, but it may cost the longest end-to-end delay. In order to improve the data transmission efficiency, we take the relay overhead as a handover factor. As shown in Fig. 9, denote $u_0$ as the source UT, $s_0$ as the candidate satellite of $u_0$, $u_n$ as the destination UT, $s_n$ as the service satellite of $u_n$. According to the datagram routing algorithm [36], relay overhead $t_i$ between $u_0$ and $s_0$ can be expressed as

$$t_i=t_0+t_n+\sum^{M}t_e+\sum^{N}t_d, \tag{13}$$

where $t_0$ is the propagation delay between $s_0$ and $u_0$, and $t_n$ is that between $u_n$ and $s_n$. $t_e$ is link delay of satellite in same orbit and $t_d$ is link delay of satellite in different orbit. M denotes the hops with same orbit between the source satellite and the destination satellite, and N denotes the hops with different orbit.

# V. QoE-Driven Intelligent Handover Algorithm

Based on the predicted handover factors discussed in the previous section, we propose a QoE-driven Intelligent Handover (QIH) algorithm for user-centric MSNs to obtain optimal handover decision. A key feature of the proposed schemes is realized by making handover decision in a distributed manner. In other words, the handover decision is performed by UT in this paper. To this end, UTs themselves are able to predict the handover factors and as agents to take actions in the satellite link state. This can avoid the message forwarding delay caused by ground station. Fig. 10 illustrates the flow chart of QIH handover procedure. At first, a UT periodically measures the handover parameters information from candidate satellites. After receiving this information, each UT predicts the handover factors and makes handover decision in advance. To minimize unnecessary network signaling, the UT determines an accessible satellite and directly sends the handover request message to it. If the satellite can support the newly-coming UT, it will respond with related handover information. The UT would then perform

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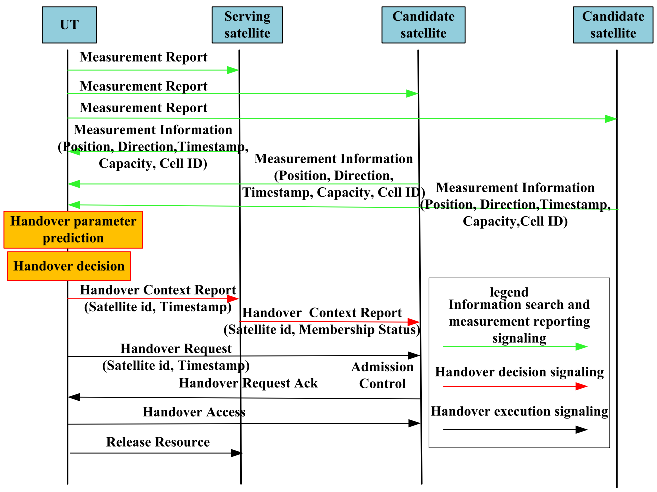


Fig. 10. Flow chart of the QIH handover procedure.

data synchronization and the access procedures. After building a session, the UT sends handover completion signal to inform the serving satellite for releasing resource.

To solve the multi-criteria optimization problem, we design a QoE-driven intelligent handover scheme, in which each UT adaptively uses the evolutionary conditions to maximize its QoE. This can be achieved by modeling the satellite handover as a RL process, where QoE of the handover decision is treated as the action reward. The environment states, actions, reward function and online learning process are defined as follows:

*1) States and Actions:* An environment state is designated as $E$, it represents the characteristics of all the available candidate satellites at each time slot, which include the predicted available channels, spatial relationship value and relay overhead. In order to reduce the state space to a finite set, the range of available channels $r_i$, spatial relationship value $p_i$ and relay overhead $t_i$ are mapped to a set of quantized values. The states is then described by the quantized $S$=$\{\{r_1, p_1, t_1\}, \{r_2, p_2, t_2\}, \ldots, \{r_i, p_i, t_i\}\}$. The action is denoted by $\alpha \in \{1, 2, \ldots, N\}$, which determining the handover decision to the selected satellite.

*2) Reward Function:* The mobile UT′s QoE determines the reward $R(E, \alpha)$ at state $E$ when action $\alpha$ is taken. The factors that affect mobile UT′s QoE depend on the service requested by a mobile UT. Based on the above analysis, $R(E, \alpha)$ includes available channels, service time, relay overhead and handover payoff, are specified by the network state s and action $\alpha$ at each time slot. Therefore, the corresponding reward function $R(E, \alpha)$ can be defined as

$$R(E, a) = w_1 N(g_i) + w_2 N(r_i) + w_3 N(c_i) + w_4 N(t_i), \tag{14}$$

where $N$ is the normalized function of each handover factor, and the weight can be determined by Analytic Hierarchy Process (AHP) in [35]. AHP makes decisions about complicated problems by dividing them into a hierarchy of decision factors, which makes it easy to analyze. It consists of the following steps:

*Step 1:* Initializing the matrix of handover factors: since the available resources determine the success rate of handover, available resources are the most important influencing factor for UT's QoE. The service time affects the numbers of handover, so it is the second important handover factor. The relay overhead affects the end-to-end delay, we define it as the third important handover factor. The last handover factor is the fourth important handover factor. Then, the handover factors are compared pairwise according to their levels of influence with respect to the scale shown in Table III. The comparison results are presented in a square matrix $A = (a_{ij})_{4\times 4}$, and $a_{ij} = 1, a_{ji} = 1/a_{ij}$.

TABLE III
T.L.SATTY SCALE OF IMPORTANCE

| Intensity of importance | Definition |
|---|---|
| 1 | Equal importance |
| 3 | Moderate importance |
| 5 | Strong importance |
| 7 | Very strong importance |
| 9 | Extreme importance |
| 2, 4, 6, 8 | Intermediate values |

$$A = (a_{ij})_{4\times 4} = \begin{pmatrix} 1 & 1/7 & 1/5 & 1/3 \\ 7 & 1 & 2 & 4 \\ 5 & 1/2 & 1 & 3 \\ 3 & 1/4 & 1/3 & 1 \end{pmatrix}$$

*Step 2:* Normalizing and calculating the relative weights: the relative weights are calculated by finding the right eigenvector ($W$) corresponding to the largest eigenvalue ($\lambda_{\max}$), as $AW = \lambda_{\max} W$. Then, we can derived $W = (0.059, 0.502, 0.305, 0.134)^T$, i.e, $w_1 = 0.305, w_2 = 0.502, w_3 = 0.059, w_4 = 0.134$.

For available channels $r_i$, the function $N(r_i)$ is formulated as

$$N(r_i) = \frac{r_i}{r_{all}}, r_i \leq r_{all}, \tag{15}$$

where $r_{all}$ is the communication channels capacity of one satellite.

After the selected satellite is accessed, the coverage time of servicing satellite would be calculated by UTs position, orbit information and satellite ID. Since satellite coverage is a necessary condition for providing communication services, the service time $g_i$ will be estimated by calculating coverage time in this paper. For service time $g_i$, the function $N(g_i)$ is formulated as

$$N(g_i) = \frac{g_i}{g_{\max}}, g_i \leq g_{\max}, \tag{16}$$

where $g_{\max}$ is the maximum coverage time of one satellite.

Similarly, for relay overhead $t_i$, the function $N(t_i)$ is formulated as

$$N(t_i) = \frac{t_{\max} - t_i}{t_{\max}}, t_i \leq t_{\max}, \tag{17}$$

where $t_{\max}$ is maximum tolerable delay for transmission data.

The last factor is the handover payoff that determines whether a UT should execute a handover. Obviously, when candidate satellites and servicing satellite have the same handover factors, handover would increase handover times [37]. Moreover, to search for the optimal satellite, UT is switched from one satellite to another every time when the handover factor of

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candidate satellites outperforms the current servicing satellite. It will result in a large number of handovers when the handover parameter changed rapidly. Hence, a larger value is assigned to non-handover. Assuming all handover payoff are the same, the normalized handover payoff function is defined as [38]

$$N(c_i) = \begin{cases} 0.1, & \text{handover}, \\ 1, & \text{non-handover} \ . \end{cases} \tag{18}$$

*3) Online Learning Process:* The objective of agent at the time $t + \Delta t$ is to find an optimal action which maximizes QoE. Thus the Q-learning recursively updates the Q-value during its multiple handovers:

$$Q_{t+\Delta t}(E_t, a) = Q_t(E_t, a) + \alpha[R + \gamma \max(Q_t(E_{t+\Delta t}, a) - Q_t(E_t, a))], \tag{19}$$

where $0 < \alpha < 1$ is the step-size parameter, or the so-called learning rate. The discount factor $\gamma \in [0, 1]$ determines the present value of future rewards. The QIH algorithm is presented in Algorithm1. Firstly, the handover parameters are initialized to calculate the handover factors for each state-action pair. Then, the current state can be derived and the Q-value corresponding to state E from the Q-value look-up table is obtained. After transitioning to the next state $E_{t+\Delta t}$, the Q-values can be updated according to (19). Finally, the candidate satellite with maximum Q-value is selected.

**Algorithm 1:** QIH Algorithm for User-Centric MSNs.

```
Initialization:
    Initialize learning rate α, discount factor γ
    Initialize satellite speed v_s, satellite motion direction q, beam occupancy channel c
    Initialize user speed v_u, user movement direction ϕ, link delay D
    Initialize termination time T
LOOP: Every candidate satellite
    Calculate the spatial relationship value by (8)
    Calculate the available channels by (13)
    Calculate the relay overhead by L_min
End of LOOP:
For event time t = 1, ..., T do
    Let s = current handover decision state Q_t(s, a)
    Choose an action a_i
    Calculate the reward value R(s, a)
    Q_{t+Δt}(E_t, a) = Q_t(E_t, a) + α[R + γ max(Q_t(E_{t+Δt}, a) − Q_t(E_t, a))]
    Update the policy Q(E, a) using (19)
    If the satellite ID of the largest Q value == the current service satellite ID then
        Remain connected to current satellite
    Else
        Perform handover to new accessible satellite
        The access satellite ID = the satellite ID of the largest Q value
    End If
End For
```

## VI. Simulation and Analysis

The satellite tool software STK is an advanced system analysis software in the aerospace field. It can provide realistic 2D and 3D visual dynamic scenes of constellation orbit. QualNet is a real-time high-performance network simulator, which can support satellite communications, mobile Ad hoc networks, heterogeneous devices, and networks with thousands of nodes. In order to evaluate the performance of QIH schemes, we first create a constellation model in STK, in which there are 156 satellites uniformly distributed over 13 orbits. Then we conduct a series of experiments in the QualNet6.1 simulator using real-world satellite parameters supplied from STK. Each satellite has four inter-satellite links. The simulation parameters are illustrated in Table IV. The discount factor $\gamma$ are set to 0.5 for maintaining the balance between current and future rewards. UTs are simultaneously covered by three candidate satellites. In the single criterion decision mechanisms, shortest distance handover algorithm (SDH) [21] and service time-based handover algorithm (STH) [24] have become common benchmark for evaluating satellite handover algorithm, load balancing handover algorithm (LBH) [16] can realize high channel utilization, and velocity-aware handover prediction method (VAH) [18] is a new algorithm that can find accessible satellite with the longest service time in advance. Furthermore, time and capacity weighting handover method (TCH) [22] has also been used in multiple criteria decision mechanism. Based on these considerations, our simulation is carried out to compare QIH with the five representative satellite handover algorithms. In specific, handover times, handover failure ratio and end-to-end delay are adopted as the performance metrics.

TABLE IV
SIMULATION PARAMETERS

| Parameters | Values |
|---|---|
| Orbital altitude (km) | 1000 |
| Inclination of orbital plane to the equator (°) | 87.4 |
| No. of planes | 13 |
| No. of satellites per plane | 12 |
| Minimum elevation angle of satellite from ground terminal for link (°) | 10 |
| Phase offset between satellites in neighbouring planes (°) | 360/12/2= 15 |
| Coverage radius of satellite R(km) | 2400 |
| The mean session duration (s) | 180 |
| Number of beam cells per satellite | 60 |
| Simulation time (s) | 3600 |

### A. Convergence

To analyze the convergence of QIH algorithm, the network is simulated 300 times, and the algorithm is executed 18000 times, starting with a random state for each trial. At the initialization stage, each UT selects a candidate satellite for handover in a random manner, which is called the exploration period. Based on its action and observation during this exploration period, each UT creates a priority list according to the Q values of candidate satellite. In the steady-state, a UT selects the candidate satellite according to the priority list for handover. Fig. 11 shows

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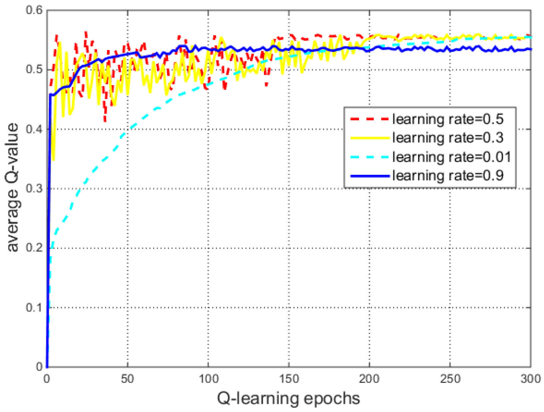


Fig. 11. Convergence comparison at different learning rates.

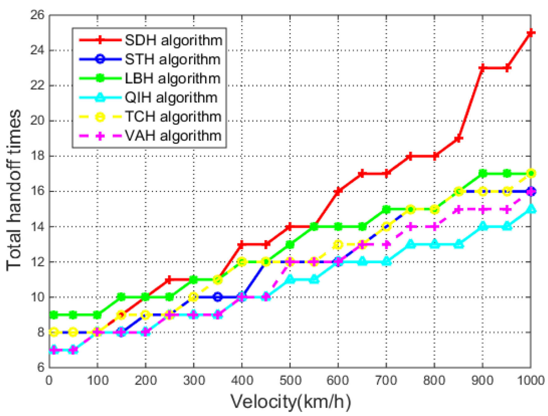


Fig. 12. Handover times versus terminal speeds.

the convergence of the algorithm at different learning rates. In the simulation, four learning rates are set for comparison, i.e., 0.01, 0.3, 0.5 and 0.9. The results indicate that the convergence speed is slowest when learning rate is 0.01, and convergence is gradually achieved after more than 270 epochs (16200 learning iterations). However, when the learning rate increases to 0.5, the convergence speed is significantly improved, and stability can be achieved after about 145 epochs (8700 learning iterations). Therefore, to balance performance of learning and convergence, the learning rate is set to 0.5 in the following simulation.

## *B. Impact of Mobility Speeds*

To study the impact of different velocity, the total handover triggered times are explored. In the simulation, the UTs speed varies from 10 km/h to 1000 km/h. Fig. 12 shows that the handover times increase with the increase of speed. Meanwhile, QIH has less handover times compared to the other three methods. The reason is that residence time of overlap area becomes shorter with the increase of UTs speed, thus handover parameters would vary greatly in a short time. The SDH, STH, LBH and TCH methods switch from one satellite to another each time when the handover factor of candidate satellites outperforms the current servicing satellite. Therefore, it results in a large number of handovers when the handover parameter changed rapidly. In VAH method, since the UTs trajectory is predicted, each candidate satellite is calculated in advance. Hence, the number of unnecessary handover would be reduced. However, in QIH method, since the handover factors of each candidate satellite are calculated in advance, the candidate satellites that have short service time could be omitted through the predicted spatial relationship criterion. Furthermore, to avoid frequent handover caused by constantly searching for an optimal satellite, the handover payoff is taken as a factor to solve the above problem; thus, the QIH method can achieve better handover times.

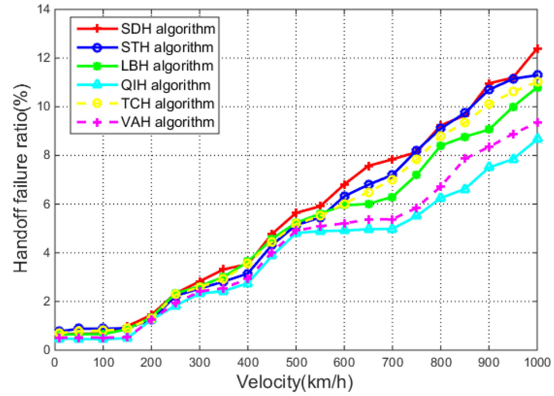


Fig. 13. Handover failure ratio at various terminal speeds.

Fig. 13 shows the handover failure ratio with terminal speeds. Obviously, when the UT velocity is small, all the six algorithms have a low handover failure rate, and it rises as the UT velocity increases. With the increasing of speed in SDH, STH, LBH and TCH algorithm, there is not enough time to judge whether the UT will leave and calculate handover factors before UT leaves the overlap area. As a result, the frequent handover will be triggered but interrupted before completion, which would finally lead to high handover failure rate. Owing to the early handover decision to correct candidate satellite, VAH and QIH have a low handover failure rate. In particular, available channels of candidate satellite in QIH are predicted, the handover failure caused by congestion can be avoided. Hence, QIH has the lowest handover failure rate among the six algorithms.

To further clarify the idea, end-to-end transmission delay with time-varying of the four algorithms in 1000 km/h is analyzed in Fig. 14. The SDH, STH, LBH and TCH algorithms scan for candidate satellites before handover. As a result, they cannot receive the traffic flow from the serving satellite, which explains the packet delay surges that occur before their handovers. Since VAH and QIH can make handover decision in advance, which can let an UT to connect with the accessible satellite a few seconds earlier than the other four algorithms. In particular, as QIH predicts the relay overhead and selects candidate satellite with optimized overhead to transmit data, QIH scheme is proved to support seamless handover via reducing end-to-end transmission delay.

## *C. Impact of Satellite Load*

To investigate the impact of available channels, the handover times and end-to-end delay are analyzed for different satellite

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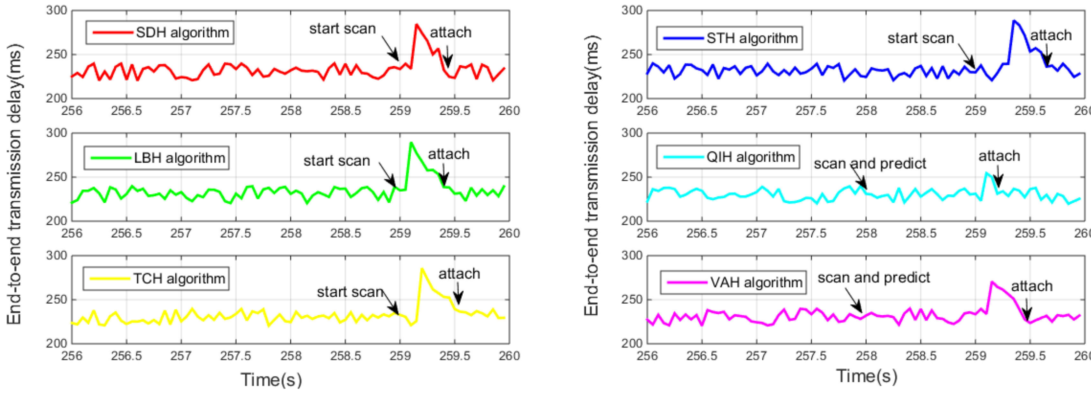


Fig. 14. End-to-end transmission delays in handover.

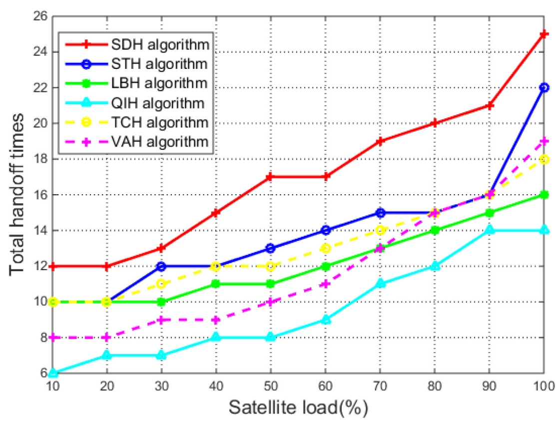


Fig. 15. Handover times versus satellite loads.

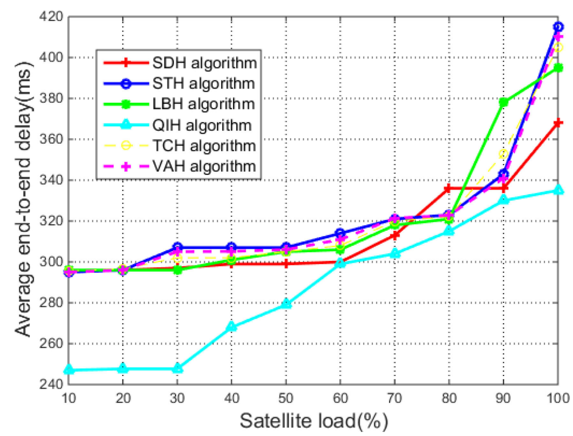


Fig. 16. End-to-end delay at various satellite loads.

load. The handover times for different load of some satellites are plotted in Fig. 15. The results indicate that the handover times of QIH are the least among different satellite loads. Due to the lack of channel guarantee mechanism in SDH, STH and VAH, the handover failure rate keeps increasing, and the handover will then be triggered again. However, since the candidate satellite with the largest sum of service time and available channels is selected as access satellite in TCH, and the satellite with the maximum available channels would be selected in LBH, there would be abundant channel resources to guarantee the success of handover. As a result, the number of unnecessary handovers would be reduced. In particular, available channels of candidate satellite in QIH are predicted, the handover failure caused by congestion can be avoided. Additionally, the predicted spatial relationship criterion avoids switching to candidate satellites that are located away from it is moving direction, thus the number of unnecessary handover would be reduced.

To investigate how satellite load affects the end-to-end delay, we vary some satellites load by changing the data rate while setting the speed of UT as 1000 km/h. In Fig. 16, all the six algorithms have a low end-to-end delay when the satellite load is low, and the end-to-end delay rises as the satellite load increases. The reason is that available communication channels become congested with the increase of satellite load, thus data packets accumulate in the node′s sending queue, which results in a sharp increasing in packet end-to-end delay. In QIH, as it predicts the relay overhead and selects candidate satellite with optimized overhead to transmit data, even though RL would lead to the learning delay, it can be neglected compared with the end-to-end delay. As presented in the figure, QIH gets the least end-to-end delay among different satellite loads.

## VII. Conclusion

In this paper, a QoE-driven intelligent handover algorithm is presented to study the high dynamic time-varying features of satellite networks. Based on the constellation characteristics of user-centric MSNs, handover factors including service time, communication channel resources and relay overhead are predicted for the handover decision. To better capture the uncertain relationship between UTs and satellites, a spatial relation coupling model is first established based on the predictability of satellite trajectories. This model constructs a quantitative expression of relative orientation and distance change between users and satellites, through which the service time of candidate satellites can then be obtained. Second, an available channel estimation model based on the deterministic satellite movement is developed, which aims at predicting available communication resources of candidate satellites. Finally, to maximize the handover success rate and minimize the handover times, the

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selection of next service satellite is constructed as a multi-criteria problem, through which the UT′s QoE can be improved significantly. In special, a RL-driven intelligent algorithm is proposed to solve the problem. Experiment results show that the proposed handover mechanism outperforms conventional methods in terms of handover times, success rate, and end-to-end delay. As future work, we intend to investigate the influence of multi-layer LEO scenario on the handover performance, and explore the possibility of using transfer learning algorithm to deal with non-repeatable path problem.

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**Huihui Xu** received the master's degree from Hohai University, Changzhou, China, in 2011. She is currently working toward the Ph.D. degree in communication and information system with Wuhan University, Wuhan, China. Her current research interests include satellite networks and 5G wireless networks.

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**Deshi Li** received the B.E. degree from the Chengdu University of Science and Technology Chengdu, China, in 1990, the M.E. degree from the Wuhan University of Electric and Hydraulic Engineering, Wuhan, China, in 1993, and the Ph.D. degree from Wuhan University, Wuhan, China, in 2001. He was a Visiting Professor with the University of California at Davis, from 2006 to 2007. He is currently a Professor and the Dean of the Electronic Information School, Wuhan University, where he directs the Laboratory for Advanced Network and Intelligent System Research Team. He is a member of the Internet of Things Expert Committee of the Chinese Institute of Electronics. His research interests include wireless sensor networks, networked robots, embedded system, system-on-chip design, and verification.

**Mingliu Liu** (Member, IEEE) received the B.E. and Ph.D. degrees from the School of Electronic Information, Wuhan University, Wuhan, China, in 2013 and 2019, respectively. Since July 2019, she has been a Postdoctoral Fellow with the School of Electronic Information, Wuhan University.

Her research interests include information search service, Internet of Things, cloud/edge caching, and big data driven applications. She is a member of IEEE Computer and IEEE Communication Society.

**Guangjie Han** (Senior Member, IEEE) received the Ph.D. degree from Northeastern University, Shenyang, China, in 2004. He is currently a Professor with the Department of Information and Communication System, Hohai University, Changzhou, China and a Distinguished Professor with the Dalian University of Technology, Dalian, China. In February 2008, he finished his work as a Postdoctoral Researcher with the Department of Computer Science, Chonnam National University, Gwangju, South Korea. From October 2010 to October 2011, he was a Visiting Research Scholar with Osaka University, Suita, Japan. From January 2017 to February 2017, he was a Visiting Professor with the City University of Hong Kong, Hong Kong. His current research interests include Internet of Things, Industrial Internet, Machine Learning and Artificial Intelligence, Mobile Computing, Security and Privacy. He has authored or coauthored more than 400 peer-reviewed journal and conference papers, in addition to 140 granted and pending patents. Currently, his H-index is 41 and i10-index is 135 in Google Citation (Google Scholar). Total citation of his papers by other people is more than 6500 times.

He is a Fellow of the UK Institution of Engineering and Technology (FIET). He has served on the Editorial Boards of up to 10 international journals, including the IEEE Network, IEEE Systems, IEEE/CAA Journal of Automatica Sinica, IEEE Access, *Telecommunication Systems*, etc. He has guest edited a number of special issues in the IEEE Journals and Magazines, including the IEEE Journal on Selected Areas in Communications, IEEE Communications, IEEE Wireless Communications, IEEE Transactions on Industrial Informatics, *Computer Networks*, etc. He has also served as chairs of organizing and technical committees of many international conferences. He had been awarded 2020 IEEE Systems Journal Annual Best Paper Award, 2017–2019 IEEE Access Outstanding Associate Editor Award.

**Wei Huang** received the B.E. degree in electronic information science and technology, in 2014 from Wuhan University, Wuhan, China, where he is currently working toward the Ph.D. degree in communication and information system. His current research interests include underwater acoustic communication, underwater sensor network and localization, intelligent system and control.

**Chan Xu** received the B.E. degree, in 2015 from Wuhan University, Wuhan, China, where she is currently working toward the Ph.D. degree with the School of Electronic Information. Her current research interests include UAV communication and wireless sensor networks.

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