Analytic Hierarchy Process Based Cell Reselection for Inactive Users in LEO Satellite Networks

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Abstract. Low Earth Orbit (LEO) satellites have a global coverage and continuity, which enable them to provide communication services for users in remote areas such as mountains and oceans. This feature makes LEO satellites one of the promising research directions for 6G. Based on the variations in satellite beam coverage angles, satellite coverage cells could be classified into Earth fixed cells and Earth moving cells. In the context of LEO satellite Earth moving cells, the high mobility of satellites leads to frequent cell reselection for users, resulting in substantial signaling overhead and excessive energy consumption. In this paper, we propose a cell reselection strategy based on the Analytic Hierarchy Process (AHP) in the LEO satellite Earth moving cell scenario. By leveraging the periodic motion of LEO satellites, the reselection time could be predicted, and the candidate list for cell reselection could be determined. Furthermore, the Received Signal Strength and the Remaining Service Time of users are weighted according to various QoS requirements, which will decide the optimal reselection cell, thereby reducing cell reselection times. Simulation results demonstrate the efficiency of the proposed AHP based cell reselection strategy.

Keywords: Cell Reselection · Earth Moving Cell · Low Earth Orbit Satellite · Analytic Hierarchy Process

1 Introduction

With the rapid development of communication technology, providing users with anytime, anywhere network access and reliable communication services has become the trend of future communication networks [2]. Due to the fact that satellite communication networks can not only provide users with stable and reliable communication services, but also achieve global wide-area coverage, which

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have become a key research topic in the future development of communication networks. Currently, in Rel-16, Third Generation Partnership Project first proposed technical research on satellite networks, and in TS 38.913 and TS 22.261 mentioned the use of satellite networks to support 5G networks [1]. In the design of satellite network architecture, mobility management is one of the key factors affecting network performance. Users could be categorised into users of three states: Idle users, Inactive users and Connected users. The Idle user is the user which connection to Radio Resource Control (RRC) has been released, and is currently in an unregistered state in the Core Network (CN). The Connected user is the user which connection with RRC is established and is registered in the CN. The Inactive user is the user which connection to RRC has been released and the RAN and CN remain connected. The user could quickly switch from the inactive state to the connected state. Due to the high speed of LEO satellites, the high mobility of cells leads to frequent cell reselection of Inactive users and handover of Connected users, resulting in long communication delays and huge signaling overheads [4].

LEO satellite cells are divided into Earth Fixed Cells, which refers to beams that do not move with the satellite and point to a fixed area on the ground, and Earth Moving Cells (EMC), which refers to beams that move with the satellite and point to a moving area on the ground.

In reference [8], a handover strategy was proposed that considers switching satellite service time to avoid predicted switching failures. In reference [6], a channel reservation handover strategy was proposed to reduce the number of switching failures and improve channel utilization. In reference [5], a multi-attribute decision satellite switching strategy was proposed that considers user received signal strength, remaining service time, and satellite idle channels to reduce switching frequency and improve user average signal strength. Currently, the reselection scheme for cells in Earth-moving cell scenarios for LEO satellites is still blank. Moreover, most existing satellite switching decisions are executed by the network side, which has high complexity and is not suitable for cell reselection of Inactive users (IUs).

In this paper, we propose a Cell Reselection Strategy based on AHP (CRSA) for IUs in LEO satellite EMC scenario. The proposed strategy could predict the time of cell reselection based on the periodic movement of LEOs, determine the candidate list of reselected cells, and calculate the weights, thresholds, and other related parameters of different IUs based on their business requirements to optimize the reselected cells and reduce the cell reselections times. Finally, the simulation results demonstrate the effectiveness of the proposed CRSA strategy in improving the cell reselection performance.

The rest of this paper is organized as follows. Section 2 presents the system model. In Sect. 3, the details of the CRSA strategy is proposed. Simulation and analysis are presented in Sect. 4. Finally, Sect. 5 concludes the paper.

2 System Model

2.1 LEO Satellite Communication System

Consider a LEO satellite communication system consists of a LEO satellite constellation, users, ground gateways, and a core network, as shown in Fig. 1. The LEO satellite connects to users through a service link and to the ground gateway through a feeder link. The ground gateway serves as a relay connecting the LEO satellite to the core network. Each LEO satellite has multiple beams, with one beam corresponding to one cell. In this paper, we consider the EMC scenario, in which the satellite beam angle is fixed, and the corresponding cell are moving with the beam.

There are $\mathrm{N_S}$ LEO satellites, represented as s_i, $i = 1, 2, \ldots, \mathrm{N_S}$. Each satellite has $\mathrm{N_B}$ beams, represented as $b_{i,j}$, $i = 1, 2, \ldots, \mathrm{N_S}$, $j = 1, 2, \ldots, \mathrm{N_B}$. M IUs are randomly distributed on the ground, denoted as u_m, $m = 1, 2, \ldots, \mathrm{M}$.

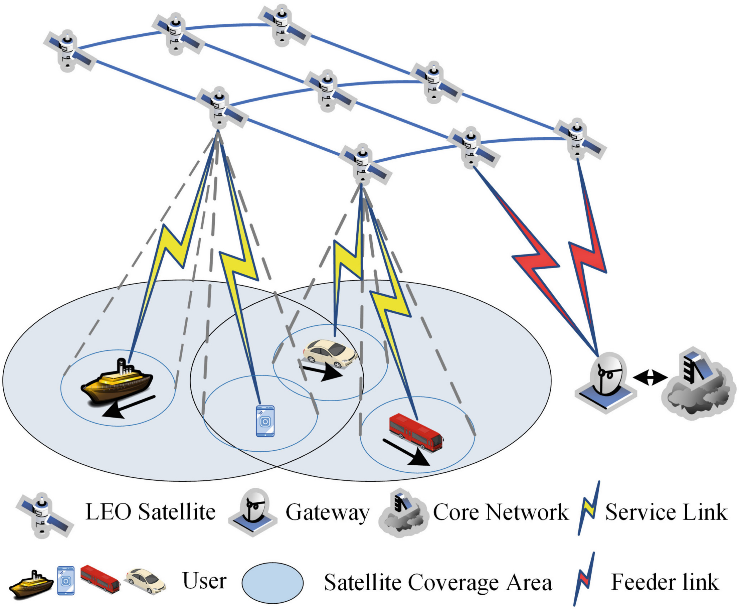


Fig. 1. LEO Satellite Communication System

Due to the high-speed movement of LEO satellites, the coverage time of each beam is quite short, and IUs need to re-select cells frequently, especially in the EMC scenario. Due to the high-speed movement of LEO satellites, the influence of IUs speed on cell reselection could be ignored. The ephemeris of LEO satellites will be broadcasted periodically, and IUs could obtain current location information through the satellite navigation system.

2.2 Received Signal Strength

The received signal strength (RSS) of IU u_m is one of the important indicators for the cell reselection, which can be represented as:

$$P = P_s + G_s + G_u - L. \quad (1)$$

where P_s represents the transmit power, G_s and G_u are the antenna gain of IUs and beams, respectively. L is the transmission loss in free space, given by:

$$L = 32.45 + 20 \lg d_{s,u} + 10 \lg f. \quad (2)$$

where $d_{s,u}$ represents the distance between IU u_m and satellite s_i, and f is the carrier frequency.

2.3 Remaining Service Time

Remaining Service Time (RST) is one of the important indicators for cell reselection, and reselecting to a cell with the longer RST could reduce reselection times. Based on satellite ephemeris, the trajectory of the satellite sub-point could be calculated. The sub-point of a satellite is the point on the Earth's surface where the line connecting the satellite and the center of the Earth intersects the Earth's surface. IUs could determine the trajectory of the satellite sub-point based on the ephemeris information.

In the EMC scenario, the beam center point remains relatively stationary with respect to the sub-satellite point, and the latitude and longitude coordinates of the beam center point could be obtained.

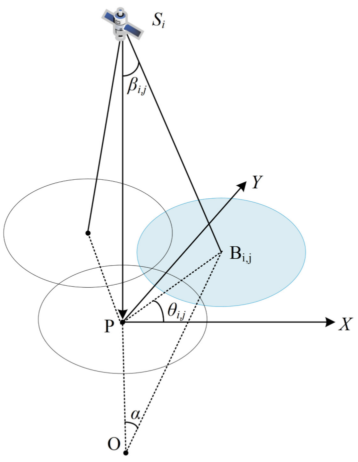


Fig. 2. Spatial Relationship between Satellites and Beams

As shown in Fig. 2, a coordinate system XOY is constructed with the sub-satellite point as the origin, where the X-axis represents longitude and the Y-axis represents latitude. The sub-satellite point is denoted as P with coordinates (S_i^{lon}, S_i^{lat}), and $B_{i,j}$ is the beam center of beam $b_{i,j}$. $\beta_{i,j}$ and $\theta_{i,j}$ are the elevation angle and the azimuth angle of beam $b_{i,j}$, respectively, which will be broadcasted to IUs. Additionally, based on the spatial relationship between satellite s_i and beam $b_{i,j}$, the geocentric angle of beam $b_{i,j}$, denoted as $\alpha_{i,j}$, can be derived as:

$$\alpha_{i,j} = \arcsin(\frac{R + h_i}{R} \cdot \sin\beta_{i,j}) - \beta_{i,j}. \tag{3}$$

where R represents the radius of the Earth, and h_i represents the altitude of satellite s_i.

Therefore, the distance $d_{i,j}$ between the center point $B_{i,j}$ of the beam and the sub-satellite point P could be calculated by:

$$d_{i,j} = \frac{\alpha_{i,j}}{180} \cdot \pi \cdot R. \tag{4}$$

Moreover, the longitude and latitude coordinates of the beam center point $B_{i,j}$ can be expressed as:

$$B_{i,j}^{lon} = S_i^{lon} + \frac{d_{i,j} \cdot \cos\theta_{i,j}}{D_l \cdot \cos S_i^{lat}}. \tag{5}$$

$$B_{i,j}^{lat} = S_i^{lat} + \frac{d_{i,j} \cdot \sin\theta_{i,j}}{D_l}. \tag{6}$$

where D_l denotes the interval between lines of latitude.

Thus, the trajectory of the beam center point and a single beam diagram under the satellite could be determined, as shown in Fig. 3. The distance of IU u_m from the center point $B_{i,j}$ of the beam could be used to determine whether it enters the coverage area of beams $b_{i,j}$ or not. U=(U_{lon}, U_{lat}) denotes the position of IU u_m, and Q denotes the point on the trajectory of the beam center closest to IU u_m.

The arc length λ_{BU} between the beam center point $B_{i,j}$ and the IU u_m can be calculated by the great circle distance formula. Similar to [10], the shortest arc length λ_{QU} from the IU u_m to $B_{i,j}$ could be obtained.

$$\lambda_{BU} = \min\{2\arcsin\Omega\}. \tag{7}$$

$$\Omega = \sqrt{\sin^2\frac{B_{i,j}^{lat} - U_{lat}}{2} + \cos B_{i,j}^{lat}\cos U_{lat}\sin^2\frac{B_{i,j}^{lat} - U_{lon}}{2}}. \tag{8}$$

Then the arc length λ_{BQ} in the right-angled spherical triangle $\mathrm{B_{i,j}}$QU can be obtained by:

$$\lambda_{BQ} = \arccos\frac{\cos\lambda_{QU}}{\cos\lambda_{BU}}. \tag{9}$$

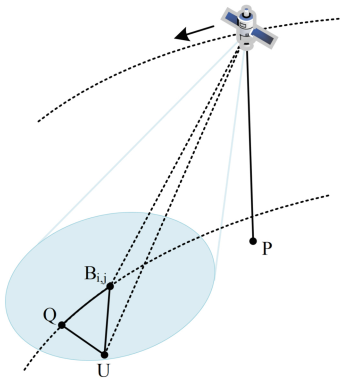


Fig. 3. Diagram of a Single Beam Under a Satellite

Based on the satellite orbit information, the angular velocity $\omega_{s,u}$ of the satellite relative to the IU can be determined.

$$\omega_{s,u} = \omega_s - \omega_e \cdot \cos\varphi. \tag{10}$$

where ω_s is the angular velocity of the satellite in orbit, and φ is the inclination angle of the satellite orbit.

Therefore, the service time of beam $b_{i,j}$ for IU u_m is given by:

$$T_b = \frac{2\lambda_{BQ}}{\omega_{s,u}}. \tag{11}$$

Assume the IU u_m enters the coverage range of beam $b_{i,j}$ at time t_0, the RST of beam $b_{i,j}$ for IU u_m at time t_1 can be expressed as:

$$T_s = T_b - (t_1 - t_0). \tag{12}$$

3 AHP Based Cell Reselection Strategy

To frequent reselection of IUs in EMC scenario, in this paper we propose a AHP based cell reselection strategy, which predicts the reselection time based on the periodic movement of the satellite, and determines the reselection candidate list according to the RSS and the RST. In additions, the AHP method is introduced to decided the weights of different IUs based on their QoS requirements, and minimize the reselection times.

3.1 Multiple-target Cell Reselection Process

The proposed multiple-target cell reselection strategy for IUs consists of two steps: cell reselection initiation and cell reselection decision, to trigger cell reselection and determine the target cell, respectively. Assume the number of cells that cover the IU u_m is N, the current serving cell is b_s, and the neighboring cells are $b_{n,l}$, where $l = 1, 2, ..., N-1$. The cell reselection process of the CRSA strategy is shown in Fig. 4. The main steps of the multiple-target cell reselection process are as follows.

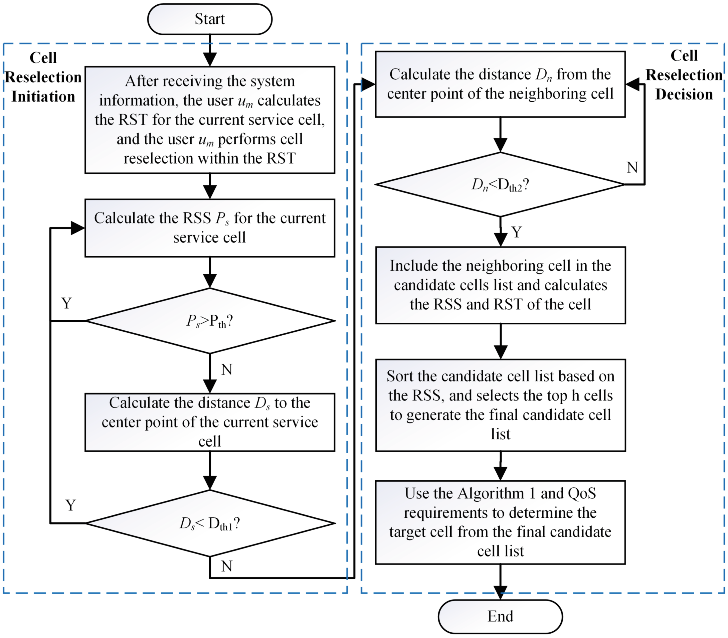


Fig. 4. Cell Reselection Process of the CRSA strategy

1) Cell Reselection Initiation.

Step 1:After receiving the system information broadcasted by the satellite, the IU u_m calculates the RST of b_s, and performs cell reselection within the RST.

Step 2: Calculates the RSS P_s of b_s and compares it with the RSS threshold P_{th}. If $P_s > P_{th}$, the IU u_m goes to the next step for further judgement.

Step 3: Calculates the distance D_s between the center point of b_s and IU u_m, and compares it with the distance threshold D_{th1}. If $D_s > D_{th1}$, the IU u_m will trigger the cell reselection.

2) Cell Reselection Decision.

Step 1: Calculate the distance D_n between the current location and the center point of neighboring cell $b_{n,l}$, and compares it with the distance threshold D_{th2}. If $D_n < D_{th2}$, the cell $b_{n,l}$ is included in the candidate cell list, and the RSS and RST of cell $b_{n,l}$ are calculated.

Step 2: Sort the candidate cell list based on the RSS, and selects the top h cells to generate the candidate cell list.

Step 3: Use Algorithm 1 and QoS requirements to determine the target cell from the candidate cell list.

3.2 AHP-Based Weights Decision Process

Due to the diversity of IU QoS requirements, the decision-making process for the target cell selection needs to consider multiple criteria. AHP is a hierarchical analysis method that combines qualitative and quantitative analysis, which can decompose complex decision-making problems into smaller and more manageable sub-problems. In the scenario, IU service types are divided into four categories: real-time(RT) data, audio, image, and video [9]. The corresponding latency and throughput requirements for each type of IU service are shown in Table 1. On one hand, a cell with longer RST could effectively reduce cell reselection times, and a cell with higher RSS could provide larger throughput. Therefore, a target cell analysis framework based on AHP is constructed, which divides the decision-making goals, criteria, and objects into three layers from top to bottom and determines the target cells with different QoS requirements, as shown in Fig. 5.

Table 1. QoS Requirements for Different Applications.

Application	Latency(s)	Throughput(Mbit/s)
RT Data	0.001–1	< 10
Audio	0.25	0.064
Image	1	2^{-10}
Video	0.25	100

Table 2. Parameter Preferences for Different Applications.

Application	Received Signal Strength	Remaining Service Time
RT Data	k_3	k_4
Audio	k_2	k_3
Image	k_1	k_1
Video	k_4	k_3

The detailed steps are as follows:

Step 1: In the decision criteria layer, calculate the weights of RSS and RST, and determine the IU's preferences for different parameters. Different values are defined to represent the preference for different parameters based on the RSS and RST requirements for different service types, as shown in Table 2. The values k_1, k_2, k_3, and k_4 represent weak preference, medium preference, strong preference and very strong preference, respectively.

The pairwise comparison of the parameters is performed to obtain the judgment matrix $P_u \in R^{2\times 2}$ for each IU service, where u=1, 2, 3, 4. The element $p_{i,j}$ in the judgment matrix P_u represents the relative importance between parameter i and j (i corresponds to the row, and j corresponds to the column). The values of $p_{i,j}$ are calculated based on the preferences of different service types for RSS and RST in Table 2. Then, the matrix P_u is column-normalized to obtain $\overline{P}_u \in R^{2\times 2}$, and the normalized eigenvector ω_u^P is calculated to represent the weight of each parameter. Based on this, the parameter matrix $W \in R^{2\times 4}$ for different service types is constructed.

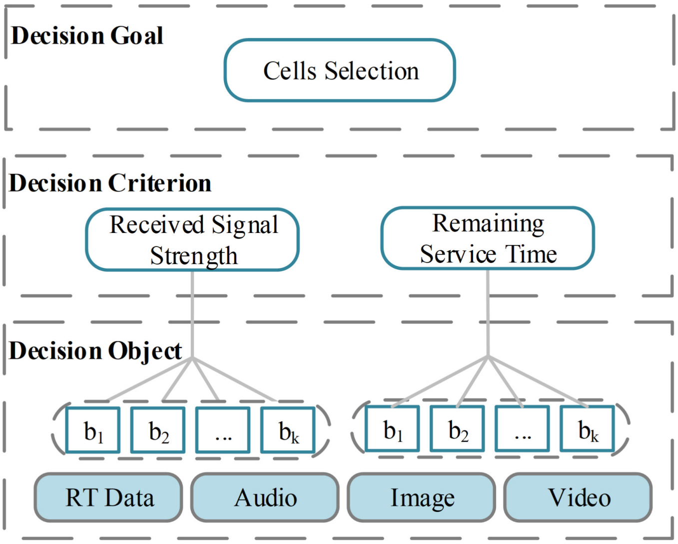


Fig. 5. AHP-based Analytical Framework for Target Cell Selection

Step 2: In the decision object layer, the candidate cells are evaluated based on each decision criterion. One decision criterion corresponds to one matrix $Q_u^d \in R^{h\times h}$, where h is the number of candidate cells, and the element $q_{i,j}$ in the matrix Q_u^d represents the relative importance of the i-th candidate cell to the j-th candidate cell for the d-th decision criterion. The matrix Q_u^d is normalized to obtain $\overline{Q}_u^d \in R^{h\times h}$, and the normalized eigenvector $\overline{\omega}_m^{s,u}$ is calculated to represent the weight of each candidate cell for the d-th decision criterion. Based on this, the matrix $O_u = \{\overline{\omega}_1^{q,u}, \overline{\omega}_2^{q,u}\}$ for candidate cells is constructed.

Step 3: In the decision goal layer, the QoS value of each candidate cell is calculated to determine the target cell. The parameter weight $\overline{\omega}_u^p$ and the matrix O_u are obtained. The IU calculates the QoS value for each candidate cell of the corresponding service type using the equation $QoS_k = o_{u,k} \cdot \overline{\omega}_u^p$, where k is the k-th candidate cell, and $o_{u,k}$ is the element in the k-th row and p-th column of the matrix O_u. The IU selects the cell with the maximum QoS value as the target cell for reselection.

Algorithm 1. AHP Based Cell Reselection Algorithm

Require: Number of candidate cells k, P_u, Q_u^d
Ensure: Target Cell
for $i = 1 : 2$ **do**
  for $j = 1 : 2$ **do**
    Normalise $p_{i,j}$ to $\overline{p}_{i,j}$
  end for
end for
Calculate ω_u^P in the parameter matrix W
$\omega_u^P \leftarrow \frac{1}{2}\sum_{i=1}^{2}\sum_{j=1}^{2}\overline{p}_{i,j}$
for $m = 1 : 2$ **do**
  Normalise $q_{i,j}$ to $\overline{q}_{i,j}$, $i, j = 1 : k$
  Calculate matrix O_u
  $\overline{\omega}_m^{q,u} \leftarrow \frac{1}{k}\sum_{i=1}^{k}\sum_{j=1}^{k}\overline{q}_{i,j}$, $O_u \leftarrow O_u \cup \overline{\omega}_m^{q,u}$
end for
for $i = 1 : k$ **do**
  Calculate every cell $QoS_k = o_{u,k} \cdot \overline{\omega}_u^p$
  Find the target cell with the largest QoS_k
end for
return

The computational complexity of Algorithm 1 is $O(k^2)$, where k is the number of target satellite candidates.

4 Simulation and Analysis

4.1 Simulation Scenarios and Parameter Settings

In this section, the performance of the proposed CRSA strategy is carried out by the STK and PyCharm platforms. Consider the Iridium satellite constellation system [3], which consists of 6 orbital planes with 11 satellites on each plane, and 48 beams per satellite. The orbit altitude is 781 km and the inclination angle is 86.4, as shown in Fig. 6. The Earth's radius is 6371 km, the cell radius is 350 km, the beam transmit power is 20 dBm, the beam antenna gain is 20 dBi, the user antenna gain is 25 dBi, the carrier frequency is 2 GHz. There are 40 randomly distributed IUs, which have four different service types, namely, real-time data, audio, image, and video.

4.2 Simulation Results Analysis

To verify the efficiency of the CRSA strategy, two strategies are introduced for comparison: The cell reselection strategy based on RSS, which selects the target cell based on the RSS. The channel reservation based on load aware (CRLA)

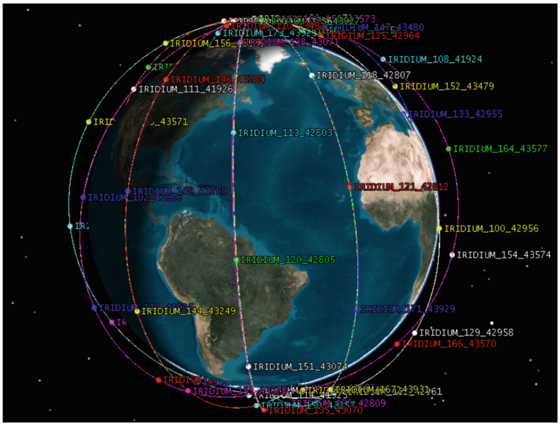
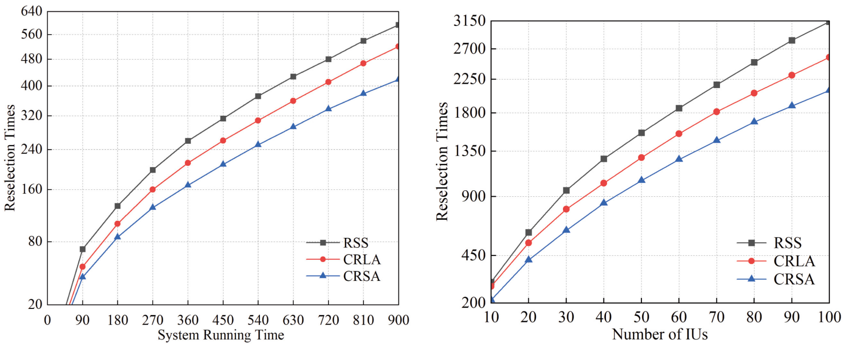


Fig. 6. Iridium Constellation

strategy [7], which reserves channel resources in advance for high-priority users to ensure their service quality.

Figure 7 shows the variations of cell reselection times for three different strategies. As shown in Fig. 7(a), with the increase of the system running time, the cell reselection times of all three strategies are increasing. Among them, the proposed CRSA strategy has the least cell reselection times. This is because it takes into account the RST of the cells, which could avoid IUs selecting cells with short RTS, result in effectively reducing cell reselection times. The RSS-based strategy only considers the RSS during the cell reselection process. However, due to the difference in the RSS between the edge and center of the cell is small, leading to unnecessary cell reselections and ping-pong effects. In addition, the CRLA strategy considers the satellite's traffic load, which ensures cell resections for high-priority IUS, resulting in performance gain than the RSS-based strategy. Figure 7(b) shows the relationship between the number of IUs and cell reselection times for different strategies when T = 450 s. With the increase of the number of IUs, cell reselection times of all three strategies will gradually increase, and the proposed CRSA strategy requires the minimum cell reselection time.

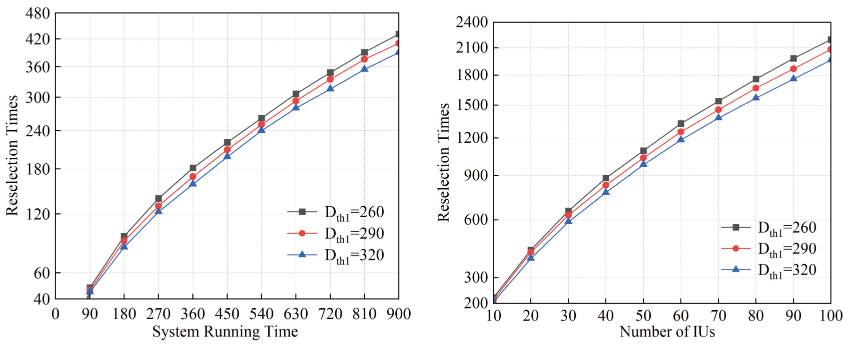
Figure 8 shows the cell reselection times of the CRSA strategy for different distance thresholds D_{th1}, which are set to 260 km, 290 km, and 320 km, respectively. As shown in Fig. 8(a), with the increase of system running time, cell reselection times increases. Moreover, the smaller the distance threshold D_{th1}, the greater the increase in cell reselection times. The reason is that with a smaller D_{th1}, the reselection decisions are more likely to be triggered, and thus the number of cell reselections will increase accordingly. Figure 8(b) shows the relationship between cell reselection times and the number of IUs for different distance threshold when T = 450 s. From the results, cell reselection times is an increasing function of the number of IUs, and the larger the distance threshold, the lower cell reselection times in the system.



(a) Relationship between Cell Reselections and System Operating Time under Different Strategies

(b) Relationship between Cell Reselections and User Quantity under Different Strategies

Fig. 7. Cell Reselection Times for Different Strategies

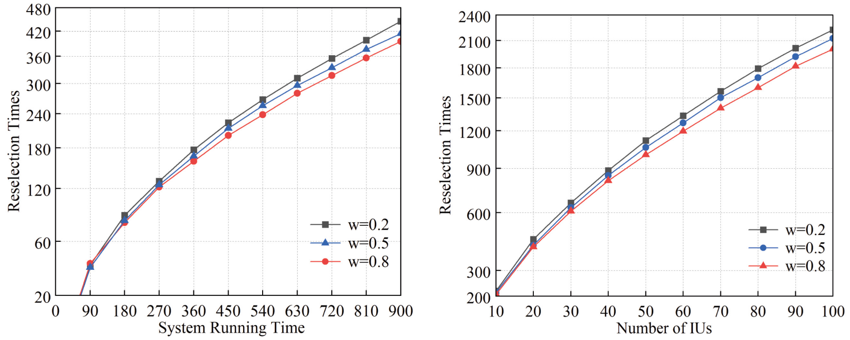


(c) Relationship between Cell Reselections and System Operating Time under Different Distance Thresholds

(d) Relationship between Cell Reselections and User Quantity under Different Distance Thresholds

Fig. 8. Cell Reselection Times for Different Distance Thresholds

Figure 9 shows the cell reselection times of the CRSA strategy with different RST weights, which are set to 0.2, 0.5, and 0.8, respectively. As shown in Fig. 9(a), with the increase of the system running time, the cell reselection times also increases. Moreover, the larger the RST weight, the slower the increase in the cell reselection times. The reason is that with a larger RST weight, it is more likely to reselect the cell with a longer RST to reduce cell reselection times. Figure 9(b) shows the relationship between the cell reselection times and the number of IUs for different RST weight when $T = 450$ s. From the results, the cell reselection time is an increasing function of the number of IUs, and the larger the RST weight, the lower cell reselection times of the LEO satellite Communication System.

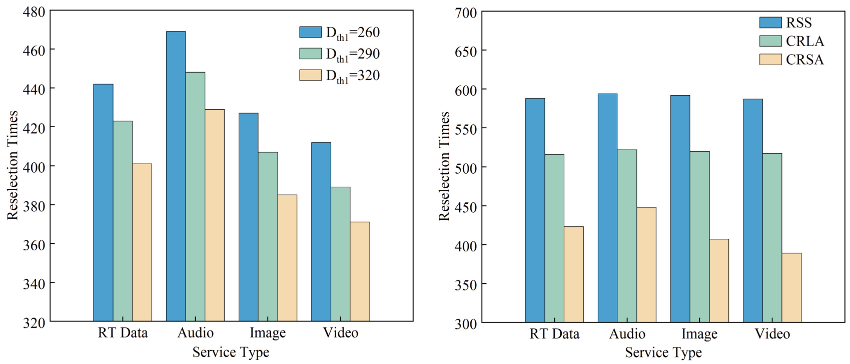


(a) Relationship between Cell Reselections and System Operating Time for Different RST Weights

(b) Relationship between Cell Reselections and User Quantity for Different RST Weights

Fig. 9. Cell Reselection Times for Different RST Weights

Figure 10(a) shows the relationship between the cell reselection times of the CRSA strategy for different distance threshold and service types, including real-time data, audio, image, and video. As shown in the simulation results, cell reselection times varies for different service types because of their different QoS requirements for RSS and RST. For example, video services have higher RST requirements, so longer RST cells are preferred, resulting in fewer cell reselection times. Figure 10(b) shows the relationship between cell reselection times and service types for different strategies. The results show that cell reselection times of the CRSA strategy are lower than comparison strategies, which could select the optimal cell for IUs with different service types.



(a) Relationship between Cell Reselections and Different Service Types under Different Distance Thresholds

(b) Relationship between Cell Reselections and Different Service Types under Different Algorithms

Fig. 10. Cell Reselection Times for Different Service Types

5 Conclusion

In this paper, we focused on the EMC scenario of LEO satellites system and proposed a cell reselection strategy based on AHP for IUs to reduce cell reselection times. By predicting the time of cell reselection, reasonably designing the threshold and other related parameters of the strategy based on QoS requirements of IUs, the proposed CRSA strategy could find the optimal cell for IUs and reduce the number of cell reselections. Simulation results verified that the proposed CRSA strategy significantly improves cell reselection performance compared to the comparison strategies.

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