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DISTRIBUTED COLLABORATIVE SCHEDULING TECHNOLOGY FOR RANDOM ACCESS IN REAL-TIME

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Abstract. The planning and deployment of mega constellations has posed increasing pressure on the existing telemetry, track and command (TTC) resource scheduling strategy. The current plan-based scheduling strategy distributes resources according to needs, however, it cannot address sudden resource requests with prompt responses. By analyzing the status quo of resource scheduling systems, we have proposed a distributed collaborative scheduling technology for random access in real-time, based on the theory of low costs and rapid transfers of scheduling task resources. First, we use knowledge graph technology to map the link between scheduling tasks and idle resources and develop a graph network. Furthermore, by analyzing and evaluating the resource transfer capability of a multi-target TTC system in hemispherical coverage (MT-TTC), we propose the concept of a virtual resource pool and develop a two-layer scheduling framework in which the central scheduling system coordinates with multiple regional systems. This scheduling strategy works well when a sudden TTC request occurs. The central system manages the satellite requests and make plans, while regional systems are responsible for handling the sudden requests and report to the central system on its resource change. With regional systems sharing some degree of autonomy, the central system making a final decision and systems across the framework coordinating in real-time, we design a model on resource transfers for MT-TTC equipment and a collaboration mechanism that coordinates the resource transfers across MT-TTC equipment and other single-beam equipment within and between regions. We do experiments in simulation scheduling environments. The results show that the regional scheduling system based on MT-TTC equipment is able to manage continuous random-access requests in real-time, and avoid resource conflicts across regions by collaborating with the central scheduling system. It is of value to be applied in real scenarios.

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1. Introduction

1.1. Background and research status

In recent years, commercial space companies represented by SpaceX, OneWeb, and Telesat have put forward Low Earth Orbit (LEO) satellite constellation plans one after another, leading a new round of upsurge in the establishment and development of LEO Internet constellation. Likewise, China's Hongyan and Hongyun constellation plans are making steady progress. The deployment of large-scale, miniaturized and intelligent satellites brings great challenges to the existing telemetry, track and command (TTC) systems, which are mainly reflected in the following aspects: (1) The LEO Internet constellation plans to deploy a large number of satellites, and Star-links plans to launch more than 30,000 satellites. If the current full-radian TTC mode based on a point-to-point satellite-ground link is adopted, it will be probably difficult to meet the massive demands. (2) The random access capability, namely the increased intelligence [1,5,6] that enables the satellites to independently initiate resource requests without relying on the mission center, asks for higher requests. However, the current "on-demand distribution and plan-driven" TTC scheduling mode cannot adapt to the new changes. (3) In the future, the modes with the coexistence of pre-distribution and random access will be the new normal in China's space TTC. However, there is a lack of a mature and available scheduling framework. In this case, an increasing amount of ground-based TTC equipment will lead to a waste of resources and a growth of the maintenance cost [10]. Therefore, it is necessary to systematically redevelop the existing scheduling architecture. The concept of a space mobile network proposed by NASA [7,11,12] aims to build a system similar to the terrestrial mobile network, which handles space communication, meets navigation requirements, responds to service requests initiated by satellite users in real-time, and has the ability to random access. By referring to the random access mechanism of the ground cellular mobile communication system, Liu *et al.* designed a new TTC mode based on the random access technology and discussed the key issues such as the multi-target TTC system in hemispherical coverage (MT-TTC) with real-time technology [9]. Cui analyzed the requirements of a large low-orbit constellation TTC system and designed a five-layer TTC system framework based upon service-oriented and container cloud technology [2]. Liu *et al.* proposed the general framework of TTC service for global coverage and random access and pointed out that the key to the effective application of TTC resource service for global coverage and random access was to solve the problem of instant response to satellite access TTC demand [8]. The above research on the TTC mode of LEO Internet constellation mainly focused on the overall system architecture, communication mode, and spectrum management, and there was less research on the scheduling scenario and real-time scheduling algorithm for random access. In accordance with the status quo of TTC, we design a distributed cooperative scheduling scenario based upon "regional autonomy", and propose a distributed collaborative scheduling algorithm in real-time for random access. Grounded on the effective integration of the random access mission and the existing TTC scheduling scenario, we are capable of responding to the continuous TTC requests initiated by the satellite in real-time.

1.2. Key problem

The distributed collaborative scheduling technology for random access in real-time makes breakthroughs in three key areas:

(1) Networking of scheduling plan results. The theoretical basis of our proposed distributed collaborative scheduling technology for random access in real-time is that the resources for scheduling tasks are able to be transferred quickly at a low cost. The premise of a fast transfer is the efficient organization of scheduling plan results, which specifically refers to the development of graph networks with multi-dimensional representations, dynamic updates, and efficient indices.

(2) Analysis of the MT-TTC transfer capability. MT-TTC equipment, the vehicle to deal with random access requests, is the main object of resource transfer. After the graph network is developed, a virtual resource pool that responds to random access requests in real time is produced by analyzing and calculating the MT-TTC task transfer capability.

(3) Two-layer scheduling framework. The two-layer scheduling framework featuring a center and region level is an inevitable choice to adapt to the new normal where centralized pre-allocation and random access TTC modes coexist. The regional scheduling system, centered on MT-TTC equipment, handles random access requests, accommodates the robustness of the scheduling plan, and responds quickly to the requests that make dynamic resource adjustments in the region. The central scheduling system had the authority to coordinate the requests for dynamic resource adjustment among different regions.

1.3. Organization of the article

Section 1 of this article describes the insertion mode of the random access task and the path transfer mode of MT-TTC resources. Section 2 illustrates the method and steps of scheduling plan networking. Section 3 designs a transfer capacity assessment model to form an MT-TTC virtual resource pool. Section 4 explains the scheduling decision model and resource transfer coordination mechanism, developing a two-layer scheduling framework. In Section 5, simulation data are collected and applied to verify the effectiveness of the proposed method. Section 6 summarizes the edges of the proposed method and points out the aspects that need to be further studied and improved in the next step.

2. Problem description

The random-access request initiated by the LEO Internet constellation features sudden occurrences and prompt responses. Different from traditional satellites, LEO Internet satellites often suddenly initiate resource requests before or after entering the visible window of the TTC equipment. The traditional single-beam TTC equipment lacks sufficient preparation time which possibly leads to a task failure. Furthermore, due to the advanced intelligence, autonomous task planning, and orbit maneuver, LEO Internet satellites have insufficient accuracy of orbit prediction and are difficult in adapting to the centralized pre-allocated TTC mode. Based on the above discussion, we propose a scheme that applies MT-TTC equipment to respond to satellite random access requests. The MT-TTC equipment allocates resources in regular cases according to the central scheduling system, processes random access requests as normal emergency tasks, and responds to random access requests in real time through the rapid transfer of MT-TTC resources.

Before introducing the random access problem, we need to clarify the basic concepts of resource transfer. Specifically, after producing the scheduling plan, there is no available TTC resource at hand when the satellite initiates a new TTC demand. In this case, the scheduling task occupying the new task resource window needs to be transferred to its standby window, to meet the TTC demand of the new task. Figure 1 is a schematic diagram of the resource transfer process, where the scheduling task window refers to a resource window that meets the constraints selected for the task in periodic scheduling. In real scenarios, multiple resource windows meet the requirements, and the unselected windows can be divided into two types: one is a conflict window, which is occupied by other tasks and cannot be used directly; the other is a standby window, which means that the window is not occupied by other tasks and can be used directly. The above two types of resource windows and scheduling task windows can be collectively referred to as the feasible solution window of a task. The idle resource window refers to the unused resource window, and the standby window is a part of the idle resource window. As shown in Figure 1, there is no need to transfer when there is an idle resource window that meets the requirements of the new task and that is directly available. On the contrary, it is necessary to find the indirectly available idle resource window by scheduling multiple resource transfers between task windows, which is the essence of resource transfer. The establishment of a transfer relationship depends on finding other scheduling task windows that share resources with the scheduling task conflict window.

2.1. Insertion mode of the random access task

The visible windows of different satellites of the same ground equipment have various degrees of deviation as orbital planes are dissimilar. Such differences exist even for the same satellite due to the influence of the perturbation force. Therefore, the probability that the task window of the random access request initiated by

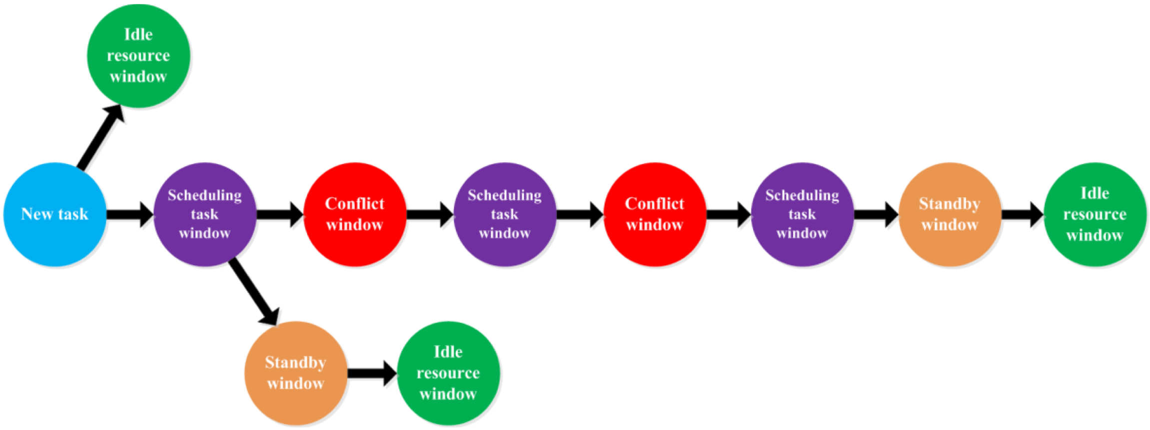

FIGURE 1. Schematic diagram of the resource transfer process.

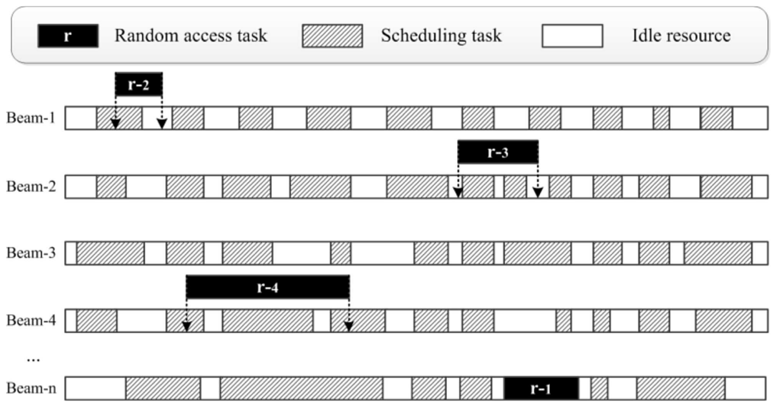

FIGURE 2. Schematic diagram of the random access task.

the satellite will completely coincide with the scheduling task window is low, and there are a variety of different modes as shown in Figure 2. For example, task r-1 can directly find the idle resource window of beam n. The length of the window of task r-2 is similar to that of the scheduling task, but it is offset and only partially overlapped. It is included in the association window composed of the scheduling task window and the adjacent idle window on the right, which belongs to the 1:1 mode and has a large proportion in practice. In addition, since the operating orbit altitude of LEO satellites is generally 160km 2000km above the earth, the difference in orbital altitude among satellites leads to differences in the visible window of ground equipment. The 1:2 and 1:3 modes of tasks r-3 and r-4 appear in Figure 2, which means that the transfer cost of completing the random access task is doubled. As for 1:4 or more complex models, the high cost of transfer and a small number in real scenarios are not considered hereby.

In addition to the available idle resource window at hand, the insertion mode of the random access request can be divided into three types: 1:1, 1:2, and 1:3. In the process of resource transfer, the quantity, length, and position of the original resource window of the equipment are changed, not only the scheduling task window is replaced directly. To further elaborate on the changes in the insertion mode of random access tasks in the process of resource transfer, we sort out five cases of the change in the resource window caused by random access tasks under different insertion modes. The 1:1 mode is taken as an example. Figure 3 (a-1) shows that

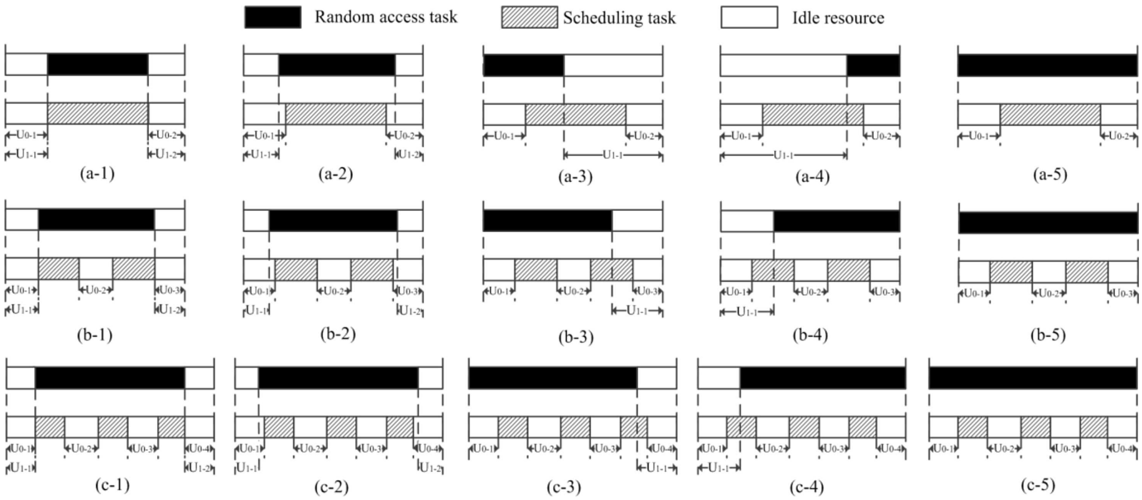

FIGURE 3. Insertion mode of the random access task.

the random access task window coincides with the scheduling task window. After resource transfer, the idle resource window remains unchanged. Figure 3 (a-2) indicates that the random access task window completely includes the scheduling task window and occupies part of the idle resource window of the scheduling task window. After resource transfer, the length of the idle resource window is shortened. Figure 3 (a-3) demonstrates that the random access task window partially overlaps with the scheduling task window, and completely occupies the idle resource window on the left of the scheduling task window. After resource transfer, the quantity and length of the idle resource window change. Figure 3 (a-4) indicates that the idle resource window on the right of the scheduling task window is fully occupied. Figure 3 (a-5) indicates that the random access task window completely includes the scheduling task window and adjacent idle resource windows of the scheduling task window. The 1:2 and 1:3 modes are similar to the 1:1 mode. In summary, the insertion modes of random access tasks are divided into three types according to the corresponding relationship between the quantity of random access task windows and the quantity of scheduling task windows, and five types of random access tasks are classified into five categories in accordance with the location relationship of random access task windows in the continuous space composed of the scheduling task and its adjacent idle resource windows.

2.2. Transfer path mode of random access task

As factors such as satellite type, orbital plane, and period vary, there are many modes between the random access task window and the scheduling task window, which also leads to many modes in the evaluation of the transfer relationship between the scheduling task windows. Similar to the insertion mode of the random access task, the transfer path mode of the random access task has three types: 1:1, 1:2, and 1:3 modes. Figure 4 shows the path transfer mode of the random access task. In Figure 4, the black solid triangle represents the random access task, the black solid square represents the scheduling task window, the black solid circle represents the conflict window, the black solid parallelogram represents the standby window, and the black solid pentagram represents the idle resource window, which contains two special graphics: the black solid circle with identifier "2" and with identifier "3" that respectively represent two parallel windows and three parallel windows. When the conflict window of a scheduling task is occupied by two or three consecutive scheduling task windows, the corresponding relationship of 1:2 or 1:3 is developed. A parallel window is created as a bridge to develop the complex transfer relationship which helps decide the quantity and name of the scheduling window associated with the conflict window in the evaluation of the transfer relationship.

2.2.1. 1:1 mode

There are three scenarios for 1:1 transfer path mode:

(i) Transfer path p_{1-1}, containing only one random access task node, one scheduling task node, one standby window node, and one idle resource node, is a single-path transfer mode. It finds available resources in idle resources through its standby window after the scheduling task transfers TTC resources to the random access task. It only transfers through one layer to meet the requirements of the random access task, which is the case with the lowest transfer cost and the shortest transfer path.

(ii) Transfer path p_{1-2}, also a single-path transfer mode, contains only one random access task node, two scheduling task nodes, one conflict window node, one standby window node, and one idle resource node. Random access task finds available resources in the idle resource through the continuous transfer of resources of two scheduling tasks and the standby window of the second scheduling task. When there are conflicting window nodes in the transfer path, the number of transfer layers increases by at least one layer, and the number of conflict window nodes in the path is positively correlated with the number of transfer layers in the path.

(iii) Transfer path p_{1-3}, a multi-path transfer mode, includes only one random access task node, seven scheduling task nodes, three conflict window nodes, four standby window nodes, and four idle resource nodes. The reason why it is a multi-path mode is due to the similarity of the corresponding relationship between the conflict window and scheduling task with the random access task insertion mode, leading to a one-to-many case in the transfer relationship. In this mode, the number of transfer layers is consistent with the number of scheduling task nodes and its transfer costs increase significantly.

2.2.2. 1:2 and 1:3 mode

The transfer path modes of 1:2 and 1:3 are the same, which can be described in two cases. We considered the 1:2 as an example for the illustration:

(i) Transfer path p_{2-1} contains only one random access task node, three scheduling task nodes, one conflict window node, two standby window nodes, and two idle resource nodes. It is a type of single-path transfer mode because the bifurcation of the path appears at the random access task node; however, it contains two independent single-paths, which meet the requirements of the random access task through one-layer and two-layer transfers, respectively.

(ii) Transfer path p_{2-2} contains one random access task node, five scheduling task nodes, two conflict window nodes, three standby window nodes, and three idle resource nodes. The transfer path p_{2-2} is composed of one single independent path and one multi-path, which is a multi-path transfer mode overall. The transfer cost increases significantly, and the incidence is practically small.

3. Networking of scheduling plans

At present, the scheduling plan is based on the traditional model of "on-demand distribution and plan-driven". The scheduling plan results are highly discrete and lack hierarchical and structured expression ability. When receiving a random access request, the scheduling system needs to quickly allocate available resources based on the existing scheduling plan. When the number of spacecraft in orbit is limited and the TTC mode is unique, we have sufficient spare resources to respond to the random access request. However, when the number of spacecraft is surging and the TTC mode is diversified, we can no longer meet the task requirements only by relying on the limited spare resources. We need to further optimize the scheduling plan and make effective use of resources, which requires efficient organization of scheduling plan results. In Section 2, we describe the insertion mode of the random access task and the path transfer mode of MT-TTC resources. Furthermore, we use knowledge graph technology to develop a graph network that expresses the relationship between scheduling task windows, scheduling task windows and standby windows, and standby windows and idle resource windows, thus providing the basis for fast multi-beam resource transfer.

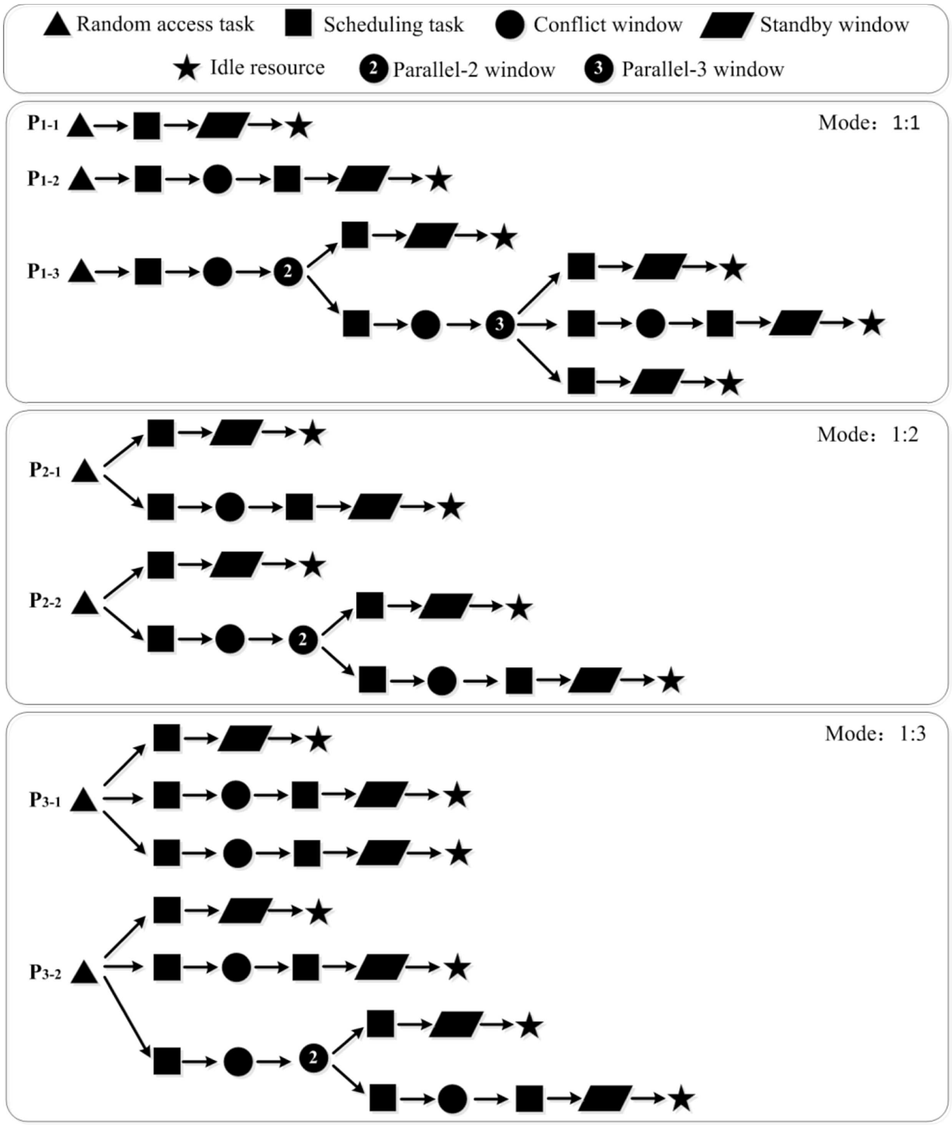

FIGURE 4. Path transfer mode of the random access task.

3.1. The concept of knowledge graph

The concept of a knowledge graph [13] was first proposed by Google on May 17, 2012. It was first applied in the field of information search and then gradually became a research hotspot in artificial intelligence. It has played a role in information search, automatic question answering, decision analysis, and other applications [14]. The knowledge graph is now used to describe various entities or concepts and their relationships in the real world, developing a semantic network graph. Nodes represent entities or concepts, and edges are composed of attributes or relationships. Today, some leading players in a general Knowledge graph are Sogou Zhicube, Baidu Zhixin, OpenKN, CN-Dbpedia, WordNet, Freebase, YAGO, Probase, and Knowledge Vault, while key roles in domain-oriented knowledge graphs include IMDB in the film industry, DrugBank in the biomedical science, ECKG in the news and information, and Acemap in the academic field. The difference between general knowledge graphs

TABLE 1. Comparison of node attributes.

Type	Property										
	name	eq	rc	st	et	fst	fet	rst	ret	ob	on
Random access	✓	✓		✓	✓						
Scheduling	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Conflict	✓	✓	✓	✓	✓						
Parallel-2	✓	✓		✓	✓					✓	✓
Parallel-3	✓	✓		✓	✓					✓	✓
Standby	✓	✓	✓	✓	✓						
Standby	✓	✓		✓	✓						

and domain-oriented knowledge graphs lies in the way of knowledge modeling and the scope of knowledge topics. First, the general knowledge graph covers everyday topics, whose development process is automatic and associated knowledge is static. The Internet is the main source of data. On the contrary, the domain-oriented knowledge graph focuses on a specific field, whose development process is semi-automatic and whose associated knowledge is dynamic. The data source is unique, and usually contains structured data or semi-structured data. Manual intervention is required in the process of knowledge extraction for high-quality knowledge output in a specific domain. As space TTC resource scheduling is a highly professional field, its knowledge graphs follow the characteristics of the domain-oriented category in the process of building knowledge graphs. Therefore, we take the scheduling plan results as the data source and use the Neo4j graphical database in a Python environment to build a special knowledge graph for space TTC resource scheduling.

3.2. Construction of knowledge graph

3.2.1. Definition of nodes and relationships

We consider random access task windows, scheduling task windows, conflict windows, parallel windows, standby windows, and idle resource windows as nodes. Information like equipment, circle number, start time, and end time of the window are stored in the node, and the relationship between windows is used as the edge. Table 1 compares node attributes which contain seven types of nodes. Four attributesname, equipment (eq), start time (st), and end time (et)are shared attributes that are included in each type of node. Only the scheduling task node, conflict node, and standby node include the relative circle number (rc) which is an important association constraint between tasks. The evaluation of the transfer relationship between nodes satisfies the association constraint between tasks to avoid preempting TTC resources in neighboring circles. Front start time (fst), front end time (fet), rear start time (rst), and rear end time (ret) are only included in the scheduling task node, which is mainly used to evaluate the type of random access task insertion mode in evaluating transfer relationship. Parallel number (ob) and parallel name (on) are only included in parallel window nodes to test the number and name of scheduling windows associated with conflict windows in transfer relationship evaluation.

The graph network developed by knowledge graph technology is a type of directed graph. Relationship types of the nodes vary due to different directions. Figure 5 shows the comparison diagram of node relationship attributes. There are three relationships among nodes of seven types:

(i) Contain relationship: The relationship between the scheduling task node and a conflict window node belongs to the contain relationship. This conflict window is only one of the feasible windows of the scheduling task. However, it does not exist in the scheduling plan due to the window resource conflict.
(ii) Friend relationship: The relationship that the conflict window node points to the scheduling task node belong to the friend relationship. This scheduling task window and the conflict window partially overlap in the scheduling plan and share window resources. Similarly, the relationship between conflict window nodes and parallel window nodes is also a friend relationship. The function of parallel windows is to establish

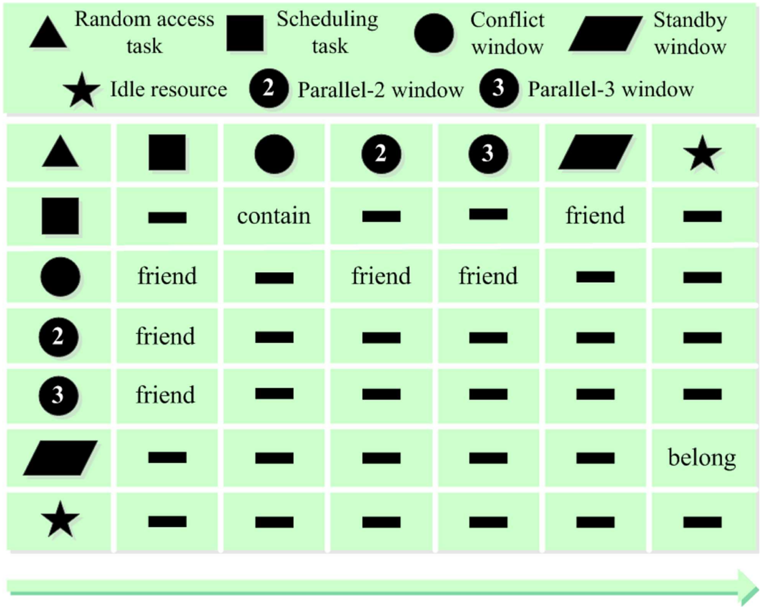

FIGURE 5. Comparison diagram of node relationship attributes.

"bridge" nodes between conflict window nodes and multiple scheduling task nodes, which is convenient for path evaluation. Additionally, the relationship that the scheduling task node points to the standby window node belongs to the friend relationship. Both the standby window and the scheduling task belong to the feasible window, which exists in parallel with the scheduling plan.

(iii) Belong relationship: The relationship that the standby window node pointing to the idle resource window node belongs to the belong relationship. The standby window is included in this idle resource window, and it is a part of the idle resource window in space.

3.2.2. Graph network development method

We define the scheduling task window set as $S = \left\{s_1^{eq,rc,st,et,fst,fet,rst,ret}, s_2^{eq,rc,st,et,fst,fet,rst,ret}, \ldots, s_n^{eq,rc,st,et,fst,fet,rst,ret}\right\}$, in which the conflict window set of any scheduling task s_i ($i \in [1,n]$) is $W_i = \left\{w_{i,1}^{eq,rc,st,et}, w_{i,2}^{eq,rc,st,et}, \ldots, w_{i,r}^{eq,rc,st,et}, \ldots\right\}$, the standby window set is $F_i = \left\{f_{i,1}^{eq,rc,st,et}, f_{i,2}^{eq,rc,st,et}, \ldots, f_{i,t}^{eq,rc,st,et}, \ldots\right\}$, and the idle resource set is $U = \left\{u_1^{eq,st,et}, u_2^{eq,st,et}, \ldots, u_v^{eq,st,et}\right\}$. The superscripts of variables in the set have the following meanings: eq represents the equipment code, rc represents the relative circle number, st represents the window start time, et represents the window end time, fst represents the start time of the front idle resource window, fet represents the end time of the front idle resource window, rst represents the start time of the rear idle resource window, and ret represents the end time of the rear idle resource window. Graph network development is performed as follows:

– Step 1: For any scheduling task window , starting from one of its conflict windows $w_{i,r}$ ($w_{i,r}^{rc} = s_i^{rc}$), when $w_{i,r}^{eq} = s_d^{eq}$, $w_{i,r}^{st} \geq s_d^{fst}$ and $w_{i,r}^{et} \leq s_d^{ret} (d \neq i)$ are true, it indicates that the conflict window $w_{i,r}$ is contained in the window composed of the scheduling task window s_d and its adjacent idle resource window. In this case, it is under the 1:1 mode. It points out that transfer relationships between s_i and s_d exist, and two directed correlations $[s_i] \xrightarrow{contain} [w_{i,r}]$, and $[w_{i,r}] \xrightarrow{friend} [s_d]$ are established. Then go to Step 7; if not, go to Step 2.

– Step 2: When $w_{i,r}^{eq} = s_{d-1}^{eq}$, $w_{i,r}^{st} \geq s_{d-1}^{fst}$ and $w_{i,r}^{et} \leq s_d^{ret}(d \neq i, d-1 \neq i)$ are true, it indicates that the conflict window $w_{i,r}$ is contained in the window composed of the scheduling task window s_d, its front scheduling task window s_{d-1}, and its adjacent idle resource window. In this case, it is under the 1:2 mode. It shows that transfer relationships between s_i, s_d, and s_{d-1} exist for continuously scheduling tasks. The parallel window node $p^{eq,st,et,ob,on}$ storing information is created, which represents the number of parallel windows and *on* represents the name of parallel windows. Furthermore, directed association relationships $[s_i] \xrightarrow{contain} [w_{i,r}]$, $[w_{i,r}] \xrightarrow{friend} [p]$,$[p] \xrightarrow{friend} [s_d]$, and $[p] \xrightarrow{friend} [s_{d-1}]$ are established. Then go to Step 7; if not, go to Step 4.
– Step 3: When $w_{i,r}^{eq} = s_{d+1}^{eq}$, $w_{i,r}^{st} \geq s_d^{fst}$ and $w_{i,r}^{et} \leq s_{d+1}^{ret}(d \neq i, d+1 \neq i)$ are true, it indicates that the conflict window $w_{i,r}$ is contained in the window composed of the scheduling task window s_d, its rear scheduling task window s_{d+1}, and its adjacent idle resource window. In this case, it is under the 1:2 mode. It shows that there exist transfer relationships between s_i, s_d and s_{d+1} for continuous scheduling tasks. The parallel window node $p^{eq,st,et,ob,on}$ storing s_d and s_{d+1} information is created, and the directed association relationships $[s_i] \xrightarrow{contain} [w_{i,r}]$, $[w_{i,r}] \xrightarrow{friend} [p]$,$[p] \xrightarrow{friend} [s_d]$, and $[p] \xrightarrow{friend} [s_{d+1}]$ are established. Then go to Step 7; if not, go to Step 4.
– Step 4: When $w_{i,r}^{eq} = s_{d-2}^{eq}$, $w_{i,r}^{st} \geq s_{d-2}^{fst}$ and $w_{i,r}^{et} \leq s_d^{ret}(d \neq i, d-2 \neq i)$ are true, it indicates that the conflict window $w_{i,r}$ is contained in the window composed of a scheduling task window s_d and two continuous scheduling task windows s_{d-1} and s_{d-2} in front of it and their adjacent idle resource window. In this case, it is under the 1:3 mode. It shows that transfer relationships between s_i,s_d,s_{d-1}, and s_{d-2} exist for continuous scheduling tasks. The parallel window node $p^{eq,st,et,ob,on}$ storing s_d,s_{d-1}, and s_{d-2} information is created, and the directed association relationships $[s_i] \xrightarrow{contain} [w_{i,r}]$, $[w_{i,r}] \xrightarrow{friend} [p]$,$[p] \xrightarrow{friend} [s_d]$, $[p] \xrightarrow{friend} [s_{d-1}]$,and $[p] \xrightarrow{friend} [s_{d-2}]$ are established. Then go to Step 7; if not, go to Step 1.
– Step 5: When $w_{i,r}^{eq} = s_{d+2}^{eq}$, $w_{i,r}^{st} \geq s_d^{fst}$ and $w_{i,r}^{et} \leq s_{d+2}^{ret}(d \neq i, d+2 \neq i)$ are true, it indicates that the conflict window $w_{i,r}$ is contained in the window composed of the scheduling task window s_d and its two successive scheduling task windows s_{d+1} and s_{d+2} and their adjacent idle resource window. In this case, it is under the 1:3 mode. It shows that transfer relationships between s_i, s_d, s_{d+1}, and s_{d+2} exist for continuous scheduling tasks. The parallel window node $p^{eq,st,et,ob,on}$ storing s_d, s_{d+1}, and s_{d+2} information is created, and the directed association relationships $[s_i] \xrightarrow{contain} [w_{i,r}]$, $[w_{i,r}] \xrightarrow{friend} [p]$,$[p] \xrightarrow{friend} [s_d]$, $[p] \xrightarrow{friend} [s_{d+1}]$,and $[p] \xrightarrow{friend} [s_{d+2}]$ are established. Then go to Step 7; if not, go to Step 1.
– Step 6: When $w_{i,r}^{eq} = s_{d-1}^{eq} = s_{d+1}^{eq}$, $w_{i,r}^{st} \geq s_{d-1}^{fst}$ and $w_{i,r}^{et} \leq s_{d+1}^{ret}(d \neq i, d-1 \neq i, d+2 \neq i)$ are true, it indicates that the conflict window $w_{i,r}$ is contained in the window composed of the scheduling task window s_d and its two adjacent scheduling task windows s_{d-1}, s_{d+1} and their adjacent idle resource window. In this case, it is under the 1:3 mode. It shows that transfer relationships between s_i, s_d, s_{d+1}, and s_{d+2} exist for continuous scheduling tasks. The parallel window node $p^{eq,st,et,ob,on}$ storing s_d, s_{d+1}, and s_{d+2} information is created, and the directed association relationships $[s_i] \xrightarrow{contain} [w_{i,r}]$, $[w_{i,r}] \xrightarrow{friend} [p]$,$[p] \xrightarrow{friend} [s_d]$, $[p] \xrightarrow{friend} [s_{d-1}]$,and $[p] \xrightarrow{friend} [s_{d+1}]$ are established. Then go to Step 7; if not, go to Step 1.
– Step 7: For any scheduling task window s_i, starting from one of its standby windows $f_{i,t}$, when $f_{i,t}^{eq} = u_v^{eq}$, $f_{i,t}^{st} \geq u_v^{st}$ and $f_{i,t}^{et} \leq s_v^{et}$ are true, it indicates that standby window $f_{i,t}$ is included in the idle resource u_v, transfer relationship between s_i and u_v existed, and directed association relationship $[s_i] \xrightarrow{friend} [f_{i,t}]$ and $[f_{i,t}] \xrightarrow{belong} [u_v]$ are established.

The development of the graph network is completed through the steps mentioned above.

4. MT-TTC virtual resource pool

The establishment and deployment of MT-TTC greatly increase the quantity of ground TTC resources, which is of great significance to alleviate the current resource scheduling tension [4,15,16]. MT-TTC, a ground-based

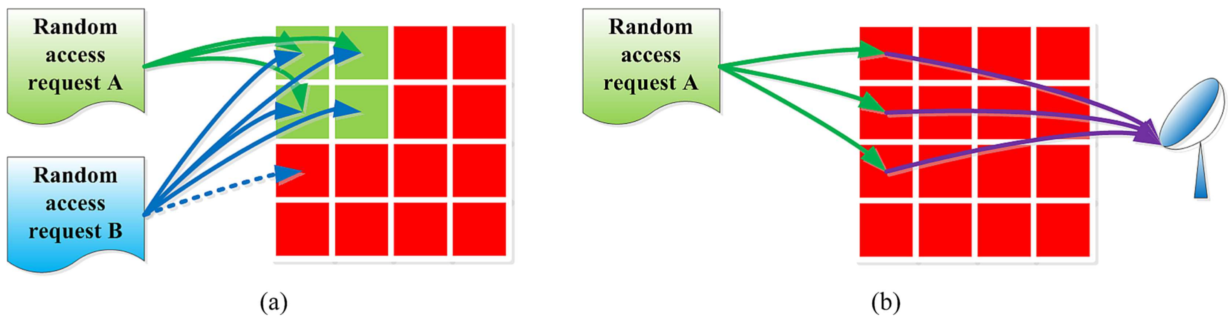

FIGURE 6. Schematic diagram of resource reservation and resource transfer.

multi-object phased array TTC system, is suitable to be used as a piece of special equipment to respond to random access requests thanks to its capabilities of multi-target tracking and rapid response. Without affecting the centralized scheduling and allocation of MT-TTC resources, we establish an MT-TTC transfer capability evaluation model to analyze and evaluate the overall utilization of MT-TTC resources and the optimal transfer scheme of scheduling tasks on a single beam. Then an MT-TTC virtual resource pool is developed to respond to TTC requests for random access tasks promptly.

4.1. Basic idea

It is common practice to reserve some idle resources for dynamic tasks as TTC resource pools. In the management of terrestrial mobile communication and communication satellite networks, network slicing technology is often used to allocate resources optimally [3]. The advantage of this approach is that it quickly responds to TTC requests, but the disadvantage is that the utilization rate of resources is low, and there is no theoretical support to reasonably determine the proportion of reserved resources. Figure 6a shows the schematic diagram of coping with random access request mode grounded on resource reservation. In Figure 6a, the green beam is reserved resources, and the red beam is resources occupied by scheduling tasks. When there are only three request tasks in packet A of the random access request, the reserved beam meets the requirements, but there is still one beam that does not participate in the task allocation, leading to resource waste. When packet B of the random access request contains five tasks, the reserved beam can only meet four tasks, and the remaining one task has no available beam (blue dashed line), thus lowering the task completion rate. The purpose of an MT-TTC virtual resource pool is to improve the utilization of resources as much as possible in addition to ensuring fast response to TTC requests. In essence, the MT-TTC virtual resource pool does not slice the MT-TTC resources, but allocates the resources in a centralized way to maximize the utilization of existing resources. In Figure 3b, there is no reserved beam. When the random access request packet A contains three request tasks, the scheduling tasks of the occupied beam are able to be transferred to other pieces of qualified equipment through limited transfers according to the principle of optimal transfer cost. The knowledge graph developed from the scheduling plan results quickly analyzes and evaluates the optimal transfer path of scheduling tasks on MT-TTC, which is convenient for rapid resource transfer in the face of random access requests.

4.2. MT-TTC transfer capability evaluation model

To confirm the resource occupancy and resource transfer capability of each beam is the first step before the MT-TTC virtual resource pool quickly responds to random access requests. The resource occupancy is calculated based on the scheduling plan results, but the resource transfer capability needs to be obtained by calculating the optimal transfer path of the scheduling tasks on the beam. Therefore, we propose an MT-TTC transfer capability evaluation model.

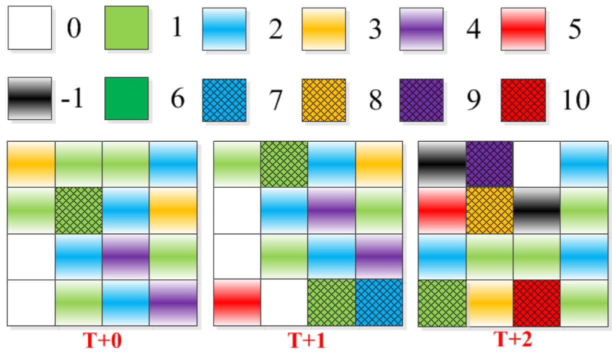

FIGURE 7. Schematic diagram of MT-TTC transfer capability evaluation model.

4.2.1. Classification of beam resources

The resource occupancy of MT-TTC is divided into two categories: one is the idle resource (white rectangle in Fig. 7, No. : 0), and the other is occupied resources which are further categorized into transferable resources and non-transferable resources. The non-transferable resources refer to beam resources whose transfer layers are greater than or equal to 6 or whose tasks have high priority and cannot be transferred (Fig. 7 black rectangle, number: -1). The transferable resources refer to beam resources with transfer layers less than 6, which can be further subdivided into intra-regional transferable resources and inter-regional transferable resources. The former refers to that the transfer paths are only distributed in the geographically concentrated regions based on beam, while the latter refers to that the transfer paths are distributed in multiple regions. Each transfer type is divided into 5 types according to the quantity of transfer layers, including beam resources with 1 transfer layer (intra-regional: green rectangle, number: 1; Inter-regional: green grid rectangle, number: 6); Transfer beam resources with 2 layers (intra-regional: blue rectangle, number: 2; Inter-regional: blue grid rectangle, number: 7); Transfer beam resources with 3 layers (intra-regional: orange rectangle, number: 3; Inter-regional: orange grid rectangle, number: 8); Transfer beam resources with 4 layers (intra-regional: purple rectangle, number: 4; Inter-regional: purple grid rectangle, number: 9); Transfer beam resources with 5 layers (intra-regional: red rectangle, number: 5; Inter-regional: red grid rectangle, number: 10).

4.2.2. Transfer capability calculation

The essence of low-cost resource transfer is to search for the shortest transfer path between the scheduling task window and the idle resource window in the knowledge graph developed from the scheduling plan results. Meanwhile, the uniqueness of nodes in the shortest transfer path of different scheduling tasks should be guaranteed. The knowledge graph we built belongs to directed unauthorized networks. The BFS algorithm is a typical example of shortest path optimization, which is used to find the shortest path between two points in complex directed unauthorized networks, and it is suitable for our application scenarios.

We define the set of equipment in a certain region as $W = \{Q, Y\}$, where the set of beams of an MT-TTC device Q is $S_Q = \{s_1, s_2, \ldots, s_n\}$. As shown in Figure 7, due to the periodic nature of the scheduling plan, the scheduling tasks of the same equipment or beam at different times are probably different. Taking time $T + 0$ as an example, we rate the transfer ability of the beam. The set of beam resource occupancy is defined as $U_Q = \{u_1, u_2, \ldots, u_n\}$, the set of optimal transfer paths of beam resource occupancy tasks is defined as $p_Q = \{p_1, p_2, \ldots, p_n\}$, the set of non-transferable task lists provided by the central scheduling system is defined as the set $R_Q = \{r_1, r_2, \ldots, s_m\}$, the set of idle resource windows is defined as $W_Q = \{w_1, w_2, \ldots, w_k\}$, and the set of scheduling task windows is defined as $T = \{t_1, t_2, \ldots, t_e\}$.

– Step 1: Starting from the beam s_1 in the set S_Q, when s_1 is an idle beam, then $u_1 = 0$,$p_1 = 0$. When $s_1 \in R$, then $u_1 = -1$,$p_1 = -1$. When $s_1 \notin R$, select the scheduling task occupying beam s_1 as the starting point and any idle resource window w_1, $1 \le i \le k$ as the ending point, and extract the local graph network G associated with the starting point and the ending point.

- Step 2: Firstly, the weight of each edge in the set G is set equal to "1" as the distance between adjacent nodes is "1". Then, the scheduling task window t with a transfer relationship with the starting point is found and added to the search sequence.
- Step 3: Take t as the new starting point to search the scheduling window with its transfer relationship, until the endpoint appears for the first time when the shortest path h between the starting point and the endpoints of the local graph network G is obtained, and the quantity of transfer layers is the quantity of scheduling task nodes in the path. When the optimal transfer path set P_Q contains no node of the shortest path h, the transfer path set$H = \{\}$ is defined h is added to the set H.
- Step 4: Continue to evaluate the shortest transfer path between the starting point and other idle resource windows, and add it to the set H. Then, according to the regional distribution difference of path nodes, it is further divided into intra-regional set H^1 and inter-regional set H^2.
- Step 5: When the number of transfer layers of the shortest path $h = \min(H^1)$ of set H^1 in the region is less than 6, $p_1 = h$, and u_1 is assigned according to the number of transfer layers. When the number of transfer layers of the shortest path $h = \min(H^1)$ of set H^1 in the region is greater than or equal to 6, further evaluation is needed.
- Step 6: When the number of transfer layers of the shortest path $h = \min(H^2)$ of set H^2 in the region is less than 6, $p_1 = h$, and u_1 is assigned according to the number of transfer layers. When the number of transfer layers of the shortest path $h = \min(H^2)$ of set H^2in the region is greater than or equal to 6, then the result is obtained as $u_1 = -1$,$p_1 = -1$.
- Step 7: Continue to perform Step 1 to Step 6 until the transfer capability of all beams in set S_Q at the current moment is calculated. Move to the next moment.

5. Two-layer scheduling framework

The centralized scheduling mode is not able to handle a large number of concurrent TTC requests all of a sudden represented by the LEO Internet constellation, so it is necessary to adjust the scheduling mode to relieve the pressure of the scheduling system. The proposed framework is a distributed scheduling structure of two layers including a central scheduling node and a regional distributed scheduling node for random access requests of the LEO Internet constellation. It can be embedded in the original scheduling mode by not changing the original scheduling mode. As shown in Figure 8, according to the principle of "regional autonomy, central decision-making and multi-region collaboration", we divide the equipment into relatively independent regions (region "A", region "B" and region "'C" in Fig. 8) according to the geographical distribution characteristics. In each region, the MT-TTC equipment is mainly used to undertake random access tasks, and other single-beam devices assist in completing resource transfer tasks. In the region, the multi-beam has the ability to directly respond to the random access request and has the right to independently allocate resources to the random access task in the region. For example, there is an idle beam (green beam) in region "C" of Figure 8, which directly responds to the random access request. An intra-area transferable beam (blue beam) exists in region "A", which responds to random access requests through intra-area resource transfer. However, when the random access task needs to transfer resources between regions (as shown in Fig. 8, there is an orange beam for inter-regional transfer in region B), the region sends a resource transfer plan to the central scheduling system and applies for an inter-regional transfer license. The central scheduling system makes decisions according to the use of equipment in relevant regions. The red beam in Figure 8 is non-transferable and is not discussed in this paper.

The two-layer scheduling framework has the following characteristics: (1) The resource scheduling model with regional autonomy as the core alleviates the pressure of centralized resource allocation in the central scheduling system, and does not affect the existing scheduling model; (2) The rapid response capability of distributed multi-region tasks improves emergency management, disaster recovery and destruction resistance of the whole

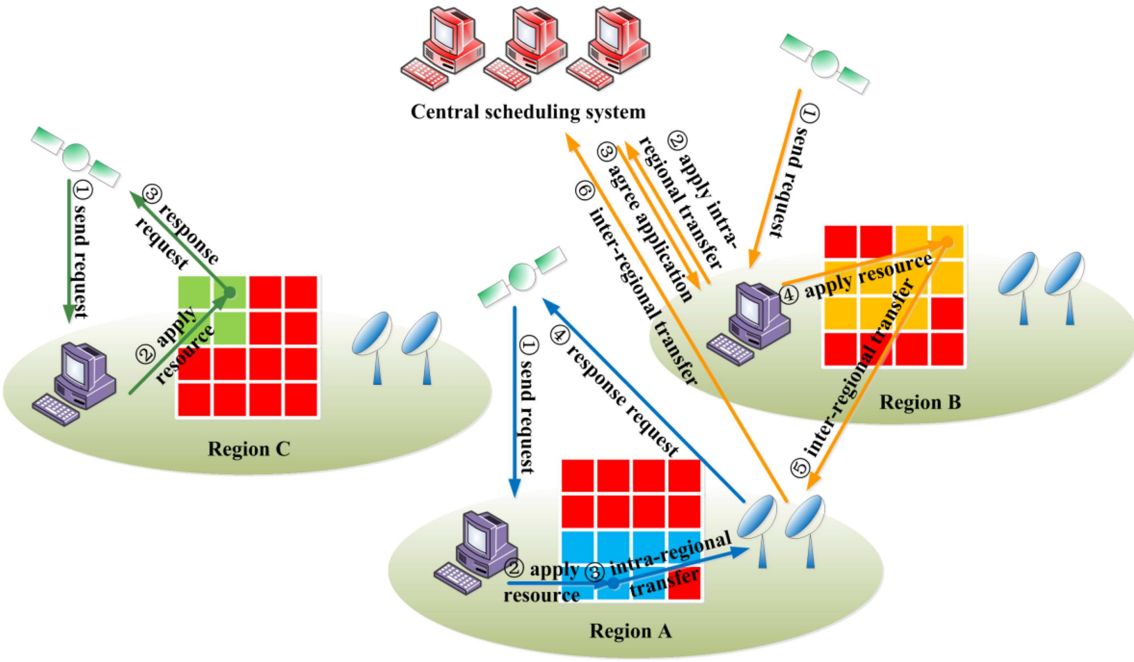

FIGURE 8. Schematic diagram of a two-layer scheduling framework.

system; (3) The central scheduling system retains the highest decision-making rights for inter-regional resource transfer schemes that affect the global robustness of scheduling results, which delivers benefits to the completion of multi-region cooperative tasks. The two-layer scheduling framework includes two key technologies, which are the resource transfer decision model and the resource transfer coordination mechanism.

5.1. Resource transfer decision model

The influence of resource transfer on the robustness of scheduling results is inevitable. When resource transfer is carried out, the impact on the resource scheduling plan should be minimized as much as possible. Specifically, the goal of resource transfer should be achieved through a lower number of transfer layers. Therefore, we propose a resource transfer decision model based on dynamic probability. A probabilistic model is developed according to the transfer ability of resources in the virtual resource pool. Following the principle of "first idle, then intra-regional, and finally inter-regional", we dynamically update the probability model with the response of random access tasks and the change of resource allocation to ensure the probability-based resource allocation mode, which satisfies the local randomness and global optimality of resource transfer costs.

The beam resource occupancy set of MT-TTC Q within the region is defined as $U_Q = \{u_1, u_2, \ldots, u_n\}$, and the beam resource occupancy type set $Z_Q = \{A, I, O, B\}$ is obtained by calculation, where A represents the idle beam set, I represents the transferable resource beam set within the region, O represents the transferable resource beam set between regions, and B represents the non-transferable resource beam set.

The beam resource transfer probability set of MT-TTC Q is defined as $Pr_Q = \{pr_1, pr_2, \ldots, pr_n\}$, and $card[Z_Q(A)]$ represents the number of idle beams. When $card[Z_Q(A)] \neq 0$, it indicates that there is an idle beam, the probability of pr_i is calculated by equation (1).

$$pr_i = \begin{cases} \dfrac{1}{card[Z_Q(A)]}, u_i = 0 \\ 0, u_i \neq 0. \end{cases} \tag{1}$$

At this time, the transfer probability of the idle beam is greater than 0, while the transfer probability of other beams is 0 in the set Pr_Q. This ensures that the idle beam is preferentially selected for random access tasks.

When $card[Z_Q(A)] = 0$, and $card[Z_Q(I)] \neq 0$, it indicates that there is no idle beam, and the probability of pr_i is calculated by equation (2).

$$pr_i = \begin{cases} \dfrac{1}{\left\{\sum_{i=1}^{n} \dfrac{1}{u_i} \times card[Z_Q(I_{u_i})]\right\} \times u_i}, u \in [1,5] \\ 0, u \notin [1,5]. \end{cases} \tag{2}$$

At this time, the transfer probability of the transferable beam in the region is greater than 0, the transfer probability of the beam with larger transfer layers is smaller, and the ratio of transfer probability between beams with different transfer layers is equal to the inverse ratio of the transfer layers in the set Pr_Q. The transfer probability of other beams is 0, so as to ensure that the random access task preferentially selects the transferable beam in the region when there is no idle beam.

When $card[Z_Q(A)] = card[Z_Q(I)] = 0$, $card[Z_Q(O)] \neq 0$ it indicates that there is no idle beam or transferable beam in the region. The probability of pr_i is calculated by equation (3).

$$pr_i = \begin{cases} \dfrac{1}{\left\{\sum_{i=1}^{n} \dfrac{1}{u_i - 5} \times card[Z_Q(I_{u_i})]\right\} \times (u_i - 5)}, u \in [6,10] \\ 0, u \notin [6,10]. \end{cases} \tag{3}$$

At this time, the transfer probability of the inter-regional transferable beam is greater than 0, and the calculation method of transfer probability is the same as that in the region in the set Pr_Q. The transfer layer number of the inter-regional transferable beam is corrected to the true value by subtracting 5 from u_i, which represents the transfer layer number of the beam. The transfer probability of other beams is 0, so as to ensure that when there is no idle beam and the inter-regional transferable beam, the random access task only preferentially selects the transferable beam between regions.

When $card[Z_Q(A)] = card[Z_Q(I)] = card[Z_Q(O)] = 0$, $card[Z_Q(B)] \neq 0$, it indicates that all beams are not transferable. At this moment, the transfer probability of all beams is 0, and there is no ability to respond to random access requests.

Since the transfer probability of the beam changes dynamically with the response of the random access task and the change of resource allocation, the state of the original beam changes whenever it responds to a random access task. The transfer probability set should be updated according to the new state, and the beam state should be synchronized in real-time to ensure the local randomness and global optimality of the resource transfer cost.

5.2. Resource transfer coordination mechanism

The two-layer scheduling framework is the implementation structure of distributed collaborative scheduling technology in real-time with the MT-TTC virtual resource pool based on knowledge graph technology and the resource transfer decision model grounded on dynamic probability as the core. We propose the resource transfer coordination mechanism as shown in Figure 9, which is the processing flow of the random access task.

The centralized pre-allocated resource scheduling mode is mainly reflected in the periodic scheduling plan, and the dynamic scheduling plan is developed for emergency tasks. The two plans are combined for a complete resource scheduling plan. Figure 9 illustrates the general process of handling random access tasks and the internal logic of the resource transfer coordination mechanism.

(1) Preprocessing of data: The central scheduling system generates periodic scheduling plans by integrating different task center requirements. This periodic scheduling plan is considered the initial resource scheduling plan because no new dynamic scheduling plan is incorporated before the start of the new scheduling period. We use the knowledge graph technology to generate a graph network of periodic scheduling plans, and slice the graph network according to the geographical distribution characteristics of devices to complete the network of scheduling results.

(2) Preparation of data: After completing the networking of scheduling results, we first extract the MT-TTC plans in the region, then classify the beam resources according to the beam resource occupancy, and finally calculate the transfer capacity of each beam one by one to produce an MT-TTC virtual resource pool.

(3) Response to idle beam tasks: When the region scheduling system receives the random access request, we first need to determine the beam resource occupancy of the MT-TTC virtual resource pool in the region. If there are idle beams, the transfer probability of beam resources in the current state is calculated by the dynamic probability model, the beam resources are selected autonomously to respond to the random access request, and the newly added scheduling plan status information is fed back to the dynamic planning module. If no idle beam exists, proceed to the next step.

(4) Respond to intra-regional tasks: When there is intra-regional beam transfer, we update the beam resource transfer probability in the current state through the dynamic probability model, select beam resources to respond to the random access request, adjust the intra-regional scheduling plan according to the intra-regional transfer scheme, and feed the newly added and changed scheduling plan status information to the dynamic planning module. If there is no intra-regional transfer beam, proceed to the next step.

(5) Responds to inter-regional tasks: When there is an inter-regional transfer beam, we update the transfer probability of beam resources in the current state through the dynamic probability model, select the inter-regional transfer scheme of beam resources independently, and issue an inter-regional resource transfer application to the central scheduling system through the regional scheduling system. If the central scheduling system finds that the transfer scheme does not conflict with the resources in the associated area, it responds to the random access request and feeds back the newly added and changed scheduling plan status information to the dynamic planning module. On the contrary, the beam resource transfer probability is updated to continue the above judgment. If there are still conflicts in the remaining resources, it does not respond to the random access request.

In addition, there is a probability that the insertion mode and path transfer mode of the random access task is 1:2 or 1:3. When the beam type is the same, the same mode will be applied; when the beam types are different, it will be processed in a relatively complex mode. For example, when the beam type includes the intra-regional transfer beam and the inter-regional transfer beam, it will be processed in an out-of-region mode. Similarly, in the transfer path, when there are out-of-region nodes, it will be processed in an out-of-region mode.

6. Experimental analysis

6.1. Graph network development

To verify the performance of distributed collaborative real-time scheduling technology, we simulate 216 sets of equipment (including 4 sets of MT-TTC equipment, each of which has 16 beams, equivalent to 16 sets of independent equipment) by using the existing resource scheduling system test platform based on the actual requirements of TTC. Also, 10127 tasks are scheduled for 806 satellites (including various high and low-orbit satellites) for three consecutive days (2021/06/25 00:00:00 to 2021/06/28 00:00:00), of which 9681 tasks are successfully scheduled. We develop the algorithm in a Python language environment and use the Neo4j graph database to build the knowledge graph. According to the graph network construction method in Section 3.2.2, the scheduling result is used to generate the knowledge graph. Figure 10 shows the knowledge graph generation results.

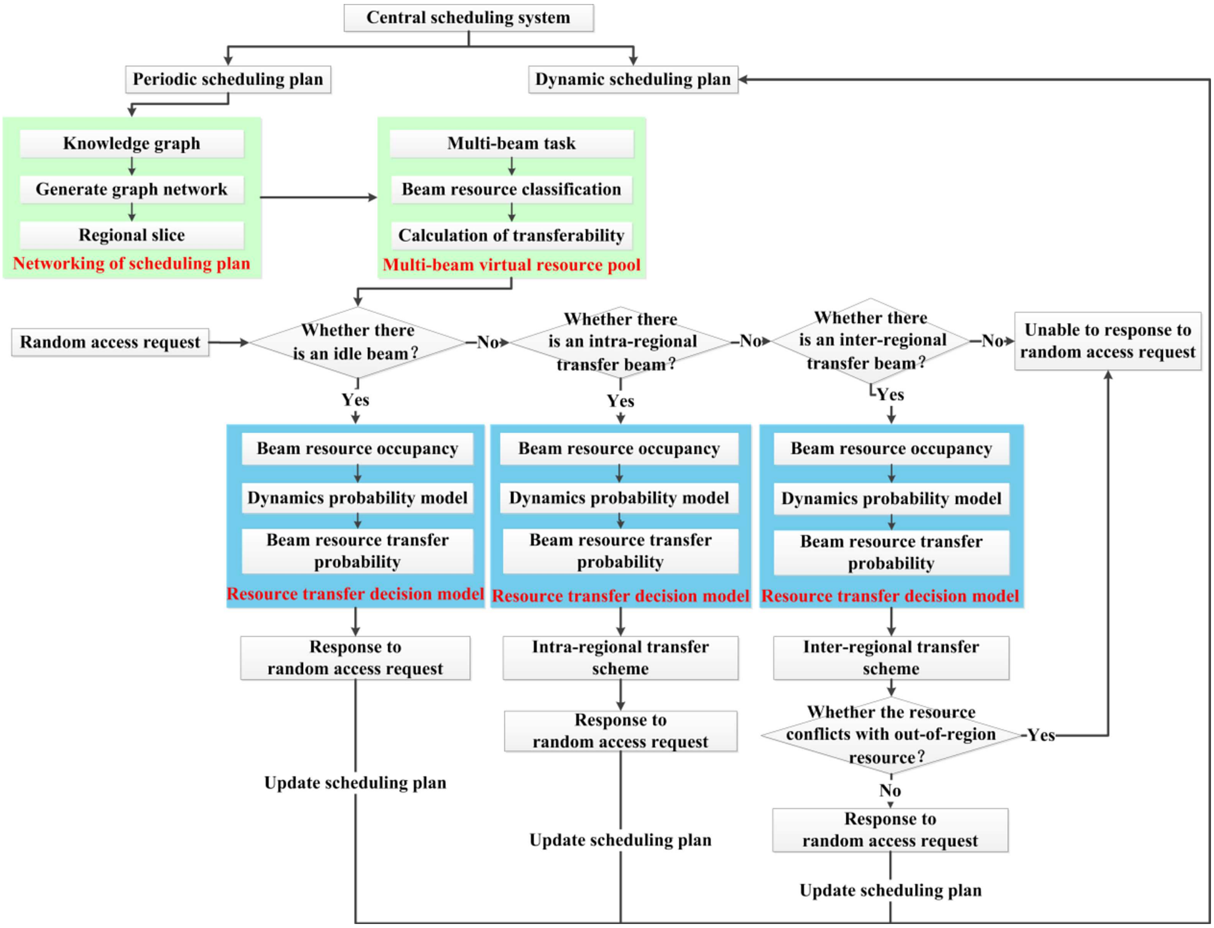

FIGURE 9. Schematic diagram of resource transfer coordination mechanism.

6.2. Virtual resource pool generation

The ground TTC equipment in China is deployed in clusters in some regions. Therefore, we deploy four sets of MT-TTC equipment in four main regions respectively and develop a regional TTC equipment cluster with other single-beam equipment in the region. Table 2 shows the statistical results of the regional distribution of TTC equipment. As the equipment in the experiments is selected based on the space resource library of the scheduling test platform, the equipment is not numbered consecutively. Overall, the amount of equipment in each area is evenly distributed.

Taking MT-TTC in region "A" as an example, we calculate the beam transfer capability of MT-TTC equipment in region "A" according to the method in Section 4.2.2. As shown in Table 3, the 16 beams of MT-TTC "A" contain a total of 1181 scheduling tasks, and the number of tasks contained in each beam is relatively balanced, while the transfer ability of tasks in each beam shows certain trends. Combined with statistical analysis of the different beam transfer abilities in Figure 11, we find that the beam transfer ability decreases continuously with the increase of the number of the beam, which is intuitively reflected in the increase in the non-transferable ("−1") task (red cylinder) number. It is due to the fact that the number of nodes that can be transferred is limited to ensure the uniqueness of the node contained in transfer paths of different beams in the process of building a virtual resource pool. In the experiment, we calculate the beam transfer ability in the increasing order

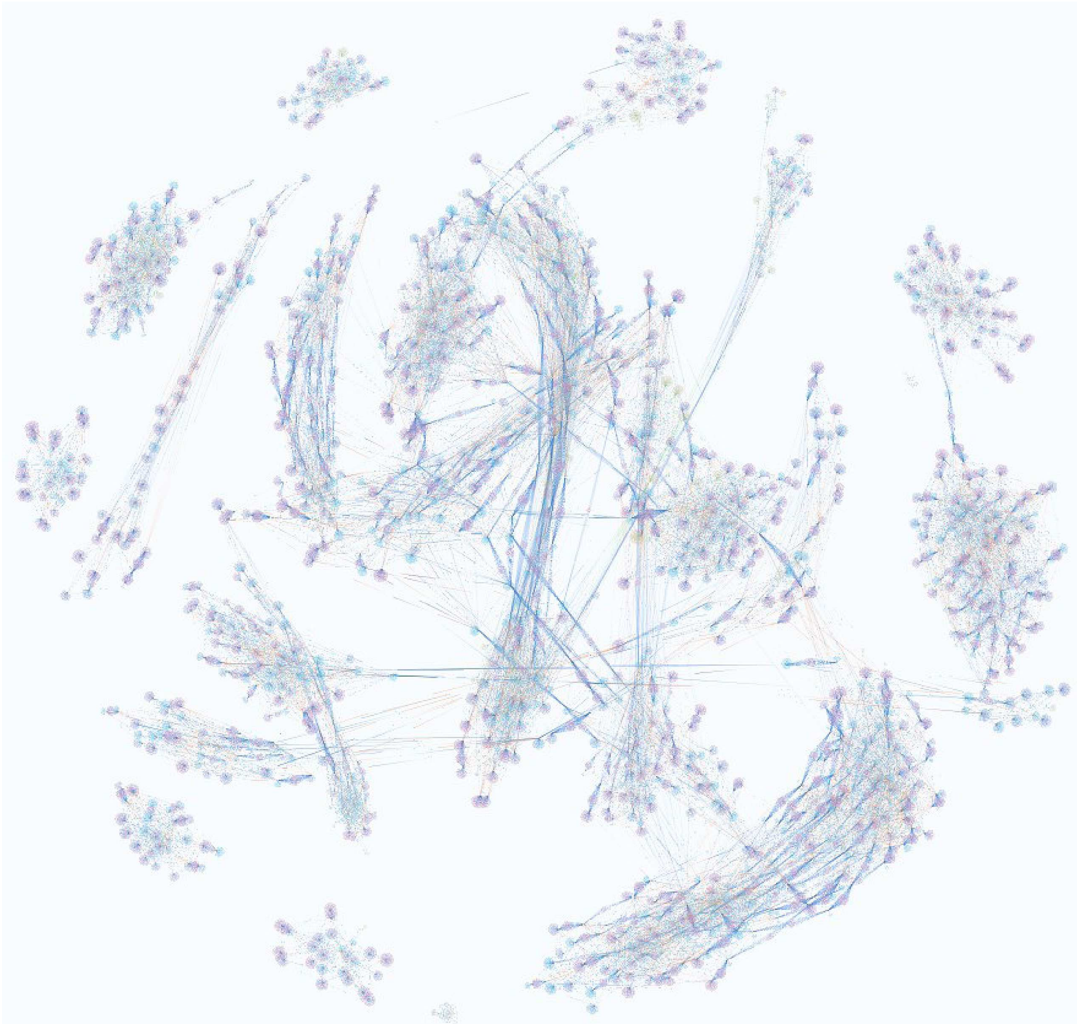

Figure 10. Knowledge graph generation results.

Table 2. Statistical results of regional distribution of TTC equipment.

Region	MT-TTC	Single-beam	Beam quantity
A	145–160	1–2,57–59,129–144,174–176,185–186,376–380	47
B	3–18	189,218,250–257,260–293	59
C	75–90	51,53–54,65–69,70–74,181–184,206–217,302–303	47
D	103–118	99–102,127–128,170–173,177–178,198–205,247,294–299,301,381–389,391–400	63

TABLE 3. Beam transfer capability of MT-TTC equipment in region.

Beam number	Property											Task quantity
	−1	1	2	3	4	5	6	7	8	9	10	
145	1	10	13	4	5	2	8	13	7	6	4	73
146	0	10	12	7	5	4	4	16	11	4	1	74
147	2	8	13	7	3	2	6	11	20	5	0	77
148	5	11	9	2	4	2	4	15	10	7	2	71
149	5	8	15	8	2	4	4	16	11	3	2	78
150	25	5	10	7	2	2	2	7	12	3	3	78
151	27	4	5	2	4	2	2	12	12	5	1	76
152	33	2	3	5	2	0	0	12	8	1	3	69
153	43	2	6	1	1	0	0	5	10	2	0	70
154	50	1	2	4	2	2	0	7	4	1	1	74
155	62	0	1	2	0	0	2	5	0	2	0	74
156	58	1	0	4	0	1	1	2	3	0	1	71
157	65	1	2	1	0	0	1	2	3	1	1	77
158	64	3	1	1	0	0	3	2	1	1	0	76
159	60	4	2	2	0	0	1	1	2	0	0	72
160	59	1	1	1	0	0	1	5	3	0	0	71
Total	559	71	95	58	30	21	39	131	117	41	19	1181

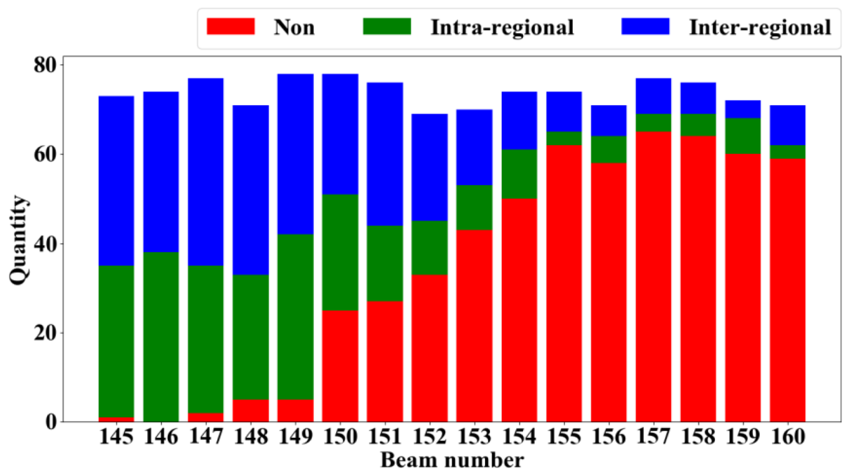

FIGURE 11. Statistical chart of transfer capability of different beams.

of beam number, which inevitably leads to fewer transfer nodes available in the subsequent beam, increasing the number of non-transferable tasks, and correspondingly reducing the transfer ability. No matter what processing order is adopted, it has no influence on the overall transfer ability of MT-TTC “A”. As shown in Table 3, as many as 52.67 % ((1181-559) /1181*100 %) tasks in MT-TTC “A” have the transfer ability. In addition, it can be seen from Figure 11 that the number of intra-regional transferable tasks (green cylinders) within each beam is the same as that of inter-regional transferable tasks (blue cylinders). This is attributed to the fact that the priority option of equipment within the region is not emphasized in the calculation of transfer capacity. Therefore, the transfer capacity within and between regions is balanced.

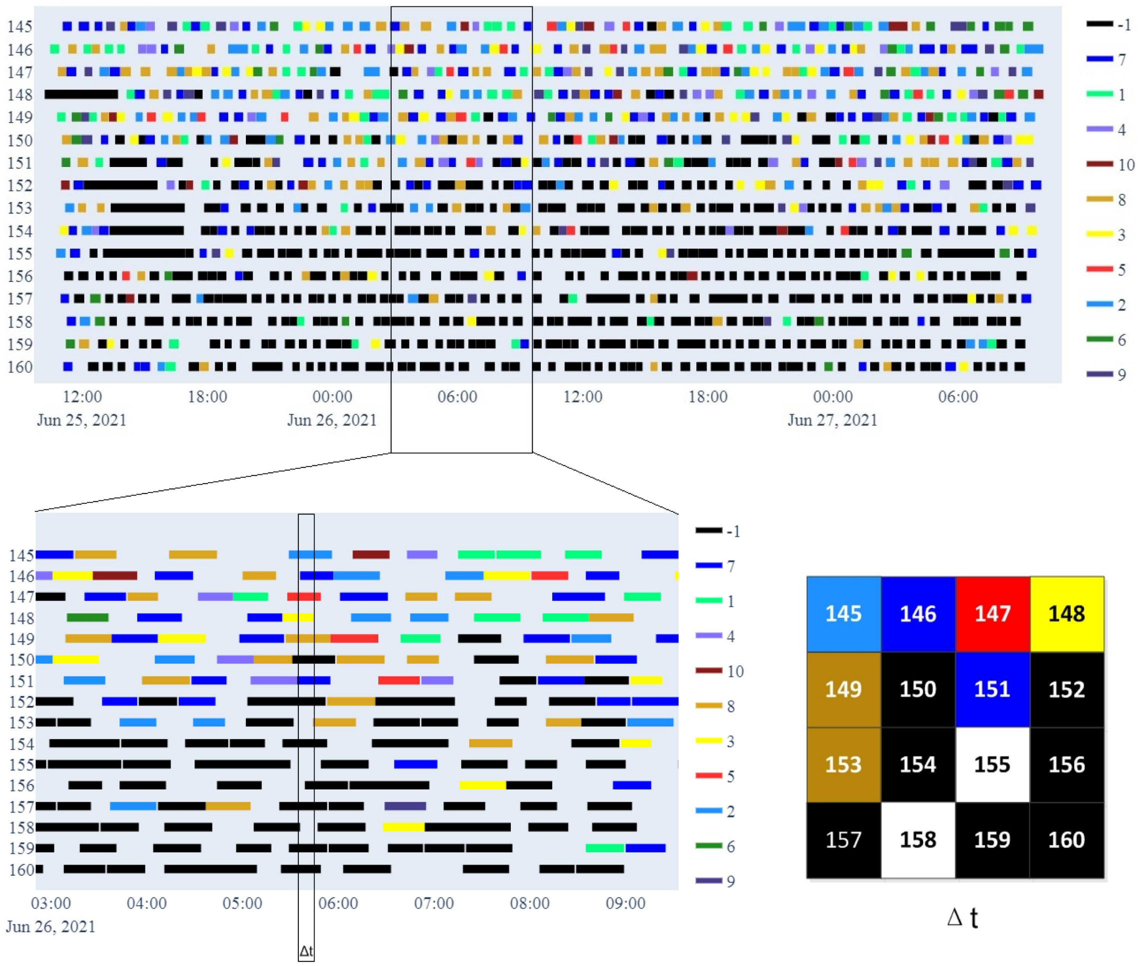

FIGURE 12. Analysis results of transfer capability of MT-TTC "A".

We use the form of the Gantt chart to show the transfer capability of MT-TTC "A". Figure 12 shows the allocation of scheduling tasks on 16 beams of MT-TTC "A" from 2021/06/25 00:00:00 to 2021/06/28 00:00:00. Progress bars with different colors represent different transfer capabilities of beams. The non-transferable black progress bar task ("-1") increases as the beam number increases, which is consistent with the statistical results in Figure 11. We find that the transfer status of the same beam varies in different periods. By intercepting part of the data (black rectangular solid line box) for a detailed display, we find that different beams presented interlaced tasks in the same period. We intercept the data in period (black rectangular solid line box) and show the result of the MT-TTC transfer capability of MT-TTC "A" in the period more intuitively on the right side. The numbers in the figure are the beam numbers, where beams 155 and 158 are free; 150, 152, 154, 156, 157, 159, and 160 are non-transferable beams; 145, 147, and 148 are intra-regional transferable beams; 146, 149, 151 and 153 are inter-regional transferable beams. MT-TTC "A" in , a total of 9 beams can perform random access tasks to generate an MT-TTC virtual resource pool.

TABLE 4. Random access tasks.

Task	Start time	End time	Task quantity
A-1	2021-06-26 15:10:00	2021-06-26 15:20:00	8
A-2	2021-06-27 08:25:00	2021-06-27 08:34:00	10

6.3. Response to the random access request

The concept of random access comes from computer networks and is widely used in cellular mobile communication systems. In the field of space TTC, random access task refers to the condition that the TTC node has full spatial beam coverage, and the satellite can enter the beam range to conduct TTC and respond to requests in real-time. LEO Internet constellation often has multiple satellites entering the coverage of MT-TTC in the whole airspace and initiates TTC requests simultaneously. In the experiment, we simulate two groups of random access requests, analyze the response process under the two-layer scheduling framework, and evaluate the effectiveness of the regional cooperation mechanism.

As shown in Table 4, the two tasks are numbered "A-1" and "A-2" respectively, which refer to the random access requests initiated against MT-TTC "A". The number of tasks in each group is 8 and 10 respectively. Beam resources are then assigned to each group of tasks based on the virtual resource pool generated in Section 6.2. Table 5 shows the beam resource allocation results of task "A-1", and Table 6 shows the beam resource allocation results of task "A-2". When each task is processed, data sets of three processes are generated, including the transfer state set, the transfer task set, and the dynamic probability set. The transfer status set contains the transfer status of each beam corresponding to the current random access task window in the virtual resource pool, and the scheduling task number corresponding to the transfer status constitutes the transfer task set. The beam allocation probability of the current random access task is calculated by dynamic probability mode. Finally, the beam resources are selected according to the collaborative transfer mechanism. In Table 5, the transfer state set of the first task is taken as the initial transfer state, and a total of four beams are idle states ("0"), which is represented by beam code in the corresponding transfer task set. Take "0-155" as an example, "0" is the code name of MT-TTC "A" in the data processing process, and "155" is the beam code name. The first four tasks all selected idle beams with the same probability, while in the transfer state of the fifth task, only "0-158" is the beam that is transferred in the region ("1"). Therefore, beam "0-158" is selected with 100 % probability, occupying the "78_-1_0_1_1" scheduling task window. The remaining beams faced by subsequent tasks are transferred between regions and selected according to dynamic probability.

Table 6 shows the beam resource allocation results of 10 tasks in task "A-2". Different from task "A-1", the nodes in the 10th task transfer path conflict with nodes outside the region and are rated as non-transferable. In Figure 13, the task "930_-1_0_1_2" is represented by the orange node (ID: 262262). The preset transfer path in the virtual resource pool is transferred once, and "idle_win999" represented by the idle window of the green node (ID: 262262) is found. As the idle window "idle_win999" is located in equipment "400" and belongs to region "D", the transfer is an inter-regional transfer. Meanwhile, the transfer path of scheduling task "936_-1_0_1_3" (Orange node (ID262262)) on the beam "3-110" under the MT-TTC "D" also occupies idle window "idle_win999" with overlapping time windows and is an intra-area transfer. Therefore, the central scheduling system rates the transfer path of scheduling task "930_-1_0_1_2" as a conflict with other regional resources, updates the beam resource transfer probability and selects beam "0-151" again to respond to the random access request.

The above experiments show that the distributed collaborative scheduling technology in real-time effectively deals with random access requests of sudden occurrences, which highlights its real-time response of regional scheduling with MT-TTC as the core, and underlines the dynamic sensing and fast decision-making abilities of a collaborative central scheduling system.

Table 5. Beam resource allocation results of task.

Index	Transfer status set	Transfer task set	Dynamic probability set	Result	Transfer layer
1	[−1,8,8,−1,7,0,8,0,−1,0,**0**,−1,8,1,−1,8]	[[903_−1_0_1_1],[704_−1_0_1_1],[803_−1_0_0_2],[906_−1_0_1_1],[1311_−1_0_1_1],[0−150],[619_−1_0_0_1],[0−152],[1144_−1_0_1_0,607_−1_0_0_3],[0−154],**[0−155]**,[811_−1_0_1_0],[352_−1_0_1_1],[78_−1_0_1_1],[185_−1_0_1_1],[724_−1_0_1_1]]	[0,0,0,0,0,0.25,0,0.25,0,0.25,**0.25**,0,0,0,0,0]	0−155	0
2	[−1,8,8,−1,7,0,8,0,−1,**0**, −1,−1,8,1,−1,8]	[[903_−1_0_1_1], [704_−1_0_1_1], [803_−1_0_0_2], [906_−1_0_1_1], [1311_−1_0_1_1], [0−150], [619_−1_0_0_1], [0−152], [1144_−1_0_1_0,607_−1_0_0_3], **[0−154]**,[0], [811_−1_0_1_0], [352_−1_0_1_1], [78_−1_0_1_1], [185_−1_0_1_1], [724_−1_0_1_1]]	[0,0,0,0,0,0.33,0,0.33,0,**0.33**,0,0,0,0,0,0]	0−154	0
3	[−1,8,8,−1,7,0,8,**0**,−1,−1,−1,−1,8,1,−1,8]	[[903_−1_0_1_1], [704_−1_0_1_1], [803_−1_0_0_2], [906_−1_0_1_1], [1311_−1_0_1_1], [0−150], [619_−1_0_0_1], **[0−152]**, [1144_−1_0_1_0,607_−1_0_0_3], [0],[0],[811_−1_0_1_0], [352_−1_0_1_1], [78_−1_0_1_1], [185_−1_0_1_1], [724_−1_0_1_1]]	[0,0,0,0,0,0.5,0,**0.5**, 0,0,0,0,0,0,0,0]	0−152	0
4	[−1,8,8,−1,7,**0**,8,−1,−1,−1,−1,−1,8,1,−1,8]	[[903_−1_0_1_1], [704_−1_0_1_1], [803_−1_0_0_2], [906_−1_0_1_1], [1311_−1_0_1_1], **[0−150]**, [619_−1_0_0_1],[0], [1144_−1_0_1_0,607_−1_0_0_3],[0],[0], [811_−1_0_1_0], [352_−1_0_1_1], [78_−1_0_1_1], [185_−1_0_1_1], [724_−1_0_1_1]]	[0,0,0,0,0,**1.0**,0,0, 0,0,0,0,0,0,0,0]	0−150	0
5	[−1,8,8,−1,7,−1,8,−1,−1,−1,−1,−1,8,**1**,−1,8]	[[903_−1_0_1_1], [704_−1_0_1_1], [803_−1_0_0_2], [906_−1_0_1_1], [1311_−1_0_1_1],[0], [619_−1_0_0_1],[0], [1144_−1_0_1_0, 607_−1_0_0_3],[0],[0], [811_−1_0_1_0], [352_−1_0_1_1], **[78_−1_0_1_1]**, [185_−1_0_1_1], [724_−1_0_1_1]]	[0,0,0,0,0, 0,0,0, 0,0,0,0,0, **1.0**,0,0]	0−158	1
6	[−1,**8**,8,−1,7,−1,8,−1, −1,−1,−1,−1,8,−1,−1,8]	[[903_−1_0_1_1],**[704_−1_0_1_1]**, [803_−1_0_0_2], [906_−1_0_1_1], [1311_−1_0_1_1], [0],[619_−1_0_0_1],[0], [1144_−1_0_1_0,607_−1_0_0_3],[0], [0],[811_−1_0_1_0], [352_−1_0_1_1],[0], [185_−1_0_1_1], [724_−1_0_1_1]]	[0,0.15,0.15,0, 0.23,0,0.15, 0,0,0,0,0, 0.15,0,0,0.15]	0−146	3
7	[−1,−1,**8**,−1,7,−1,8,−1, −1,−1,−1,−1,8,−1,−1,8]	[[903_−1_0_1_1],[0],**[803_−1_0_0_2]**,[906_−1_0_1_1], [1311_−1_0_1_1],[0], [619_−1_0_0_1],[0], [1144_−1_0_1_0,607_−1_0_0_3],[0],[0], [811_−1_0_1_0], [352_−1_0_1_1],[0], [185_−1_0_1_1], [724_−1_0_1_1]]	[0,0,**0.18**,0,0.27,0,0.18,0, 0,0,0,0,0.18,0,0,0.18]	0−147	3
8	[−1,−1,−1,−1,**7**,−1,8,−1, −1,−1,−1,−1,8,−1,−1,8]	[[903_−1_0_1_1],[0],[0], [906_−1_0_1_1], **[1311_−1_0_1_1]**,[0], [619_−1_0_0_1],[0], [1144_−1_0_1_0,607_−1_0_0_3],[0],[0], [811_−1_0_1_0], [352_−1_0_1_1],[0], [185_−1_0_1_1], [724_−1_0_1_1]]	[0,0,0,0,**0.33**,0,0.22,0, 0,0,0,0,0.22,0,0,0.22]	0−149	2

Table 6. Beam resource allocation results of task "A-2".

Index	Transfer status set	Transfer task set	Dynamic probability set	Result	Transfer layer
1	[8,2,1,**0**,1,3,8,1,−1,−1,6,0,−1,0,−1,−1]	[[79_−1_0_1_3], [351_−1_0_1_3], [1286_−1_0_1_2], **[0−148]**, [1246_−1_0_1_3], [1244_−1_0_1_3], [1250_−1_0_1_3], [1243_−1_0_1_3], [373_−1_0_1_3], [1281_−1_0_1_2], [930_−1_0_1_2], [0−156],[372_−1_0_1_3],[0−158], [471_−1_0_1_3],[179_−1_0_1_3]]	[0,0,0,**0.33**,0,0,0,0,0,0,0,0.33,0,0.33,0,0]	0−148	0
2	[8,2,1,−1,1,3,8,1,−1,−1,6,0,−1,**0**, −1,−1]	[[79_−1_0_1_3],[351_−1_0_1_3], [1286_−1_0_1_2],[0],[1246_−1_0_1_3], [1244_−1_0_1_3],[1250_−1_0_1_3], [1243_−1_0_1_3], [373_−1_0_1_3], [1281_−1_0_1_2],[930_−1_0_1_2], [0−156],[372_−1_0_1_3],**[0−158]**, [471_−1_0_1_3],[179_−1_0_1_3]]	[0,0,0,0,0,0,0,0,0,0,0,0,0.5,0,**0.5**,0,0]	0−158	0
3	[8,2,1,−1,1,3,8,1,−1,−1,6,**0**,−1,−1,−1,−1]	[[79_−1_0_1_3],[351_−1_0_1_3], [1286_−1_0_1_2],[0], [1246_−1_0_1_3], [1244_−1_0_1_3],[1250_−1_0_1_3], [1243_−1_0_1_3],[373_−1_0_1_3], [1281_−1_0_1_2],[930_−1_0_1_2], **[0−156]**,[372_−1_0_1_3],[0], [471_−1_0_1_3],[179_−1_0_1_3]]	[0,0,0,0,0,0,0,0,0,0,0,0,**1.0**,0,0,0,0,0]	0−156	0
4	[8,2,1,−1,1,3,8,**1**,−1,−1,6,−1,−1,−1,−1,−1]	[[79_−1_0_1_3],[351_−1_0_1_3], [1286_−1_0_1_2],[0],[1246_−1_0_1_3], [1244_−1_0_1_3],[1250_−1_0_1_3], **[1243_−1_0_1_3]**,[373_−1_0_1_3], [1281_−1_0_1_2],[930_−1_0_1_2], [0],[372_−1_0_1_3],[0],[471_−1_0_1_3], [179_−1_0_1_3]]	[0,0.13,0.26,0,**0.26**, 0.09,0, 0.26,0,0,0,0,0,0,0,0,0]	0−152	1
5	[8,2,**1**,−1,1,3,8, −1,−1,−1,6,−1,−1,−1,−1,−1]	[[79_−1_0_1_3],[351_−1_0_1_3], **[1286_−1_0_1_2]**,[0],[1246_−1_0_1_3], [1244_−1_0_1_3],[1250_−1_0_1_3],[0], [373_−1_0_1_3],[1281_−1_0_1_2], [930_−1_0_1_2],[0],[372_−1_0_1_3],[0], [471_−1_0_1_3],[179_−1_0_1_3]]	[0,0.17,**0.35**,0,0.35,0.12,0, 0,0,0,0,0,0,0,0,0,0]	0−147	1
6	[8,2,−1,−1,**1**,3,8,−1, −1,−1,6,−1,−1,−1,−1,−1]	[[79_−1_0_1_3],[351_−1_0_1_3],[0],[0], **[1246_−1_0_1_3]**,[1244_−1_0_1_3], [1250_−1_0_1_3],[0],[373_−1_0_1_3], [1281_−1_0_1_2],[930_−1_0_1_2],[0], [372_−1_0_1_3],[0],[471_−1_0_1_3], [179_−1_0_1_3]]	[0,0.27,0,0,**0.54**,0.18,0,0, 0,0,0,0,0,0,0,0,0]	0−149	1
7	[8,**2**,−1,−1,−1, 3,8,−1,−1,−1, 6,−1,−1,−1,−1,−1]	[[79_−1_0_1_3],**[351_−1_0_1_3]**, [0],[0],[0],[1244_−1_0_1_3], [1250_−1_0_1_3],[0],[373_−1_0_1_3], [1281_−1_0_1_2],[930_−1_0_1_2],[0], [372_−1_0_1_3],[0],[471_−1_0_1_3], [179_−1_0_1_3]]	[0,**0.6**,0,0,0,0.4,0, 0,0,0,0,0,0,0,0,0,0]	0−146	2
8	[8,−1,−1,−1,−1,**3**, 8,−1,−1,−1,6,−1,−1,−1,−1,−1]	[[79_−1_0_1_3], [0],[0],[0],[0], **[1244_−1_0_1_3]**,[1250_−1_0_1_3],[0], [373_−1_0_1_3],[1281_−1_0_1_2], [930_−1_0_1_2],[0],[372_−1_0_1_3],[0], [471_−1_0_1_3],[179_−1_0_1_3]]	[0,0,0,0,0,**1.0**,0,0, 0,0,0,0,0,0,0,0,0]	0−150	3
9	[**8**,−1,−1,−1,−1,−1, 8,−1,−1,−1,6,−1,−1, −1,−1,−1]	[**[79_−1_0_1_3]**,[0],[0],[0],[0],[0], [1250_−1_0_1_3],[0],[373_−1_0_1_3], [1281_−1_0_1_2],[930_−1_0_1_2], [0],[372_−1_0_1_3],[0], [471_−1_0_1_3],[179_−1_0_1_3]]	[**0.2**,0,0,0,0,0,0,0.2, 0,0,0,0.6,0,0,0,0,0]	0−145	3
10	[−1,−1,−1,−1,−1,−1, 8,−1,−1,−1,**6**,−1, −1,−1,−1,−1]	[[79_−1_0_1_3],[0],[0],[0],[0],[0], [1250_−1_0_1_3],[0],[373_−1_0_1_3], [1281_−1_0_1_2],**[930_−1_0_1_2]**,[0], [372_−1_0_1_3],[0],[471_−1_0_1_3], [179_−1_0_1_3]]	[0,0,0,0,0,0,0,0.25,0, 0,0,**0.75**,0,0,0,0,0]	conflict	−
10+	[−1,−1,−1,−1,−1,−1, **8**,−1,−1,−1,−1,−1, −1,−1,−1,−1]	[[79_−1_0_1_3],[0],[0], [0],[0],[0],**[1250_−1_0_1_3]**, [0],[373_−1_0_1_3],[1281_−1_0_1_2], [930_−1_0_1_2],[0],[372_−1_0_1_3], [0],[471_−1_0_1_3],[179_−1_0_1_3]]	[0,0,0,0,0,0,0,**1.0**,0, 0,0,0,0,0,0,0,0]	0−151	3

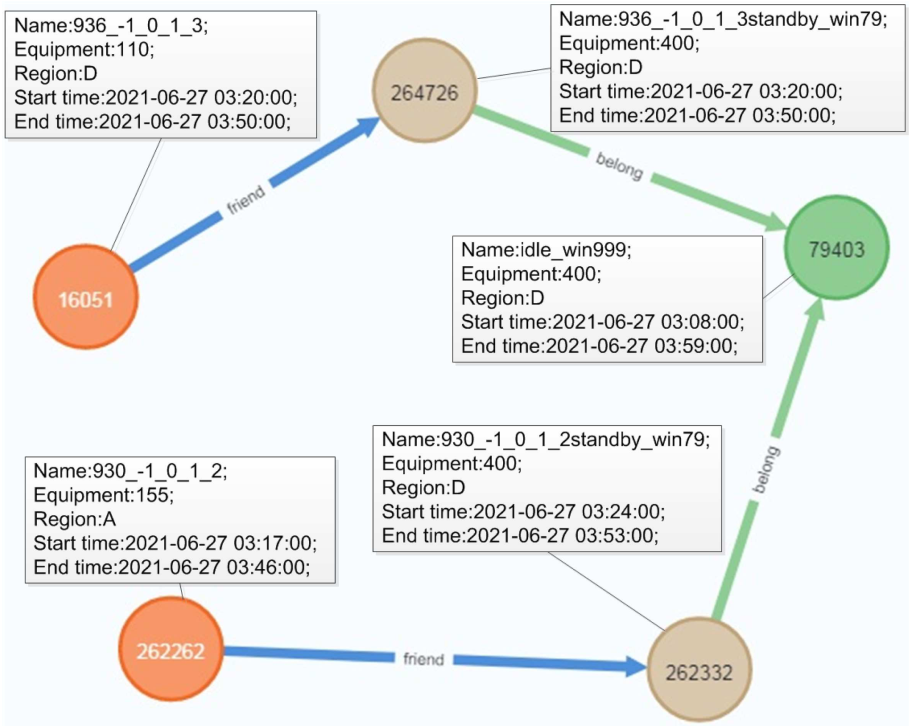

Figure 13. Experimental diagram of the transfer path node.

7. Conclusion

We propose a distributed collaborative real-time scheduling technology for random access, which resolves a challenge when the LEO Internet constellation satellite users actively initiate a real-time response to TTC requirements. As a result, the scheduling system has the ability of real-time resource scheduling, which meets the demand of TTC in the best possible way, and reduces the response time significantly. To sum up, it has great value in real scenarios and projects with the following three advantages:

(1) Based on the principle of "regional autonomy, central decision-making, and multi-region cooperation", the two-layer scheduling framework of "center-region" effectively relieves the pressure of large-scale random access requests on the central scheduling system, while preserving the decision right of the central scheduling system to transfer cross-regional resources. It delivers benefits to maintain the global robustness of the scheduling plan.
(2) Different from the traditional technology featuring resource pre-allocation, the virtual resource pool effectively avoids resource waste and balances the resource requirements for periodic scheduling and random access.
(3) The knowledge graph technology structures and networks scheduling plans, which enables a multi-layer fast transfer of MT-TTC resources to become a reality and the key support for random access requests with real-time response.

Also, further research and improvement are expected in the following aspects:

(1) The research on the collaborative transfer mechanism of resources lacks sufficient depth. It is necessary to further study the collaborative mechanism of resource transfer in the case of concurrent processing of random access requests in multiple regions.

(2) The development of a graph network based on the knowledge of graph technology takes a long time and lacks the capabilities of handling large-scale concurrent scheduling tasks. Therefore, it is necessary to further optimize the development scheme of the graph network to improve the operation efficiency.

Data Availability Statement. The code used in this paper is available online in a figshare item: https://figshare.com/s/64b1b25ee9fd364d77f0.

References

[1] S.W. Baek, S.M. Han, K.R. Cho, D.W. Lee, J.S. Yang, P.M. Bainum and H.D. Kim, Development of a scheduling algorithm and gui for autonomous satellite missions. *Acta Astronaut.* **68** (2011) 1396–1402.

[2] W. Cui, B. Wang, X. Gan, Y. Gao and N. Li, Design of the Five Layers Large-scale Low-orbit Communication Constellation tt&c System. IOP Publishing Ltd (2022).

[3] Y. Drif, E. Chaput, E. Lavinal, P. Berthou, B.T. Jou, O. Grémillet and F. Arnal, An extensible network slicing framework for satellite integration into 5g. *Int. J. Satell. Commun. Netw.* **39** (2021) 339–357.

[4] E. Guangxi, C. Lin and L. Yunge, Study on tt&c antenna for multi- target in hemispherical coverage. *Telecommun. Eng.* **55** (2015) 1112–1117.

[5] Y. He, Y. Chen, L. Xing, Z. Yuan and G. Li, Autonomous mission planning system design for novel imaging satellite. *Syst. Eng. Electron.* **39** (2017) 806–813.

[6] Z. Heping, To build a highway to spacecraft intelligentization with avionics technology. *Spacecr. Eng.* **24** (2015) 1–6.

[7] D.J. Israel, G. Heckler and R.J. Menrad, Space mobile network: A near earth communications and navigation architecture. In: *2016 IEEE Aerospace Conference* (2016).

[8] L. Jianping, Z. Tianyu, L. Wei and L. Zhiyuan, Service conception of satellite operation control network for global coverage and random access. In: *China Satellite Navigation Conference* (2020).

[9] L. Peijie, J. Wenyi, L. Yandu and Z. Tengfei, Random access ttc in space-ground integration ttc network system. *Telecommun. Eng.* **60** (2020) 1278–1285.

[10] G. Qi and L. Min, System construction conception for future china's tt&c equipment reconstruction. *Telecommun. Eng.* **50** (2010) 111–114.

[11] C.J. Roberts, M. Morgenstern, D.J. Israel, J.M. Borky and T.H. Bradley, Preliminary results from a model-driven architecture methodology for development of an event-driven space communications service concept. In: *IEEE International Conference on Wireless for Space & Extreme Environments* (2017).

[12] H.C. Shaw, D.J. Israel, C.J. Roberts, J.C. Burke, J.S. Kang and J.T. King, Space mobile network (smn) user demonstration satellite (suds) for a practical on-orbit demonstration of user initiated services (uis). In: *Space Ops Conference* (2018).

[13] A. Singhal, Introducing the knowledge graph. In: *Official Blog of Google* (2012).

[14] H. Tingting and F. Jun and L. Jiaming, Knowledge graph construction technology: Taxonomy, survey and future direction. *Comput. Sci.* **48** (2021) 175–189.

[15] P. Wang, Y. Kong and H. Wu, Flexible hemispherical simultaneous multi-beam tt&c technology. In Vol. 32 *Conference of Spacecraft TT&C Technology in China* (2013) 42–47.

[16] L. Zhilun and Z. Lidong, Flexible hemispherical simultaneous multi-beam ttc technology. *Radio Commun. Technol.* **45** (2019) 162–166.