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Adaptive Network Routing Technology for Near-Moon Space Cross-Domain Transmission

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Abstract: Communication transmission in the near-Moon space is a critical enabler of scientific exploration in this region. However, the communication network in near-Moon space shows trends of diversification, heterogeneity, and collaboration, posing significant challenges to the management of an integrated communication network. This paper proposes a networking routing method for near-Moon-space cross-domain network transmission. Considering the constraints of heterogeneous networks including Moon–Earth, Moon–surface, and relay transmission, the method enhances transmission routing efficiency at the network layer of near-Moon-space systems, thereby improving the overall efficiency of heterogeneous network interactions. This research focuses on the networking routing of cross-domain networks. To simplify the research problem, a mixed link resource and scheduling model of heterogeneous networks is proposed. Based on this model, a time-varying and fixed topology network sub-network clustering method was designed to reduce the complexity of the routing algorithm. A routing scheduling algorithm is provided in combination with hierarchical routing search, and related experiments and comparisons were carried out. Finally, considering the practical issues of communication relay channels and rate limitations in relay satellites, time windows and communication rate constraints were used to enhance the reliability of the simulation validation. Simulation results show that this method effectively addresses the issue of low transmission interaction efficiency in heterogeneous networks within cislunar space. Compared with previous designs, it improves link load rate by 31%, reduces average service delay by 8%, and significantly enhances link stability and load rate.

Keywords: cross-domain; adaptive routing network; near-Moon space; sub-network cluster

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1. Introduction

With the gradual implementation of lunar exploration programs in recent years, as well as the planned construction of lunar space stations and moon surface laboratories in the future, communication and transmission between the Earth and the moon, and within the near-Moon space, have become a hot topic of current research as a fundamental infrastructure for exploration missions [1,2]. Compared to decades ago, the purpose of missions and the comprehensiveness of explorations have greatly improved, and the application of various types of payloads has placed higher requirements on the models and applications of networking communications [3,4]. Currently, lunar exploration programs around the world include a series of unmanned and manned exploration equipment applications, involving autonomous exploration, unmanned driving, collaborative observation and other scientific research tasks, which place high requirements on lunar–Earth, Moon surface, and relay communications [5–7], and this will continue in the future.

Near-Moon-space scientific exploration includes basic tasks such as resource utilization, environmental monitoring, and multi-point exploration. In these processes, scientific instruments and equipment such as lunar soil manufacturing, water ice oxygen production, and spectral imaging analysis are applied. These devices come from different countries and research institutions. The information exchange and transmission between various payloads and devices affect the success of scientific exploration missions [8]. Currently, near-Moon-space communication transmission mainly relies on S-band TT&C (Telemetry Tracking and Command) control and Ka/X band data transmission, and future development of 10 Gbps laser communication [9] is planned. Surface interaction mainly relies on UHF and Wi-Fi networking, with possible future establishment of 5G base stations [10,11]. Some close-range payloads use technologies such as Bluetooth and Zigbee to achieve low power consumption and lightweight interactive transmission to meet different application needs [12,13]. Different communication bandwidths and their corresponding mobility capabilities are given in Figure 1.

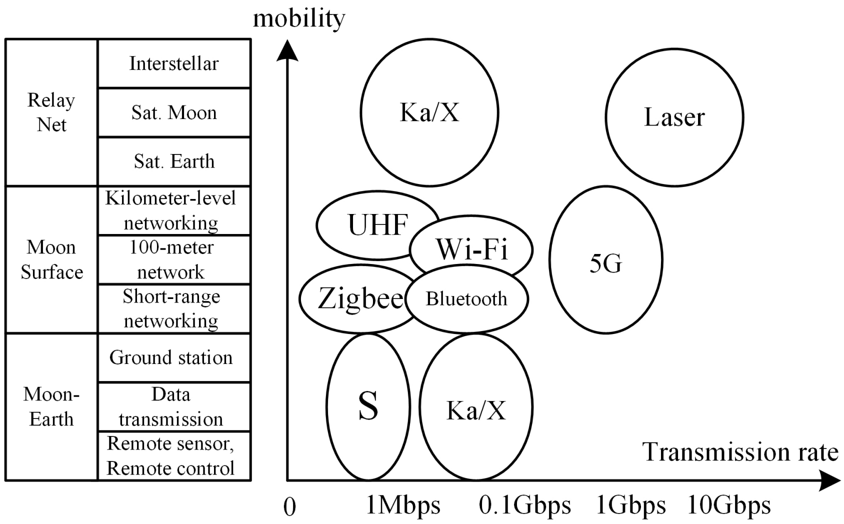

Figure 1. Schematic diagram of heterogeneous communication networks in the space near the Moon.

Therefore, facing the trend of diversification, isomerization, and collaboration in near-lunar space communication networks, providing appropriate services for different application needs also poses challenges to the management of integrated communication networks [14,15]. The main problem faced by cross-domain network convergence networking of platform and payload communications in space near the Moon is how to achieve effective data transmission of each network with different transmission rates, switching frequencies, and on–off ratios [16,17]. There are significant differences in communication systems, protocols, rates, and routing mechanisms between cross-domain network transmissions, making it difficult to achieve stable cross-network data transmission. Currently, this problem is mainly solved through network prediction, intermediate transfer, and general/dedicated network partitioning [18,19].

The use of 5G communication on the lunar surface will encounter the Doppler effect, near-far-end interference, and large delay issues [20], which also makes it difficult to build a 5G network similar to those on the ground in near-lunar space [21,22]. Artemis plans to provide a 1 Gbps high-speed data communication architecture for Earth–Moon transmission on the lunar surface by 2030, ultimately achieving 5 Gbps [23]. Adopting a unified communication interaction model for different mobile nodes based on different coverage areas and predicting communication capabilities based on lunar radio propagation can achieve good results for small networks but cannot meet the needs of a large number of heterogeneous network nodes [24]. Reference [25] designed two types of lunar transmission models for 1.8 GHz communication, which were used for interactive communication between lunar robots and astronauts. Heterogeneous network fusion interaction analysis showed the advantages of the fusion of different communication systems. In order to form a similar ground communication capability, reference [26] adopted WLAN networking to achieve information exchange between lunar devices around 20 m, which can achieve unified wireless data exchange between payload systems. For heterogeneous communication networks, software radio technology is mainly used to achieve the reconstruction of different link and protocol layers [27]. Reference [28] proposed a minimum data loss model for lunar and ground lunar network relay and established a ground lunar relay communication scheduling model. Considering the particularity of the orbit of space vehicles near the Moon, the heterogeneous network compatibility method based on unified communication protocols for low-Earth-orbit networking may not be applicable [29,30].

Common cross-domain network routing communication relies on the capabilities of relay or relay platforms [31], which makes it difficult to quantitatively analyze specific relay systems in the process of establishing a unified communication model [32,33]. The space network system near the Moon not only needs to ensure timely and reliable routing and forwarding of key instructions under high information latency conditions but also achieve new rapid chain building in the event of communication link failure. This requires the entire network to have time tolerance and decentralized self-organization capabilities, as well as the ability to interact with heterogeneous networks and backup and interconnect multiple domains in complex environments [34,35]. In the event of navigation information failure, it is necessary to have a certain channel prediction ability to quickly search for channels that may achieve chain building [36].

Traditional cross-domain networking mainly uses relay or relay satellites to transmit different types of data. In this process, the efficiency of data transmission between different networks depends on the forwarding ability of the relay channel. Networks between different domains undergo separate routing planning, and cross-domain data are limited and constrained by the relay platform [37]. With the increasing number of space vehicles and lunar rovers approaching the Moon in the future, achieving cross-domain network routing transmission, especially routing forwarding in case of emergency failures, is the key to the establishment of the near-Moon-space communication network [38]. To address these issues, a networking and routing method is proposed in this paper for cross-domain network transmission in cislunar space. The method takes into account the constraints of heterogeneous networks, including Earth–Moon, lunar surface, and relay transmissions, and establishes a hybrid link resource prediction and scheduling model. A hierarchical transmission chain architecture is designed with the priority goal of achieving maximum efficiency in completing key instructions and telemetry transmission and achieving unified node model architecture by equating intermediate nodes to critical paths. A delay tolerance mechanism is established for various nodes in heterogeneous networks, whereby communication interruptions and data loss based on storage and energy margins are minimized and transmission rates are predicted based on past data during the chain construction process to achieve fast ad hoc network connectivity for visible nodes. Transmission routing efficiency from the network layer of the near-lunar space system is established to improve the transmission interaction efficiency of the entire heterogeneous network.

This paper is arranged as follows: Section 2 provides a hybrid link resource prediction and scheduling model for heterogeneous networks; Section 3 provides a routing scheduling algorithm based on the model in Section 2; Section 4 describes the experiments and comparisons conducted in this study. Section 5 summarizes the entire text.

2. Hybrid Link Resource Prediction and Scheduling Model

2.1. Problem Description

The interaction of information in the space near the Moon is shown in Figure 2. The communication network system is composed of three parts: the lunar surface network, the relay network, and the Earth–Moon network. In the future, there will be several types of users in the space near the Moon: lunar landers, inspectors, scientific research stations, astronauts, circumlunar satellites, lunar space stations, relay satellites, translational point navigation satellites, lunar surface base stations, etc. The task requirements for information transmission in the entire near-lunar space network include remote control, telemetry, data transmission, voice, video, navigation, and other data. Remote control commands and key telemetry are real-time tasks, while others are delay-tolerant services. For the various nodes and corresponding communication types in Figure 2, this article studies how to reasonably achieve the minimum data routing transmission time under different network conditions, reduce data loss rate, and improve the resource utilization of the entire network.

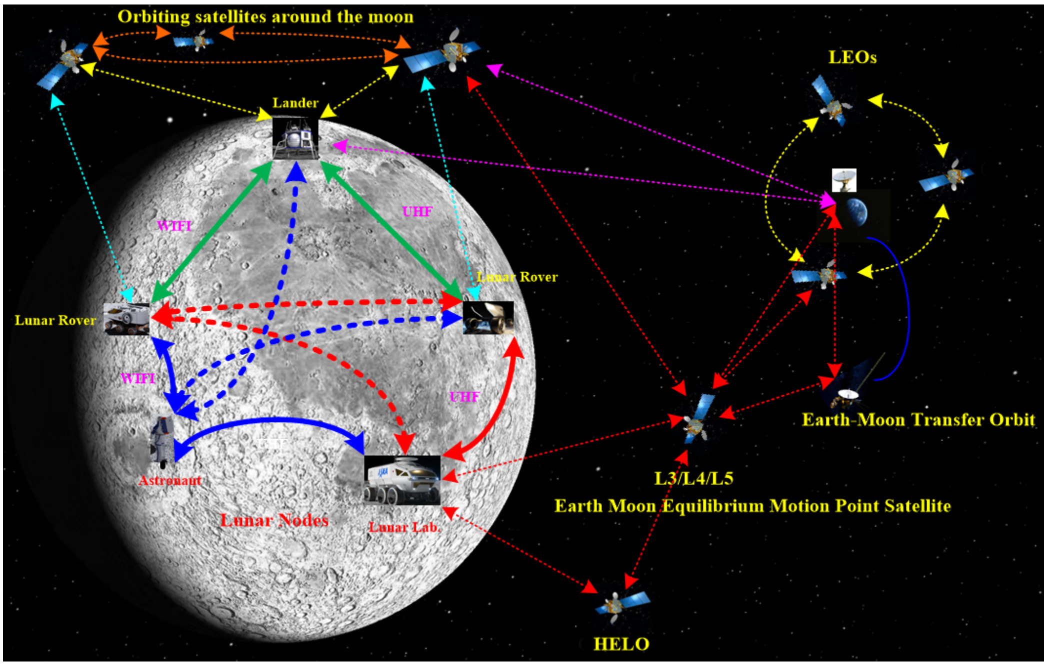

Figure 2. Schematic diagram of spatial information exchange near the Moon.

With the continuous increase in future lunar surface inspection equipment and near-lunar orbiters, the number of communication nodes will increase accordingly. Relying on relay satellites as the main node to achieve interaction, thus forming a local area self-organized network, is a difficult means of ensuring quantity and bandwidth. At the same time, using a delay tolerance mechanism for relay nodes is the best mechanism for near-lunar space integration network.

This study mainly focuses on the networking routing of cross-domain networks. To simplify the research problem, the following assumptions are made: (1) For a single node, the network domain it belongs to is known, and there is no situation where the node changes its network domain during operation; (2) Regardless of the physical layer channel switching and chain-building process time, the duration of data collection and transmission is equivalent to the shortened time window for chain building; (3) Not distinguishing between static and dynamic routing transmission, modeling the data transmission of the link mainly focuses on the on/off time window and transmission rate. Communication resources, including power supply and storage information, are considered to meet application requirements (negligible compared to whole satellite control and propulsion); (4) The orbit change process and abnormal area shutdown are not considered, only whether the orbits of each satellite node block the communication chain; (5) For the communication relay channel and rate limit of the relay satellite, it is equivalent to the established chain time window and communication rate limit.

Therefore, when routing and transmitting data in the entire near-lunar space network, the following must be considered: (1) A unified communication model, interaction protocol, and fault mechanism for heterogeneous networks must be designed; (2) For different networks, they can be designed from a network domain and divided into a secondary network as a whole, with transit satellites as intermediate interaction nodes; (3) When a node requests a data transmission task, it submits the data volume, priority, duration, earliest and latest start times of the task, as well as the minimum amount of data that can represent the completion of the task.

2.2. Communication Networking Model

In this design, we consider that all communication nodes are equal and propose a communication data transmission method based on probability, as well as an optimal routing search method based on this model. The notations and definitions are listed in Abbreviations. The entire networking system is divided into four communication domains, namely, the lunar node domain U_m, circumlunar node domain U_a, near-Earth node domain U_e, and Earth–Moon transfer node domain U_t, with $U = \{U_a, U_e, U_t, U_m\}$. The system contains $M = M_m + M_a + M_e + M_t$ satellites, where M_m, M_a, M_e and M_t represent the number of communication nodes in different domains.

The near-Earth node domain U_e, circumlunar node domain U_a, and Earth–Moon transfer node domain U_t maintain relatively stable movement, which could be modeled as the two clusters of fixed topology sub-networks $T_{e,i}(i \in [0, Q_{e,i} - 1], i \in Z^+)$, $T_{a,j}(j \in [0, Q_{a,j} - 1], j \in Z^+)$, and $T_{s,k}(k \in [0, Q_{t,k} - 1], k \in Z^+)$, where $\sum Q_{e,i} = M_e$, $\sum Q_{a,j} = M_a$, $\sum Q_{t,k} = M_t$, and Q represents the node number of a single network. Then, the fixed topology sub-network group can be denoted as $T_F = \{\vec{T}_e, \vec{T}_a, \vec{T}_s\} = \{T_{e,i}, T_{a,j}, T_{s,k}\}$, in which the data transfer in the three domains depends on the scheduled routing principle, and the inter-data transfer of domains relies on the fixed relay nodes.

It is difficult to maintain a fixed relative position in lunar node domain U_m for a long time, and it belongs to the time-varying topology structure $T_{m,p}(p \in [0, Q_{m,p} - 1], p \in Z^+)$. Therefore, the time-varying topological sub-network set is labeled as $T_V = \{\vec{T}_m\} = \{T_{m,p}\}$. The interaction between the time-varying topology structure and the fixed topology sub-network set also requires interaction through fixed relay communication nodes, which may not be a single node.

It is necessary to clarify the data path relationship between two clusters. The communication interaction between two different sub-networks $\vec{T}_i$ and $\vec{T}_j$ is denoted as $I_{(\vec{T}_i, \vec{T}_j)}$. At any time t, the sub-network interaction communication relationship is as follows:

$$I_{(\vec{T}_i, \vec{T}_j)}(t) = \bigcup C_{(q_0, q_1, q_0', q_1')}(t) \tag{1}$$

where $q_0, q_1 \in \vec{T}_i, q_0', q_1' \in \vec{T}_j$. $\cup$ represents the aggregation operation, and the communication channel between any two links is $C_{(q_0, q_1, q_0', q_1')}(t)$. The communication rate function is $f(q_0, q_1, q_0', q_1', t)$, which represents the communication rate between the q_1-th channel $(n \in [0, N_m - 1])$ of the q_0-th node and the $q_1{}'$-th channel of the $q_0{}'$-th node at time t, where $q_0 \neq q_0{}'$.

The complete description of the optimal communication topology architecture for cross-domain networks is as follows: There is data interaction and communication between each node domain, and the total communication efficiency E_C is proportional to the reciprocal of the communication rate variance ξ / δ_f between each node. The input output balance of communication rate is guaranteed by a single node and planned in advance, where ξ represents the efficiency coefficient and δ_f represents the communication rate variance of each node:

$$\delta_f = \mathrm{var}\{f(q_\psi, q_v, q_\psi{}', q_v{}', t)\}, \psi \in [0, 2, \cdots, 10], v \in [1, 3, \cdots, 11] \tag{2}$$

Therefore, under the optimal communication topology architecture conditions, it is hoped that each node will achieve a rate balance as much as possible to reduce the additional increase in individual node power and storage costs caused by rate differences. From a model perspective, it is required to search for the topology architecture when E_C

is the maximum in the communicable node architecture. In addition, it is also necessary to ensure that at any time, at least one pair of node channels in the four communication domains can connect for communication and interaction, as shown below.

$$\begin{cases} I_{(T_{e,i},T_{a,j})}(t) = \bigcup C_{(q_0,q_1,q_0{}',q_1{}')}(t), q_0, q_1 \in T_{e,i}, q_0{}', q_1{}' \in T_{a,j} \\ I_{(T_{e,i},T_{s,k})}(t) = \bigcup C_{(q_2,q_3,q_2{}',q_3{}')}(t), q_2, q_3 \in T_{e,i}, q_2{}', q_3{}' \in T_{s,k} \\ I_{(T_{e,i},T_{m,p})}(t) = \bigcup C_{(q_4,q_5,q_4{}',q_5{}')}(t), q_4, q_5 \in T_{e,i}, q_4{}', q_5{}' \in T_{m,p} \\ I_{(T_{a,j},T_{s,k})}(t) = \bigcup C_{(q_6,q_7,q_6{}',q_7{}')}(t), q_6, q_7 \in T_{a,j}, q_6{}', q_7{}' \in T_{s,k} \\ I_{(T_{a,j},T_{m,p})}(t) = \bigcup C_{(q_8,q_9,q_8{}',q_9{}')}(t), q_8, q_9 \in T_{a,j}, q_8{}', q_9{}' \in T_{m,p} \\ I_{(T_{s,k},T_{m,p})}(t) = \bigcup C_{(q_{10},q_{11},q_10{}',q_11{}')}(t), q_10, q_{11} \in T_{s,k}, q_10{}', q_11{}' \in T_{m,p} \\ \forall q_\psi \forall q_v, C_{(q_\psi,q_v,q_\psi{}',q_v{}')}(t) = C_{(q_{\psi+\lambda},q_{v+\lambda},q_{\psi+\lambda}{}',q_{v+\lambda}{}')}(t), \lambda \in [2,4\cdots,10] \\ \max\{E_C\} \end{cases} \quad (3)$$

3. Routing Scheduling Algorithm

3.1. Sub-Network Clustering

After filtering out available communication nodes according to Formula (3), there are still many remaining nodes, and direct routing processing may cause calculation delay. Meanwhile, due to the large number of nodes, the search strategy can only focus on local optimization, and the resulting routing results may not necessarily be the optimal choice. Sub-network clustering mainly divides effective nodes into sub-networks based on predetermined clustering rules. In this design, it is mainly divided into two types of sub-network clustering: the fixed topology sub-network set T_F and time-varying topology sub-network set T_V. In the clustering process, T_V only needs to consider limiting the distance so that the closer nodes are networked according to the principle of proximity, while T_F needs to consider factors such as the occlusion of the Earth and Moon, as well as the rate attenuation caused by distance.

3.1.1. Time-Varying Topology Sub-Network Set Sub-Network Clustering

For any node to search with a physical distance D_{sub} as the radius, it is necessary to ensure that the current network topology remains unchanged for a certain period of time Δ. Therefore, it is necessary to search at the current time and two time points after time Δ. The target is considered to move at a uniform speed within time Δ, so position prediction can be performed based on simple kinematics. If some nodes have moved within the time frame, it is necessary to continue checking whether they belong to the sub-network at the new location. If the two searches do not belong to the same network, the sub-network home search continues for the location after time 2Δ.

The clustering process of time-varying topology sub-networks is as follows:

Step 1: Sub-network tables G_w, $w \in Z^+$, with $G_w \in U_m$ are constructed, representing a set of multiple communicable neighboring nodes. Taking node S(0) as an example ($S(j) \in G_w, j \in Z^+$), if $d(0, j) \leq D_{sub}$ exists, where j represents any one of the communicable nodes, then $S(0) \in G_0$;

Step 2: If the distance between nodes S(1) and S(0) is $d(0, 1) \leq D_{sub}$, then $S(1) \in G_0$. If S(1) and nodes other than S(0) have $d(1, j) \leq D_{sub}$ and $j \neq 0$, then $S(1) \in G_1$;

Step 3: The same operation is performed on node S(2) until all current nodes are traversed;

Step 4: Based on the positions $x + v_x\Delta$ and $y + y_x\Delta$ of node S(0) after time Δ, the coordinate attributes of the new position can be calculated according to uniform motion. Steps 1 to 3 are repeated for the updated node;

Step 5: The same operation as step 4 is performed based on the node location after time 2Δ. The sub-network belonging to three time points operates in a two-out-of-three mode. Nodes belonging to different sub-networks three times operate according to the last node to which they belong.

3.1.2. Fixed Topology Sub-Network Set and Sub-Network Clustering

For fixed topology sub-networks, the link state routing method is used to achieve rapid deployment of data transmission. Considering that the fixed topology described here is actually relatively fixed at a finite time scale, the method of sub-network clustering and partitioning as nodes approach the link transmission state can obtain a uniform sub-network partitioning structure under fixed topology conditions, forming flexible communication under different application requirements.

In the sub-network search process, similar to Equation (2), the criterion is that the communication rate variance of each node in sub-network $G_w{}'$ ($w \in Z^+$) is less than a certain threshold Ω, and the calculation starts from the initial fixed node neighboring nodes to the distant nodes gradually until the threshold is met.

The clustering process of fixed topology sub-networks is as follows:

Step 1: Sub-network tables $G_w{}'$, $w \in Z^+$ are constructed with $G_w{}' \in \{U_a, U_e, U_t\}$, and node $S'(0)$ is taken as an example to define $S'(i) \in G_w{}'$, $i \in Z^+$, $i \neq 0$, which is a neighboring node. Then, for node 0 of the $G_w{}'$ sub-network at time t, the communication rate variance $\delta_{f,G_w{}'}(0,t) = \text{var}\{f(q_0, q_i, q_0{}', q_i{}', t)\}$ is determined;

Step 2: It is determined whether $\delta_{f,G_w{}'}(0,t)$ exceeds the threshold Ω. If it does, the variable i in step 1 is expanded. After the expansion, the selection range of i is expanded to the neighboring nodes of node 0, and then the process skips to step 1 for calculation. If it does not exceed the threshold, it indicates that the neighboring node of node 0 is the minimum envelope of the sub-network combination. Other nodes are selected to search for the next sub-network, and the process proceeds to step 3;

Step 3: The sub-network table $G_w{}'$ is updated, one node from the remaining nodes is randomly selected, and the process skips to step 1 for the next sub-network search until all nodes belong to a certain sub-network.

3.2. Hierarchical Domain Value Routing Search

In cross-domain hybrid topology networks, due to the high complexity of the overall architecture and the constantly changing local areas, there is great uncertainty in prediction. At the same time, routing search increases rapidly with the increase in the number of nodes and communication loads. This section presents a hierarchical routing search method for cross-domain networks. Based on the predicted communication rate between nodes, a hierarchical search strategy is designed. Compared to the traditional pre-planned search method used in fixed topology sub-networks to obtain the local optimal path, and combined with the random search method used in time-varying topology structures to obtain the optimal path between fixed topology sub-networks, this paper presents a unified search architecture.

The routing search process is mainly divided into the following 5 steps:

Step 1: The routing purpose is to transmit the communication payload $q_{v,start}$ from node $q_{\psi,start}$ to node $q_{\psi,end}$ through node $q_{v,end}$, with a maximum routing delay time constraint of $\Delta_{\max}$ and a maximum number of routing hops constraint of $\Phi_{\max}$, a minimum communication rate of $F_{\min}$ during link transmission, a task start time of t_{start}, and a task end time of $t_{end} = t_{start} + \Delta$ ($\Delta \leq \Delta_{\max}$);

Step 2: The sub-network table of node $q_{\psi,start}$ is determined as G''_{start}, where $G'' \in \{G_w, G_w{}'\}$ determines that the sub-network of node $q_{\psi,end}$ is G''_{end}, and the communication interaction between the sub-networks is marked as $I_{(G''_{start}, G''_{end})}(t)$. The optimal path within the sub-network can be obtained by looking up the table;

Step 3: A search for sub-networks G''_{start} and G''_{end} within time $t_{valid} \subseteq [t_{start}, t_{end}]$ is conducted based on node orbit/path prediction results, and a set of sub-networks that can be linked is established. A search for each sub-network in the obtained set of sub-networks is carried out again for the set of sub-networks that can be linked within time $t_{valid} \in [t_{start}, t_{end}]$, and the two search results are merged until no new sub-networks are added. At this point, the set of sub-networks that can be linked within the marked task cycle is $\vec{G}''_{mid} = \{G''_{mid\_0}, G''_{mid\_1}, \cdots, G''_{mid\_V-1}\}$, so the set of valid linked sub-networks

$\vec{G}''_{valid} = \{G''_{start}, \vec{G}''_{mid}, G''_{end}\} \subseteq \vec{G}''_i$ within a single task corresponds to the effective search time $t_{valid} \subseteq [t_{start}, \vec{t}_{mid}, t_{end}]$;

Step 4: A set of related routing sequences is randomly selected, that is, the routing sequence $\vec{I}_{(G''_{k(u)}, G''_{j(u)})}(t)$ satisfies $k(u), j(u) \in \{start, mid\_0, mid\_1, \cdots, mid\_V-1, end\}$, and number of hops $u \leq \Phi_{\max}$ and $G''_{j(u-1)} = G''_{k(u)}$, $G''_{k(0)} = G''_{start}$, $G''_{j(V-1)} = G''_{end}$.

Step 5: The maximum routing delay that must meet the following is defined

$$\sum_{U}\sum_{G''}\sum_{t''} Data(q_\psi, q_v{}', t_{mid\_v}) / f(q_\psi, q_v, q_\psi{}', q_v{}', t'') \leq \Delta_{\max} \quad (4)$$

where $Data(q_\psi, q_v{}', t_{mid\_v})$ represents the amount of data that needs to be transmitted in time window t_{mid_v} for load q_v at node q_ψ, and $t'' \in [t_{old\_s}, t_{old\_e}]$, $t_{old\_e} \leq t_{mid\_v}$; if it does not meet the requirements, the process returns to step 4.

4. Simulation and Verification

Based on the hybrid link resource prediction and scheduling model in Section 2, the routing scheduling algorithm was constructed, as outlined in Section 3. To verify the effectiveness of the routing scheduling algorithm, this study conducted simulation validation by constructing a communication node motion model within the cross-domain region of adjacent lunar space. A total of 108 related nodes are planned according to the possible future constellations, research stations, and mobile devices between the Earth and the Moon. Among them, three sub-networks are arranged for low-Earth-orbit satellites, each of which includes 12 satellites for alternate transmission between the Earth and the Moon. Four sub-networks are arranged for the Earth–Moon transfer orbit, each of which includes two aircraft for long-term round-trip interaction between the Earth–Moon transfer orbit. Two sub-networks are arranged in the vicinity of the Moon, with a translational point network consisting of 12 spacecraft and a lunar orbit consisting of 12 spacecraft. There are two sub-networks arranged in the lunar region, namely, the Antarctic scientific research area network consisting of 20 nodes and the equatorial exploration scientific research area network consisting of 20 nodes.

A single near-Earth satellite has 1–4 communication payloads, with a communication rate range of 4 Kbps to 10 Gbps for each payload. A single lunar transfer orbiter has 1–2 communication payloads, with a communication rate range of 1 Kbps to 10 Mbps for each payload. The spacecraft in the vicinity of the Moon has 1–2 communication payloads, with a single payload communication rate range of 1 Kbps to 1 Mbps. The nodes in the lunar region have 1–4 communication payloads, with a single payload communication rate range of 4 Kbps to 20 Mbps. On this basis, a cross-domain node transmission model was constructed to obtain data such as the periodic motion trajectory, position distance, and time window of each node. At the same time, a network model of the time-varying communication system caused by lunar surface inspection tasks was also considered.

In order to verify the overall performance of the algorithm in responding to different routing requirements, a route application of 10^5 orders of magnitude was randomly input within the routing delay time for simulation verification testing. The maximum routing delay time was constrained to $\Delta_{\max}$, the maximum routing hops to $\Phi_{\max}$, and the minimum communication rate during link transmission to $F_{\min}$ as input parameters. Different parameters for simulation verification were selected and compared with the software-defined networking-based wireless sensor networks (SDN-WSNs) [27], the discrete firework algorithm (DFWA) [28], and the on-orbit real-time planning technology (ORPT) [38] for link stability, link load, and routing delay. The routing delay is represented by the average service delay of a single node, while the formulas for link stability and link load are shown below:

$$L_s = \frac{T_v}{T_a} \tag{5}$$

$$L_l = \frac{R_t}{B_t} \tag{6}$$

where L_s represents link stability, T_v is the link visibility time, and T_a is the total simulation analysis time. L_l represents link load, where R_t is the actual data transmission rate, and B_t is the total link bandwidth.

4.1. Link Stability Comparison

Figure 3 shows the comparison of link stability between this design and other literature methods under the same routing requirements of $\Delta_{\max} \leq 30$ s, $\Phi_{\max} \leq 10$ hops, and $F_{\min} \geq 1$ *Kbps*. It can be seen that due to the unified consideration of communication optimization under mixed topology conditions, the stability of this design does not sharply decrease when the routing request is larger than 10^5 compared to other algorithms. This is mainly because the comparative ORPT only considers the unified search of communication node routing and does not separately consider local areas under different rate and topology conditions, resulting in the routing process often being directly ignored when a node's speed is low, ignoring the time delay caused by multiple jumps that may be required for other transmission paths; the DFWA, on the other hand, excessively focuses on minimizing data loss rather than considering the highest overall network transmission efficiency, resulting in a sharp decrease in stability when routing requests are large. At the same time, its minimum loss rate strategy results in difficulty in convergence of the search process and recovery of interrupted networks when topology changes. Therefore, the overall performance of cross-domain network communication applications in near-lunar space is limited; the SDN-WSN constrains the transmission strategy based on service quality indicators, making it difficult to transmit low-quality critical information when the number of applications is large, resulting in a decrease in the stability of data transmission throughout the entire network.

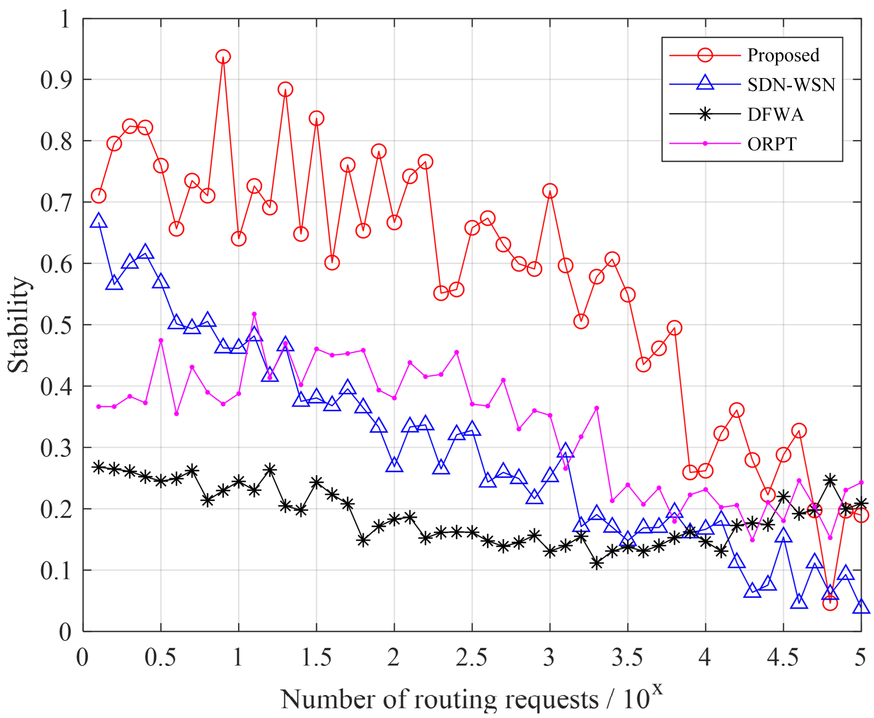

Figure 3. Comparison of link stability with different route application times.

Figure 4 shows the average stability of our algorithm for the same number of routing applications (105 times) and different maximum routing delay times (5–30 s). It can be seen that our design is superior to other methods in the literature. When the delay time is relaxed to 30 s, the link stability approaches 0.8; when the link stability drops sharply below 7 s, it is difficult to satisfy in orbit applications like other methods, indicating that effective routing is difficult to complete under strict routing delay time constraints. Compared with this design, the SDN-WSN has a certain degree of monotonicity in terms of stability and time delay, as it adopts a strategy based on quality of service, which tends to improve communication service quality when delay time constraints increase. The DFWA adopts a minimum data loss strategy, which leads to an increase in the number of information routes as the routing time delay increases, exceeding the maximum hop limit and resulting in routing functionality failure. The ORPT conducts a unified, exhaustive search because it barely considers the characteristics of different domains, and its stability is not significantly related to the routing delay time constraint.

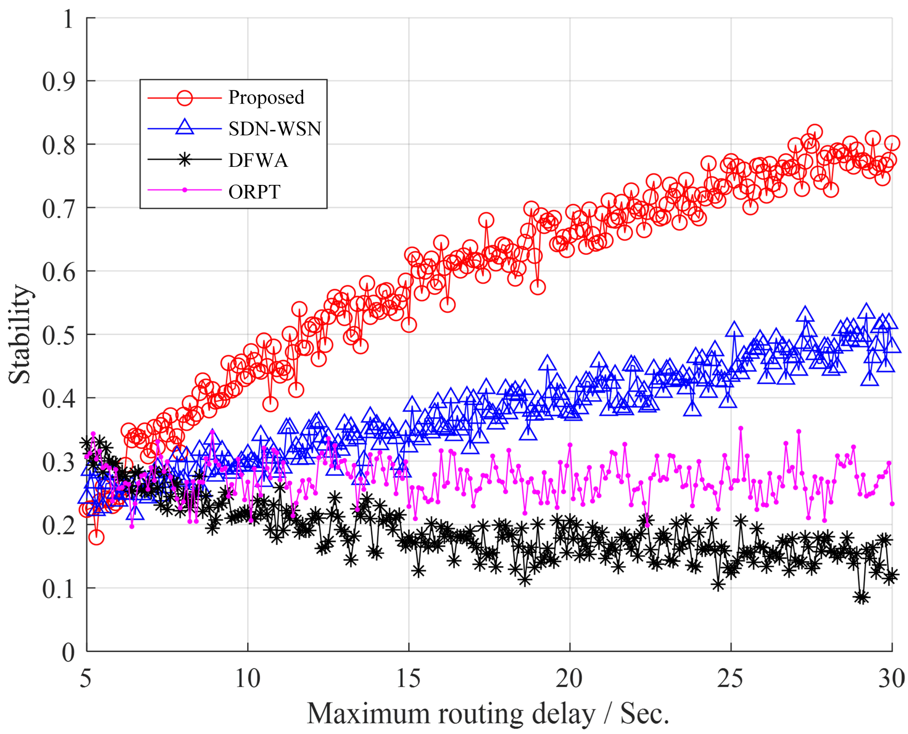

Figure 4. Link stability corresponding to different maximum route delay times with fixed route application times.

4.2. Link Load Comparison

Figure 5 shows the comparison of link load between the relevant literature and this design in cross-domain networks with the same routing request requirements. Due to the fact that this algorithm simultaneously establishes the adaptability of time-varying and fixed type networks, it has more flexible routing links and path planning compared to previous literature methods, with the minimum average load degree of around 0.4, which is reduced by 31% compared to the literature methods. In order to ensure communication quality, the design of the SDN-WSN continuously increases the load as the number of applications increases; the DFWA chooses a more conservative routing strategy to reduce data loss, which makes it difficult to reduce load. Due to the use of exhaustive search method in the ORPT, the load degree presents a random state with different subnets, with weak regularity.

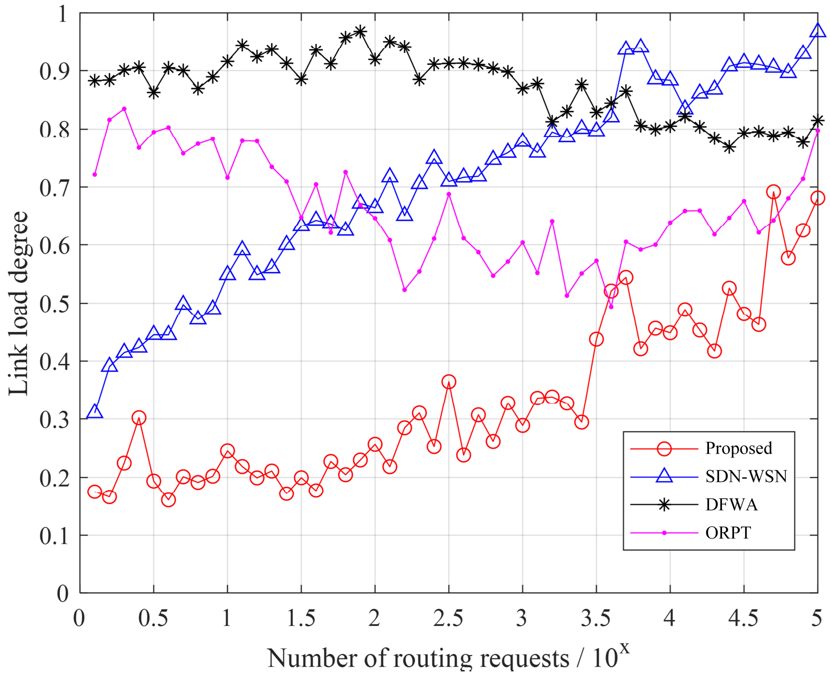

Figure 5. Comparison of link load for different route application times.

4.3. Comparison of Routing Time Delay

Figure 6 shows the average service delay of several algorithms for a single node in typical communication environments and routing task objectives in each sub-network. With different routing application times, the average delay of the cross-domain network based on this algorithm is 0.46 s, while other algorithms are above 0.5 s, reducing the average service delay by 8%. It can be seen that when the number of routing applications is exceeded, the average maximum communication delay in the ORPT is smaller than the algorithm in this paper. This is because the routing blocking delay reduces the routing efficiency improvement caused by different network strategies when there are more applications.

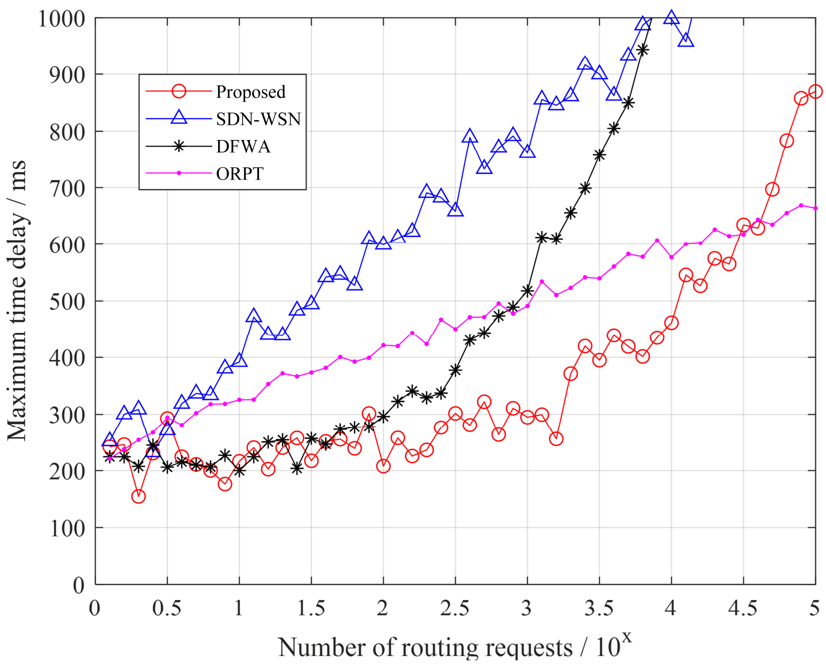

Figure 6. Maximum service time delay for different routing application times.

4.4. Discussion

This paper proposes a routing method for cross-domain network transmission in near-lunar space, addressing the constraints of heterogeneous networks in Earth–Moon communication, lunar surface operations, and relay transmissions. The method involves searching for and establishing transmission routes from the network layer of the near-lunar space system, thereby enhancing the overall efficiency of data exchange across the heterogeneous network. By tackling the unique challenges of lunar-space communication—such as heterogeneous networks, varying transmission speeds, and delays—this method effectively improves data exchange efficiency. Simulation results demonstrate its capability to increase link load by 31% and reduce average latency by 8%, indicating its feasibility for real-world deployment. Furthermore, the integration of relay satellite constraints and adaptive routing suggests that this approach is well-suited for near-lunar space missions.

In terms of practical applicability, the adaptive routing model offers significant advantages for upcoming lunar missions that require efficient and reliable communication systems, particularly for scientific tasks involving data relay from lunar rovers, landers, and space stations. The model's flexibility in handling dynamic and fixed topologies suggests that it could be employed in a variety of space environments. Overall, this work provides a solid foundation for developing advanced networking technologies in extraterrestrial settings, potentially contributing to future lunar exploration and infrastructure development.

5. Conclusions

The proposed cross-domain network transmission routing method for near-lunar space fully considers the various limitations and characteristics of heterogeneous networks such as the lunar surface, lunar surface, and relay transmission, and establishes a comprehensive hybrid link resource prediction and scheduling model. In order to simplify the research problem, we focus on cross-domain network networking and routing. From the perspective of the near-lunar space system network level, we designed time-varying and fixed topology network subnet clustering methods to reduce the complexity of routing algorithms. Combined with hierarchical routing search, an effective routing scheduling algorithm is proposed. During the experiment and comparison process, attention was paid to the performance of link stability, service latency, and other aspects. The experimental results indicate that our proposed method has significant advantages in solving the problem of cross-domain network transmission in space near the Moon. The link load rate was increased by 31% compared to previous design methods, and the average service delay was reduced by 8%. The link stability and load rate were greatly improved compared to previous designs. In addition, a compromise was made for the communication relay channel and rate limit of the relay satellite, taking into account the established chain time window and communication rate limit. Through simulation verification, the designed method can effectively address these challenges and achieve more efficient network transmission. The method proposed in this article has certain innovation and practicality in the field of cross-domain network transmission in near-lunar space, providing an effective solution for improving the transmission interaction efficiency of the entire heterogeneous network.

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Abbreviations

The following abbreviations are used in this manuscript:

Notation	Definition
a	The circumlunar domain
e	The near-Earth domain
m	The lunar surface domain
t	The Earth–Moon transfer domain
U	The communication nodal domain
M	Number of communication nodes
U_i	The communication nodal domain of $i, i \in m, a, e, t$
M_i	Number of domain i's communication nodes, $i \in m, a, e, t$
$T_{d,n}$	The topological sub-network of domain $d, d \in m, a, e, t, n \in [0, Q_{d,n} - 1], n \in Z^+$
T_F	Set of fixed topological sub-networks
T_V	Set of time-varying topological sub-networks
$I_{(T_i,T_j)}$	Communication interactions between two distinct sub-networks T_i and T_j
C	The communication channel between links
f	The communication rate function
q	The identification number of communication nodes or communication channels
E_C	The communication efficiency
ξ	The efficiency coefficient
D_{sub}	The physical distance of the search radius
G_w	The communication sub-network
δ	The routing delay time
ϕ_{max}	Maximum routing hop count constraint
L_s	The link stability
L_l	The link load

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