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SDSN: Software-defined Space Networking — Architecture and Routing Algorithm

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Abstract

Space networking has captured increasing attentions because of its wide application scenarios. Facing to the technical challenges of space networking including topology alteration, non-realtime condition capture and control, and instable communication and control reliability, this article introduce software-defined networking (SDN) into space networking and proposes software-defined space networking, named SDSN. The architecture and the detailed strategy based routing algorithm are designed. SDSN has three key features: the predeterminate rules, strategy based routing algorithm, and redundant space-ground controlling strategy. These features address the three challenges pointedly. The simulation results confirm the advantages.

Keywords Space network · Satellite network · Software-defined network · Routing algorithm

1 Introduction

Over the past few decades, space networking that consists of a series of spacecrafts such as satellites together with infrastructures on the ground significantly enriches human lives in many domains such as scientific exploration, global communications, global positioning, and other public services [1, 2]. Moreover, space network based Internet of Things (IoTs) are increasingly growing. Therefore, many researchers pay increasing attentions to space networks. Nevertheless, space is now still full of unknown for human beings. To fully explores space around the earth and the outer space, a more efficient, reliable and controllable space network is sorely needed.

Space networking is quite different from wired and wireless networking in several aspects. 1) Topology alteration. Space networking consists of many satellites, other spacecrafts, and terrestrial infrastructures. These spacecrafts maybe move around the earth or other planets. And, even if all of them revolve around the earth, they probably locate at different orbits. In addition to the relative location between spacecrafts and the terrestrial infrastructures, the topology of space networking is continuously altering. 2) Non-realtime condition capture and control. For the distance between any two nodes in the space networks is quite far. This results in inconsistent latency. More important, the continuous altering topology leads to the non-realtime condition capture and control for the network administrator. 3) Instable communication and control reliability. The channel environment of space networking is quite complicated. Thus, the communication reliability of any space link is instable. Further more, it is also difficult to guarantee reliability of the control signalling. Based on the above features of space networking, it is nearly impossible to directly apply wired or wireless network solutions into space network.

Software-defined networking (SDN) is a general solution by separating control function of networks and data process function of networks and introducing a centralized controller to config and program the behaviors of whole network and its devices [3, 4]. SDN is firstly introduced in wired network and supposed to be the key technology of future Internet architecture. Then, many researchers naturally extend SDN to wireless and mobile networking domain [5–7], such as cellular networks [8–10], WiFi net-

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works [11, 12], IoTs [13, 14], *and etc*. SDN simplifies the distributed networking protocol, and improves the flexibility and global optimization effects of space networking. Thus, in recent years, some researchers pay their attentions to introduce SDN into satellite networks and propose several valuable solutions [15–21]. However, to the best of our knowledge, most of the related studies just propose the concept of SDN enabled satellite networks. Simply apply SDN into space network can hardly address the special challenges. Few of them focus on designing the targeted SDN architecture and the studying the detailed routing algorithm based on the SDN architecture facing to the characteristic of space networking such as topology alteration, non-realtime condition capture and control, and instable communication and control reliability.

Directly facing to the characteristic of space networking, this article proposes software-defined space networking solution, named SDSN. We firstly design the SDSN architecture. SDSN possesses three key feature: the predeterminate rules, strategy based routing algorithm, and redundant space-ground controlling strategy in order to address topology alteration, non-realtime condition capture and control, and instable communication and control reliability, respectively. After that, we describes the proposed strategy based routing algorithm in detail, which costs both scant storage resources and communication resources. Simulation results confirm the performance advantages of SDSN.

The contributions of this article can be summarized as follows:

- To the best of our knowledge, this is the first work to propose the SDN based space networking that systematically addresses the unique characteristic of space networking including topology alteration, non-realtime condition capture and control, and instable communication and control reliability.
- To the best of our knowledge, this is also the first work to propose a strategy based routing algorithm for SDN based space network, which costs both scant storage resources and communication resources.
- This article analyzes and lists the open problems and possible research directions of SDN based space network.

The rest of this article is organized as follows. Section 2 analyzes the related work. Section 3 describes the System Model. In Section 4, this article proposes the architecture design of SDSN. After that, Section 5 proposes the strategy based routing algorithm for SDSN. Then, Section 6 evaluates the system performance of SDSN. Section 7 analyzes and lists some possible directions of SDN based space networking. Finally, this articles concludes in Section 8.

2 Related work

2.1 SDN based space networking

Many researchers naturally extend SDN to wireless and mobile networking domain [5, 6], such as cellular networks [8–10], WiFi networks [11, 12], Internet of Things (IoTs) [13, 14], *and etc*. SDN simplifies the distributed networking protocol, and improves the flexibility and global optimization effects of space networking. Thus, in recent years, some researchers pay their attentions to introduce SDN into satellite networks and propose several valuable solutions [15–21]. However, to the best of our knowledge, most of the related studies just propose the concept of SDN enabled satellite networks. Simply apply SDN into space network can hardly address the special challenges. Few of them focus on designing the targeted SDN architecture and the studying the detailed routing algorithm based on the SDN architecture facing to the characteristic of space networking such as topology alteration, non-realtime condition capture and control, and instable communication and control reliability.

2.2 Routing algorithm for space networking

There are various versions of routing algorithms on Space Networking, mainly including the following categories. Virtual Topology Routing (VTR) [22–24] adopts periodicity and predictability of satellite networks to divide the constellation period into several small time segments, i.e., snapshot. in which the routes can be regarded as fixed. So in each snapshot the static routing is calculated. And Virtual Node Route (VNR) [25–27] is the concept of virtual network considering the satellite logical position, and each node in the network is a virtual node, which is served by the nearest satellite (real node). Therefore the VNR strategy can shield the movement of satellites and simplify the computation of routes. Unlike the first two methods, Dynamic Topology Routing (DTR) [28–30] adopts automatic packet addressing. The method is based on real-time satellite network topology for routing calculation. QoS Routing (QoS) [31–33] is a routing algorithm that uses hybrid routing to guarantee QoS. On-Demand Routing (ODR) [34–36] can solve the problem of time-varying topology and link frequent switching in Space Networking based on the idea of wireless ad-hoc network. In addition, for the different altitudes of satellite orbits, many studies have been conducted specifically for Multi-layer Satellite Routing (MSR) [37–39].

Virtual Topology Routing (VTR) typically takes the snapshot concept [22], and Fischer et al. [23] gives its formal description. In snapshots, once any inter-satellite link is temporarily disconnected or reconnected, a different snapshot is formed, in each snapshot the satellite topology is invariable. Recently, Huang and others [24] optimized the snapshot of the GNSS constellation system. Although the overhead of VTR is low and the implementation is simple, due to the large number of discrete topology sequences in the system periodicity, a large amount of storage space is required on the satellite, and these algorithms generally use offline or centralized computing methods, which have poor real-time performance and lack of adaptability to traffic congestions and satellite failures.

The concept of virtual node routing (VNR) was first proposed by Mauger et al. [25]. Later, Lu et al. [26] formalized and optimized the virtual topology based on virtual node strategy. Recently Lu et al. [27] analyzed the complexity of virtual node routing. Although the VNR is uncomplicated, due to the rotation of the earth and the movement of the satellite, each satellite needs to update the topology information of the network. Before the source satellite relays data, it needs to calculate the corresponding destination satellite according to the geographic coordinates of the destination node, which has a higher requirement to satellite onboard processing.

The basic idea of dynamic topology routing (DTR) is an IP-based routing technology. The DTR algorithm for LEO satellite networks was first proposed by Hashimoto et al. [28]. Recently, Wu et al. [29] studied packet-switched routing based on hop-number constraints for non-synchronous orbit satellites. And Zheng et al. [30] studied the DTR algorithm of satellite networks for laser communication. DTR-based algorithms are limited to local information and cannot be optimized globally. DTR performs better than ordinary algorithms under normal network traffic. However, in burst traffic it lacks of traffic balance which is likely to cause link congestion.

QoS-guaranteed hybrid routing is referred to as QoS routing. Chen [31] proposed a QoS-based routing algorithm that considers inter-satellite handover and link handover in LEO satellite networks. The delay jitter and rerouting frequency can be reduced as much as possible while maintaining QoS services. Recently, Muhammad et al. [32] proposed a QoS routing framework for high throughput satellite (HTS) systems using very high frequency (EHF) bands. Li et al. [33] proposed a service quality (QoS) routing framework based on software defined radio. Although these QoS-based algorithms have strong routing adaptability and can guarantee certain routing performance for some specific QoS application scenarios. However QoS routing demands additional on-board computing load, which puts forward higher requirements for on-board computing capacity. Moreover, the flexibility and versatility of these QoS routing are poor.

On-demand routing (ODR) technology is a wireless ad hoc network routing. For the characteristics of topology changes, Papapetrou et al. [34] first introduced the idea of on-demand routing AODV into space network, and proposed Location-assisted on-demand routing (LAOR) for LEO satellite networks. LAOR calls the path discovery process to find the shortest delay path, and updates the failed path according to a certain period for the inter-satellite link switching. Recently, Ji et al. [35] proposed a Hierarchical Low Earth Orbit/Medium Orbit Satellite Network ODR Protocol based on hierarchical star algorithm. Kondrateva et al. [36] proposed a joint ODR optimization method based on linear programming for routing and link scheduling. The ODR can achieve the goal of balancing network traffic to a certain extent, but its routing request area is a local area, which cannot achieve the goal of traffic balance from a global perspective.

The multi-layer satellite routing method (MSR) is a routing algorithm for group management of satellites based on orbital altitude. Akyildiz et al. [37] proposed a routing protocol MLSR for 3-layer LEO/MEO/GEO satellite networks. Liu et al. [38] proposed an improved multi-path MEO and LEO satellite multipath routing algorithm (IMP). Shi et al. [39] proposed a contact graph routing algorithm that uses the contact information between satellites to calculate routes in a multi-layer satellite terrestrial network. Although MSR technology based on the concept of satellite group and group management reduces the computational complexity and the additional load of communication to a certain extent, the main limitation of this topology control strategy is that only the changes of satellite group members are considered. Once the topology of the LEO layer responsible for data transmission changes, the reliability cannot be fully guaranteed.

3 System model

This article focuses on the space networking around the earth. It means we assume all the space aircrafts are on the earth orbits. But, it is worth noting that the key idea of this paper can be easily extended to the deep space networking.

3.1 System elements and locations

Figure 1 depicts the system topology and example scenario of this article. For generality, we assume there are N^O orbits around the earth, that are denoted by $\{o_1, o_2, \cdots, o_{N^O}\}$. The heights of these orbits are denoted by $\{r_1, r_2, \cdots, r_{N^O}\}$. The linear velocity of any orbit $o_i, i = 1, 2, \cdots, N^O$ can be obtained through the law of gravity by

$$v_i = \left(GM/r_i\right)^{1/2}, \tag{1}$$

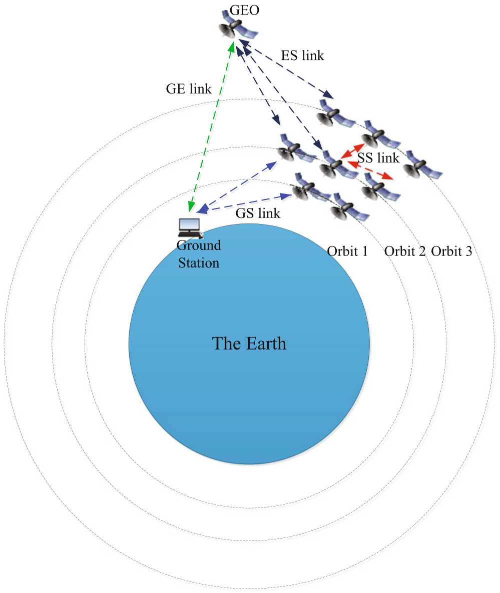


Fig. 1 System topology and example scenario

where G and M indicate the gravitation constant and the mass of the earth. For any orbit $o_i, i = 1, 2, , N^O$, there are N_i^S spacecrafts on it, which are denoted by $\left\{s_1, s_2, \cdots, s_{N_i^S}\right\}$. We assume that the whole system contains N^S spacecrafts. Thus, the total spacecraft number can be obtained by $N^S = \sum_{i=1}^{N^O} N_i^S$.

For any spacecraft s, we can located it by the location vector $\mathbf{v}^s \triangleq \{x^s, y^s, z^s\}$, where x, y and z indicate the latitude, latitude and height of the spacecraft, respectively. In is noting that height means the distance between the orbit and the earth-core.

Of course, ground stations are also a part of our system. We assume there are N^G ground stations that can be denoted by $\{g_1, g_2, \cdots, g_{N^G}\}$, and each of them can be located by $\mathbf{v}^s \triangleq \{x^s, y^s, 0\}$, where x and y indicate the latitude and latitude, respectively. The attribute ”0”inidicates that all the ground station are deployed on the ground whose height is zero.

3.2 Communication links

We assume geosynchronous orbit (GEO) is included in the system. This assumption can be easily extended when GEO is not included. For simplicity, unless otherwise specified, we use the term ”spacecrafts” to denote all the spacecrafts except the ones on the GEO. Then, as shown in Fig. 1, the system possesses four types of communication links: the link between ground station and spacecrafts (GS links), the link between spacecrafts (SS links), the link between GEO spacecrafts and other spacecrafts (ES links), and the link between ground station and GEO spacecrafts (GE links). We highlight that the space networking characterize by the proposed system model can support various of missions and scenarios.

4 Architecture description of SDSN

4.1 SDSN overview

Directly facing to the challenges of space networking including topology alteration, non-realtime condition capture and control, and instable communication and control reliability, we introduce SDN into space networking and propose SDSN architecture. As shown in Fig. 2, the physical elements — ground stations, spacecrafts, and the physical communication links — are almost the same as the system model depicted in Section 3. But, the logical architecture, running strategies, and functions are designed accordin to the SDN paradigm.

Likes wired and wireless SDN, the key concept of SDSN can be summarized as follows:

- C&D separation. SDSN separates control functions from the physical elements.
- Logical control plane. Then, SDSN abstracts a logical control plane who makes the rules and strategies of the whole network.
- Rule-Action and data plane programmability. The control plane makes the rules based on the whole network vision. These rules are sent to the corresponding data plane elements through southbound interface. Each rule requires one or more data plane elements to deploy a series of actions. Since the rules and actions can be configured by the control plane, this rule-action strategy can also be called as data plane programming.
- Control plane configurability. The control plane will provide several open interfaces named northbound interface to the network managers. Managers can configure the whole network according to the special missions and/or scenarios.

4.2 Function description and three features

The control plane takes charge of maintaining the whole network status and arranging and optimizing the rules of the data plane elements. The control plane are embedded

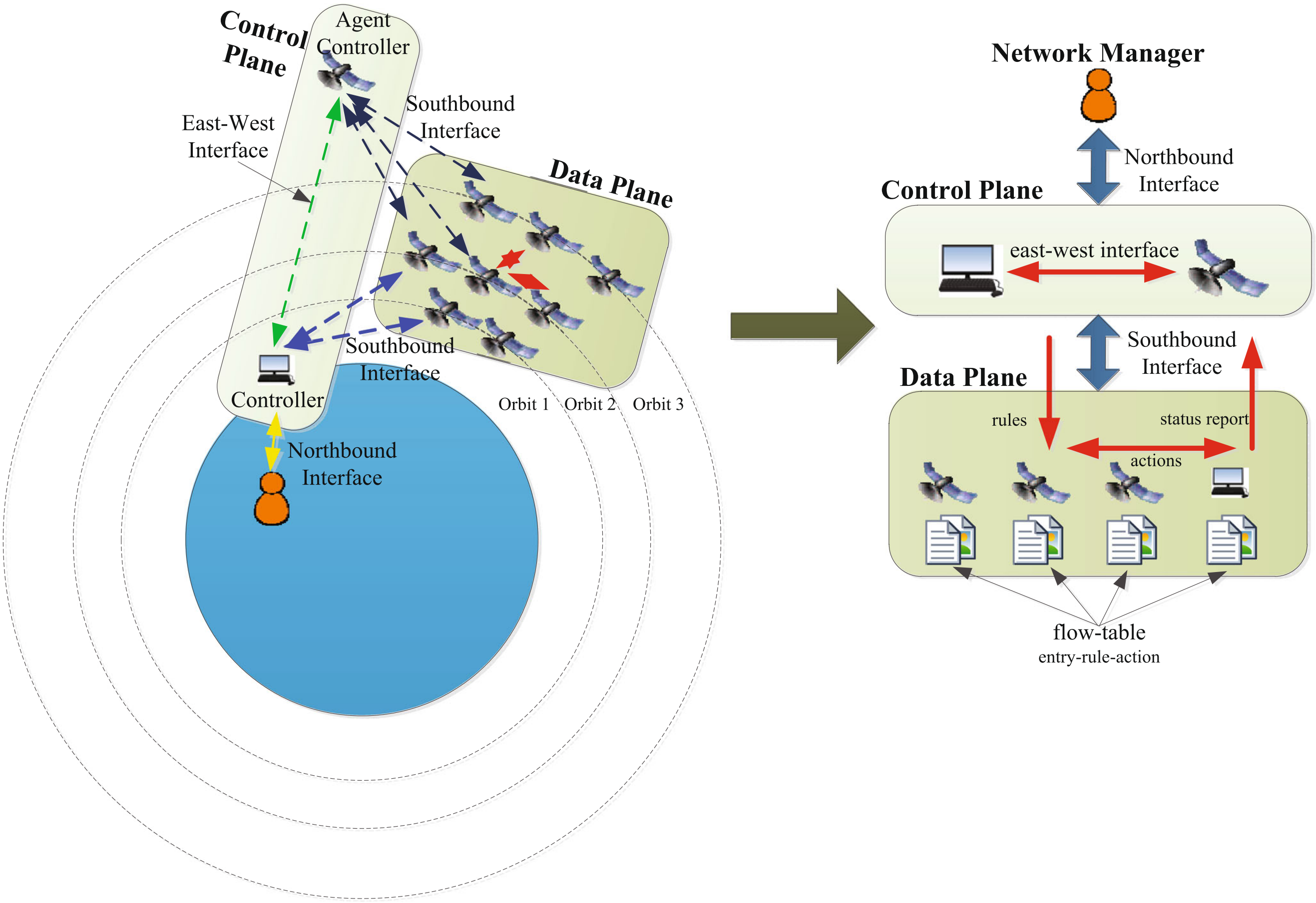


Fig. 2 SDSN architecture

in two types of physical elements: the ground stations and the GEO spacecrafts. We introduce *primary-agent* method to distinguish the control functions of ground stations and GEO spacecrafts. The control functions embedded in the ground stations are named as the primary controller. It means the original rules and actions are made by the ground station. This is because the ground station not only is quite reliable for the network managers, but also always has great resources and fast response features. The control functions embedded in the GEO spacecrafts are the agent-controller. It is obvious that the GEO spacecrafts have quite large coverage. They are always served as the relay of the primary controllers. They are used in the scenarios that the ground stations cannot directly contact the spacecrafts or need to inform them with some urgent rules. The strategy based routing algorithm is deployed in the control plane.

The data plane is embedded in all the physical elements including spacecrafts, ground stations, and GEO spacecrafts. It is worth noting and very important that ground stations and GEO spacecrafts are served as both control plane and data plane because they simultaneously have the functions of SDSN controller and data processing. The data plane elements need to maintain flow-tables. Flow-table is a kind of data structure consisting of a series of items. Each item have a flow entry and an action indication. If one packet matches the flow-entry, it will be processed by way indicated according to the action indication. It is noting that all the flow entries and action indications are preconfigured by the control plane. Moreover, the data plane elements need to report the network status periodically or nonperiodically.

The northbound interface is the interface between control plane and network managers. The control plane needs to abstract and open some useful interfaces to the managers so that they can flexibly configure the network according to the missions and scenarios. But, the northbound interface needs to obtain a tradeoff between flexibility and reliability.

The southbound interface is the interface between controllers and data plane elements. The controllers send rule-action through this interface, while the data plane elements report the network status including the topology varying, traffic changing, and emergency events to the controllers.

The east-west interface is the interface between multiple controllers. Some possible scenarios are illustrated as follows: 1) many ground stations need to communicate with each other to negotiate the control functions, and, 2) the primary controllers want to send rules to the agent controllers and require them relay these rules to data plane elements, 3) the agent controllers want to report some network status to the primary controllers.

SDSN possesses three key features:

The predeterminate rules is proposed in order to address topology alteration problem. The space networking has one special feature that the topology is predictable. But, the controller may not communicate with every data plane element at any time. Thus, the control plane opportunistically sends the rules and actions to the data plane elements, and the rules and actions are predetermined according to the future topologies and traffic requirements.

Strategy based routing algorithm is proposed in order to address the non-realtime condition capture and control problem. The traditional static and fully distributed routing algorithms have both own disadvantages. This article proposes a strategy based routing algorithm, which simultaneously costs the storage resources and the communication resources. This algorithm is described in Section 5.

The redundant space-ground controlling strategy is proposed in order to address the instable communication and control reliability problem. This article introduces redundant space-ground controller to improve the controlling reliability.

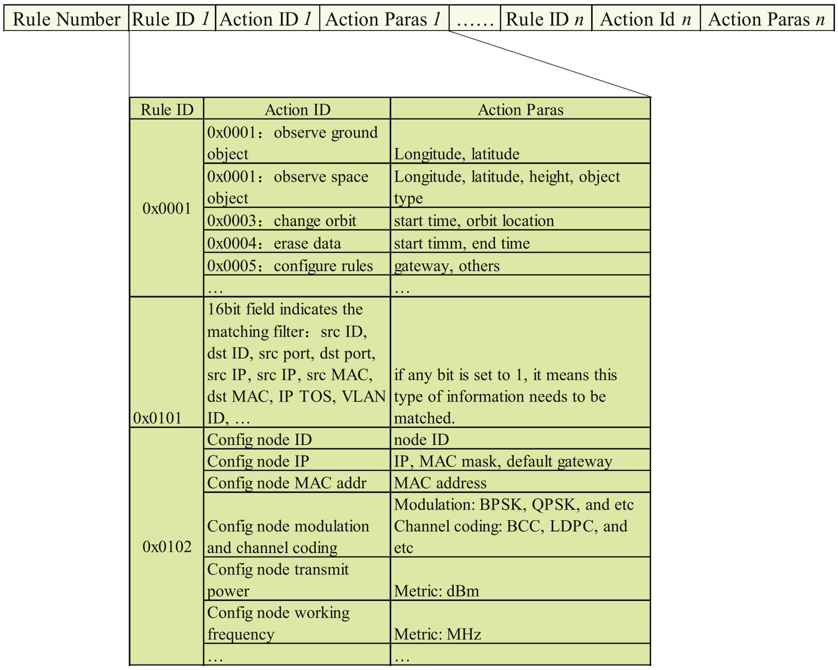
4.3 Rule-action design

One possible rule-action design is shown in Fig. 3. This structure is flexible enough that can be easily extended or add other new rules and actions.

5 Strategy based routing algorithm for SDSN

The traditional static routing algorithms of satellite networks always cost plenty of storage resources. It is increasingly impractical when the missions or scenarios become complicated. So, the scalability and the flexibility are quire limited. On the other hand, the fully distributed routing algorithms of satellite networks require a perfect communication performance. Unfortunately, communication performance

Fig. 3 Rule-action design



Rule Number	Rule ID *1*	Action ID *1*	Action Paras *1*	……	Rule ID *n*	Action Id *n*	Action Paras *n*

Rule ID	Action ID	Action Paras
0x0001	0x0001：observe ground object	Longitude, latitude
	0x0001：observe space object	Longitude, latitude, height, object type
	0x0003：change orbit	start time, orbit location
	0x0004：erase data	start timm, end time
	0x0005：configure rules	gateway, others
	…	…
0x0101	16bit field indicates the matching filter：src ID, dst ID, src port, dst port, src IP, src IP, src MAC, dst MAC, IP TOS, VLAN ID, …	if any bit is set to 1, it means this type of information needs to be matched.
0x0102	Config node ID	node ID
	Config node IP	IP, MAC mask, default gateway
	Config node MAC addr	MAC address
	Config node modulation and channel coding	Modulation: BPSK, QPSK, and etc Channel coding: BCC, LDPC, and etc
	Config node transmit power	Metric: dBm
	Config node working frequency	Metric: MHz
	…	…

is far from perfect for the space networking and this is also one basic constrain for space networking. Therefore, this paper proposes a strategy based routing algorithm for SDSN. The routing algorithm is based on several basic strategies. We highlight that this routing algorithm can be used in both SDN based architecture and distributed architecture. For the later scenario, this algorithm calls for much less communication resources.

Before describing the routing algorithm, the following definitions are first introduced:

$link(A, B) = 1$ represents that there is a direct transmission link between nodes A and B; on the contrary, $link(A, B) = 1$ denotes that there is a no direct transmission link between nodes A and B. Specifically, it is necessary to determine whether there are direct transmission links between A and B according to the distance and the other factors. For instance, it can be considered that a direct transmission link can be determined as long as it can be visually connected. Moreover, a distance threshold can be given, if the threshold is exceeded, it means that the signal cannot be directly communicated; otherwise the signal can be directly communicated. The specific situation needs to be further decided by the user.

Without loss of generality, we assume there are two orbits: a lower orbit and a higher orbit. We assume that the gateway node is in the lower orbit, and the communication direction of cross orbit is from high to low. The proposed satellite network routing algorithms is described in Algorithm 1 and Algorithm 2. Algorithm 1 depicts the routing strategy for higher-orbit nodes, while Algorithm 2 depicts the routing strategy for lower-orbit nodes.

Input:

- N^R high-orbit satellites: $H = H_1, H_2, \cdots, H_{N^H}$
- N^L low-orbit satellites: $L = L_1, L_2, \cdots, L_{N^L}$ which corresponds to nodes, the number of links that can be received at the same time for each node is
  $\{N_1^L, N_2^L, \cdots, N_{N^L}^L\}$.
- The position of all $N^R + N^L$ satellites;
- Downlink node: L^* (only one satellite);
- Number of links that downlink node can receive simultaneously: N^P
- N^R, low-orbit satellites have $\{R_1, R_2, \cdots, R_{N^R}\}$ corresponding satellites as relay nodes for transmitting data between inter-orbit links. If the downlink node is also merged into the relay nodes set, it is recorded as
  $R = \{L^*, R_1, R_2, \cdots, R_{N^R}\} = \{R_0, R_1, R_2, \cdots, R_{N^R}\}$
  The number of links that each corresponding node can receive at the same time is
  $\{N_0^P, N_1^P, N_2^P, \cdots, N_{N^R}^P\}$, where $L^* = R_0$.

Output: route planning results

Algorithm 1 Routing strategy for higher-orbit nodes.

```
Sort $R = \{L^*, R_1, R_2, \cdots, R_{N^R}\} = \{R_0, R_1, R_2, \cdots, R_{N^R}\}$ according to the distance in descending order between the node with gateway nodes, which is denoted by $\{N_0^p, N_1^p, N_2^p, \cdots, N_{N^R}^p\}$. //Give priority to the near-distance node for downlink.
$X = \{X_0, X_1, X_2, \cdots, X_{N^R}\} = \{\phi, \phi, \phi, \cdots, \phi\}$ // indicates whether there is a direct link between the relay-node and the high-orbit node.
$s_{1\times(N^R+1)} = 0$ // indicates whether there is a direct link between the relay-node and the high-orbit node.
$y^H_{1\times(N^H+1)} = 0$ // indicates whether the routing of high-orbit node has been planned.
for all $i = 0, 1, 2, \cdots, N^R$ do
    for all $j = 0, 1, 2, \cdots, N^H$ do
        if $1 = link(H_j, R_i)$ then
            $X_i = X_i \cup H_j$
            $s_i = s_i + 1$
        end if
    end for
end for
$t = \{N_0^p, N_1^p, N_2^p, \cdots, N_{N^R}^p\}$ // Represents the remaining downlink capability of each relay node.
for all $i = 0, 1, 2, \cdots, N^R$ do
    if $s_i \le t_i$ then
        for all $j = 0, 1, 2, \cdots, s_i$ do
            if $0 == y^H_{X_{i,j}}$ then
                $Schedule(X_{i,j}, R_i)$ //Plan a routing for $X_{i,j}$ and $R_i$
                $t_i = t_i - s_i$ //Update $R_i$ remaining capabilities.
                $y^H_{X_{i,j}} = 1$ //The routing of node $X_{i,j}$ has been planned.
            end if
        end for
    else
        $X_{i,j}$ is arranged in descending order according to the transmission rate, which is also arranged in descending order according to interference intensity.
        for all $j = 0, 1, 2, \cdots, t_i$ do
            if $0 == y^H_{X_{i,j}}$ then
                $Schedule(X_{i,j}, R_i)$ //Plan a routing for $X_{i,j}$ and $R_i$
                $t_i = 0$ //Update $R_i$ remaining capabilities.
                $y^H_{X_{i,j}} = 1$ //The routing of node $X_{i,j}$ has been planned.
            end if
        end for
    end if
end for
```

Algorithm 2 Routing strategy for lower-orbit nodes.

```
Sort $L = \{L_1, L_2, \cdots, L_{N^L}\}$ according to the distance in descending order between the node with gateway nodes, which is denoted by $\{N_0^L, N_1^L, N_2^L, \cdots, N_{N^L}^L\}$. //Give priority to the near-distance node for downlink.
$Y = \{Y_0, Y_1, Y_2, \cdots, Y_{N^L}\} = \{\phi, \phi, \phi, \cdots, \phi\}$ //indicates whether there is a direct link between the relay-node and the high-orbit node.
$s_{1\times N^L} = 0$ //represents the number of low-orbit nodes directly connected to each low-orbit node.
$y_{1\times N^L}^L = 0$ //indicates whether the routing of low-orbit node has been planned.
for all $i = 0, 1, 2, \cdots, N^L$ do
    for all $j = 0, 1, 2, \cdots, N^L$ do
        if $1 = link(L_j, L_i)$ then
            $Y_i = Y_i \cup L_j$
            $s_i = s_i + 1$
        end if
    end for
end for
$r = \{N_0^L, N_1^L, N_2^L, \cdots, N_{N^L}^L\}$ //Represents the remaining downlink capability of each low-orbit node.
$t \longrightarrow r$ //Synchronize the remaining downlink capability of relay nodes.
for all $i = 0, 1, 2, \cdots, N^L$ do
    if $s_i \le t_i$ then
        for all $j = 0, 1, 2, \cdots, s^j$ do
            if $0 == y_{Y_{i,j}}^L$ then
                $Schedule(Y_{i,j}, L_i)$ //Plan a routing for $Y_{i,j}$ and $L_i$
                $r_i = r_i - s_i$ //Update $L_i$ remaining capabilities.
                $y_{Y_{i,j}}^L = 1$ //The routing of node $Y_{i,j}$ has been planned.
            end if
        end for
    else
        $Y_i$ is arranged in descending order according to the transmission rate, which is also arranged in descending order according to interference intensity.
        for all $j = 0, 1, 2, \cdots, t_i$ do
            if $0 == y_{Y_{i,j}}^L$ then
                $Schedule(Y_{i,j}, L_i)$ //Plan a routing for $Y_{i,j}$ and $L_i$
                $r_i = 0$ //Update $L_i$ remaining capabilities.
                $y_{Y_{i,j}}^L = 1$ //The routing of node $Y_{i,j}$ has been planned.
            end if
        end for
    end if
end for
Output routing assignment result of $Schedule()$
The node finds from the route assignment result whether this node is both a receiving and a sending one, and marks it.
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In this article, we assume that all the traffic generated by the spacecrafts need to backhaul to the ground stations. The strategies are summarized as follows:

- Rule 1: Inter-orbit link is prior to intra-orbit link.
- Rule 2: It is prior to choose the next hop node who is nearer to the gateway node, where gateway node means the node that can directly communicate with ground stations.
- Rule 3: It is prior to choose the next hop node who possesses the higher speed link.
- Rule 4: It is prior to choose the next hop node who is more conducive to maximizing the resources of the gateway node.
- Rule 5: It is prior to choose the next hop node who leads to the minimal interferences.
- Rule 6: The link is not scheduled in this phase.

6 Performance evaluation

6.1 Simulation settings

The system architecture and routing algorithm of SDSN designed in this paper are simulated. Firstly, the coverage characteristics of the satellite and the observation duration of various orbital altitude satellites are simulated, and then the performance of the routing algorithm is verified.

The simulation time is set to 48 hours. Five satellites and two ground stations were added to the scenarios. The five satellites for earth observation mode adopt semi-conical model with an angle of 45. The basic orbital parameters are shown in table 1:

There are five satellites in Table 1, two of which are in the 800km orbit and three in the 500km orbit, assuming that the satellite A is the downlink satellite. Beijing China is a ground station for receiving downlink data, and Xi'an China is an observation station. The B, C, D, and E satellites transmit the observed observation data to the satellite A through the inter-satellite link, and the satellites A transmits all the aggregated data to the ground station.

only when the angular relationship between the center of the earth, the ground observing station and the satellite reaches a certain condition can the data be generated to simulate the ground observation, that is, when angle 1 is greater than 90 degrees and angle 2 is less than 45 degrees, the observation of Xi'an China will begin. As shown in Fig. 4.

Table 1 Satellites orbit parameters

satellite	Perigee height	Apogee height	Orbital inclination	Perigee angle	Ascending ascension	Ascending angle
A	500 km	500 km	45 deg	0 deg	0 deg	0 deg
B	500 km	500 km	45 deg	0 deg	0 deg	0.5 deg
C	500 km	500 km	45 deg	0 deg	0 deg	-0.5 deg
D	800 km	500 km	45 deg	0 deg	0 deg	0.5 deg
E	800 km	500 km	45 deg	0 deg	0 deg	0 deg

6.2 Simulation results

6.2.1 Coverage observation simulation

Xi'an China earth station is observed by one lower height LEO satellite, one higher height LEO satellite, one lower height LEO satellite plus one higher height LEO satellite, three lower height LEO satellites plus two higher height LEO satellites. Because the proportion of the satellite observation time to the satellite system operation period is very small, the graph representation is not very intuitive. The percentages of the observable duration of Xi'an China Station to the total observation time under the above four conditions are calculated, as shown in Table 2.

The results of Table 2 present:

- The observation duration of five satellites is 3.16 times longer than that of a 500 km height satellite and 1.48 times longer than that of an 800 km height satellite. It shows that satellite networking can improve the observation duration.
- The observation duration of the 800km height satellite is 2.14 times longer than that of the 500km height satellite, which indicates that the higher the satellite altitude is, the more favorable the observation is.
- In the case of "3+2" the observation duration is similar to "1+1" and the performance is only about 8% higher, which indicates that the satellite networking scheme has great potential in dealing with satellite failure.
- Even in the case of five satellites networking, only 1.36% of the whole day can be observed in Xi'an China, indicating that the communication conditions of Delay Tolerance Network (DTN) are indeed quite severe.

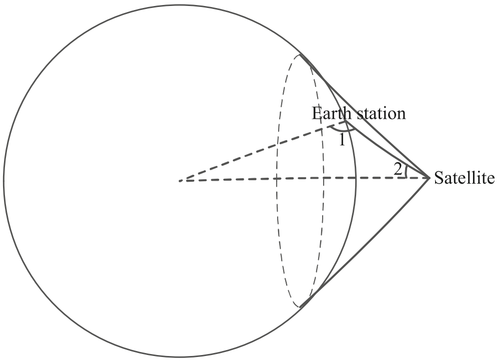


Fig. 4 Conditions for generating data

The following is a simulation of the current coverage of the satellite and the cumulative coverage observation duration. Figure 5 simulates and compares the coverage of the earth in two scenarios of one single satellite A and five satellites. Figure 5 demonstrates that:

- In terms of the current satellite coverage percentage characteristics, the scenario in which a single satellite is not networked is much lower than that in the case of five satellites networking scenario. The current coverage percentage of a single satellite is less than half of the coverage percentage of five satellites networking scenario.
- As far as the cumulative satellite coverage characteristics are concerned, the scenario of single satellites not being networked is slightly lower than that of five satellites. As time goes on, the cumulative percentage coverage of a single satellite can reach 70% of the global surface, while the cumulative percentage coverage of five satellites can reach 80% of the global surface area. The performance is basically due to the difference in satellite height.
- Comparing with lower height satellites, higher height satellites have more advantages in the earth observation duration and coverage characteristics.

6.2.2 Throughput simulations

Next the performance of satellite networking system and its routing algorithm are simulated.

We simulated the durations of different height satellites for observation Xi'an China earth station. As shown in Fig. 6, in which the red curve shows the time variation of 800km height satellites, and the blue curve shows the time variation of 500 km height satellites. The observation duration of the higher height satellite is roughly 2.2 times than that of the lower height satellite. It is proved that the higher the satellite height, the longer the ground observation duration.

Table 2 Observation time comparison

Scenarios	Observation duration (seconds)	Percentage (%)
One lower height LEO satellite	735.583	0.43
One higher height LEO satellite	1581.146	0.92
One lower plus one higher height satellite	2160.661	1.25
Three lower plus two higher height satellite	2350.252	1.36

The transmission and reception of data packets from lower height LEO satellite B is simulated, as shown in Fig. 7. From the upper part of Fig. 7, we find that the cumulative observation duration curve of satellite B increases twice, indicating that Xi'an China is observed twice, and the data can be generated twice; the middle part of Fig. 7 is a statistic of the node itself, indicating the antenna reception. Packet rate, the discovery curve has three peaks, that is, in three time periods, three higher height satellites generate data and send it to lower height satellites; the lowest part of Fig. 7 is also a statistics of the node itself, indicating the antenna transmit data packet rate, the discovery curve has two peaks, that is, in two time periods, This satellite node sends data packets, which coincide with the observation time, indicating that the satellite B is transmitting data packets to satellite A during this period.

The transmission and reception of data packets from higher height LEO satellite B is simulated, as shown in Fig. 8. The upper part of Fig. 8 is the cumulative observation duration of the higher height LEO satellite E. It can be seen that the curve has risen three times, indicating that the satellite E has observed Xi'an China three times and generated data synchronously. The middle part of Fig. 8 is a statistic of the node. The antenna transmits the data packet rate. It finds that there are three peaks, which coincides with the time when satellite E observes Xi'an China. That is to say, after the data is generated, if there is no suitable LEO satellite, it forwards to itself. Because the higher height satellite does not act as a routing relay, the receiving data packet rate of the higher height LEO satellite is not counted.

7 Discussion and open problem of SDSN

This article proposes a general architecture for SDN based space networking, a series of technologies needs to be researched in the near future. The possible open problems and directions are discussed as follows:

1) The consistency problem of flow table.

   The consistency problem of SDSN to guarantee the new rules to be carried out simultaneously. Otherwise, some ambiguities may happen, which further leads to the uncontrollable status. This problem becomes serious in the space networking because the topology of space networking is constantly changing and the propagation time is large. Therefore, it is quite important to study how to guarantee the consistency of flow table.

2) Controller placement problem.

   It is obvious that where to place the controller is quite important since the topology of space networking is constantly changing. In this paper, the GEO satellite

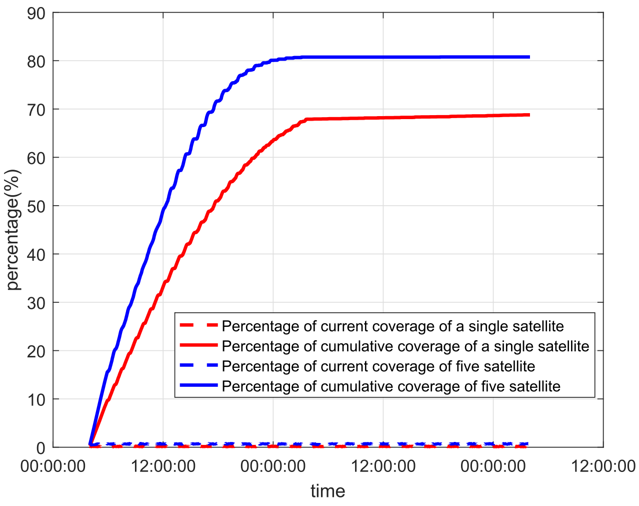


Fig. 5 Coverage comparison of LEO satellite

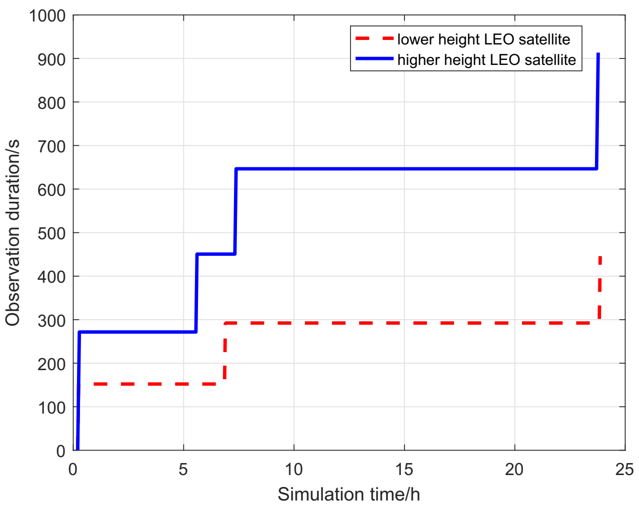
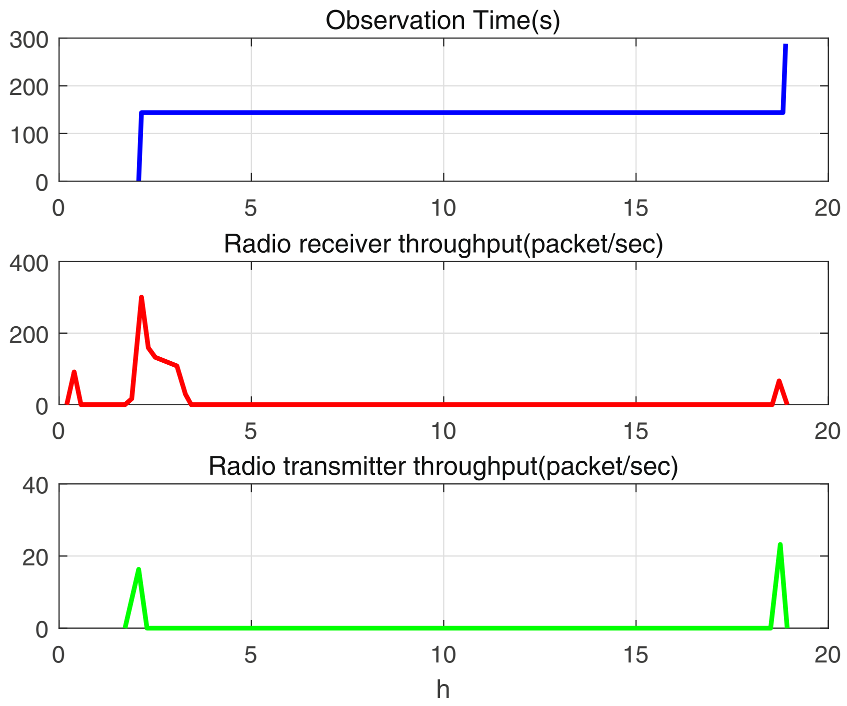


Fig. 6 Observation comparison between lower and higher height LEO satellite

Fig. 7 Throughput comparison of lower height LEO satellite

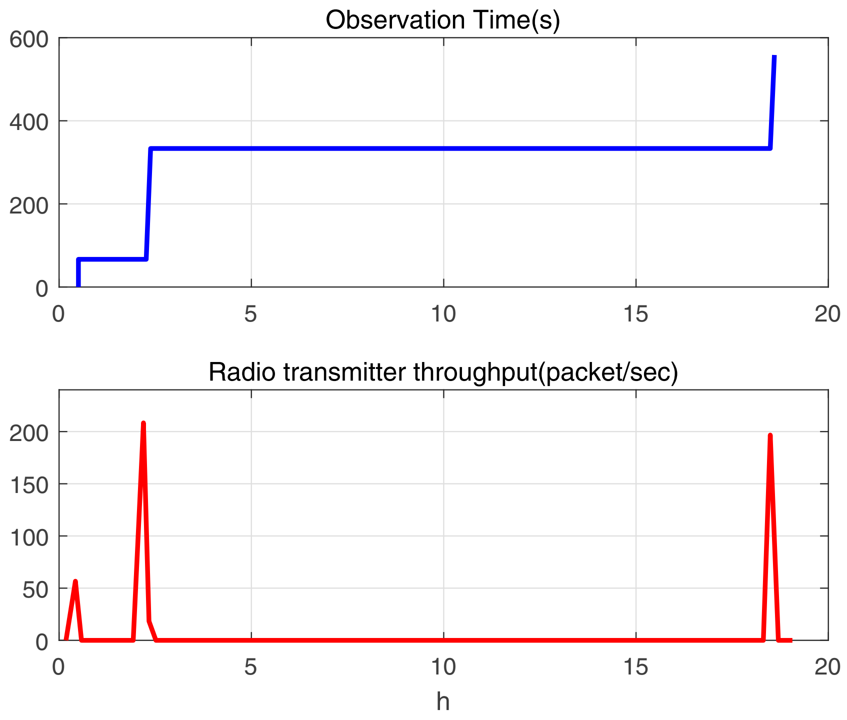


is designed to be the controller. But, in practice, there are not enough GEO satellites to use. So, maybe the medium-earth orbit (MEO) satellites and the LEO satellites are much more flexible and sufficient. In this case, the controller also moves around the earth. Thus, where to place the controller is an optimizing problem to be addressed.

3) Rule-action & data-plane programmability design.

A series of features, parameters, and rules in all the network layers, including higher layer, network layer, MAC layer, and PHY, need to be configured and optimized dynamically. Thus, to enhance the programmability of data-plane is quite important. Firstly, the specific rules

Fig. 8 Throughput comparison of higher height LEO satellite



and actions need to be designed. After that, the inner programmability in each data plane node needs to be designed and implemented.

8 Conclusion

Facing to the technical challenges of space networking including topology alteration, non-realtime condition capture and control, and instable communication and control reliability, this article proposes software-defined space networking, named SDSN, architecture and the detailed strategy based routing algorithm. SDSN has three key features: the predeterminate rules, strategy based routing algorithm, and redundant space-ground controlling strategy. The simulation results confirm the advantages. Future work includes the controller placement solutions and the Rule-action & Flow-table design.

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