# A Dynamic QoS Routing Mechanism for Deep Space Network Based on SDN Architecture

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**Abstract.** Some characteristics of deep space communication network are well known, such as nodes limited resources, long communication delay and nearly no guarantee for the transmission quality, this paper proposes a dynamic QoS routing mechanism for deep space network based on SDN architecture, which uses heuristic algorithm to discover and update the routing paths dynamically. According to the changing of network topology and performance constantly, the algorithm can select the optimal path according to the current real-time network performance state. In case of the characteristics of deep space network, the heuristic algorithm makes a lot of improvements from the global point of view, so that it can be more suitable for deep space network environment. Finally, the paper verified the performance of the algorithm by simulation experiments.

**Keywords:** Deep space communication network · Dynamic routing · Heuristic algorithm

## 1 Introduction

Deep space exploration is an important way for human beings to explore unknown world, along with the implementation of China's lunar exploration project and Mars exploration project. Our country has been in the forefront of the world in the field of deep space exploration, and has gradually established our deep space communication network. Future deep space exploration missions, including follow-up missions of lunar exploration, manned lunar exploration and asteroid exploration, will further expand the scale of China's deep space communication network and the types of space services it carries. It is an important trend of development for the integration of deep space communication network with near-earth satellite network and terrestrial Internet, which is considered by many researchers as an important part of the next generation Internet.

The deep space network is well known for its long delay, asymmetry in uplink and downlink, etc. The network with this characteristic is called DTN (delay tolerant network). The research and construction of the deep space network is still in the preliminary stage. The scale of the network is not very large, with only a small number of nodes, and no higher QoS requirements. At the same time, it is also limited by the computing and storage power of network nodes.

Q. Guo et al. (Eds.): WiSATS 2021, LNICST 410, pp. 257–266, 2022.
https://doi.org/10.1007/978-3-030-93398-2_26

Deep space networks routing often uses static methods or a combination of dynamic and static methods. With the expansion of the deep space network, the types of data increasing sharply. They are not considering the load status of the node, so they may also cause even a sharp drop in the performance of the entire network. [1] In order to alleviate this situation, researchers have tried a variety of solutions. Software-defined network (Software Defined Network, SDN) technology is one of the most promising technologies. It reduces the complexity of the data plane effectively, through the deconsolidation of data plane and control plane, which is easier to realize the centralization of the real-time network status and logic control. In this way, it can achieve more flexible controlling and processing of the network architecture, and applying efficient routing strategies. At present, researchers have carried out a lot of research on routing strategies for satellite networks, and proposed a variety of programs. These schemes use the regularity and periodicity of satellite movement, but most of them only aim at finding shorter paths or maintaining routes by improving flooding methods, without considering the inherent characteristics of deep space network nodes which may lead to routing performance problems. With the enrichment and development of space applications in deep space network, the demand for service quality is also higher and higher.

In order to solve these problems, this paper proposes a dynamic routing mechanism based on SDN Architecture for Deep Space Network (SADR). According to the status of the deep space network QoS guarantee capability, the target node can be found, while avoiding excessive load on nodes and affecting network performance.

## 2 Related Work

Chen et al. [2, 3] proposed the Satellite Grouping and Routing Protocol (SGRP). SGRP is applied to the LEOMEO network structure of double-layer satellites. It uses the relative position relationship between satellites in different orbits. The upper MEO is collecting the link time of the satellites in its group. The routing table is calculated according to the principle of transmitting data packets along the shortest delay path. When a LEO satellite moves to the position belongs to another group, the grouping member information is changing. At the same time, a new snapshot is generated. The topology in each timeslot can be considered unchanged. This method is mainly applied to near-Earth satellite networks, and does not focus on the application scenarios of deep-space networks.

Lindgren et al. [4] proposed a probabilistic routing protocol using history of encounters and transitivity (PROPHET). Unlike epidemic routing, which blindly forwards messages to all neighboring nodes, each node in probabilistic routing will estimate the probability of reaching the destination node based on historical successful routing information. Each node estimates a predicted distribution probability value for each known identical node, and when two nodes contact, the probability value is updated according to the algorithm. At that same time, the prediction distribution probability value among the node also has transitivity, so that the routing table of the whole network can be calculate. The method designs a routing method based on the probability of contact between nodes, changes the traditional fixed routing method, and can be more suitable for DTN application scenarios. However, the method does not consider the QoS service provision capability of the nodes, and may lead to poor network operation efficiency and stability. Xu et al. [5] proposed a QoS routing algorithm for LEO satellite network, DQA). The algorithm considers states of the satellite node, can be more effective to avoid overloading of nodes. When it performs routing calculations, it combines and optimizes the two performance parameters of satellite network delay and link utilization, which can reduce the probability of network congestion. However, the algorithm is only designed according to specific limited QoS parameters, which limits the applicability of the algorithm, and does a lot of work to the local optimization of the link, which make the algorithm convergence slower.

The deep space network QoS routing algorithm based on SDN architecture proposed in this paper uses the SDN controller to grasp the global information and obtain the real-time status of the network. It adopts a heuristic intelligent optimization method based on the ant algorithm and combines the use of deep space network scenarios. Comprehensive consideration of various QoS parameters to complete the deep-space network QoS intelligent routing calculation, which can prevent a large amount of data from passing through certain high-load nodes, and optimize it from the global perspective.

It further speeds up the collection time of the algorithm and can effectively solve the problems in the above-mentioned research.

## 3 SDN-Based Deep Space Network Architecture

SDN technology is a new technology in the research of network architecture in recent years. It realizes flexible control and centralized management of the network by separating control from data and combining programmable control [6–8]. For the actual deep space network, the control plane is responsible for collecting network-wide information, and performing complex routing calculations, and then sending the routing rules to the data plane node. The nodes of the data plane no longer need to perform tasks such as complex calculation, state acquisition and heavy storage. They can focus on data forwarding. This feature of SDN technology is very suitable for satellite nodes with severely limited resources. It can effectively reduce node overhead, and ensure more stable and efficient operation of satellite networks. The control plane needs to complete functions such as node search, state collection, routing calculation, rule distribution, etc. It requires higher basic performance such as higher processing power and storage capacity. Therefore, the control plane nodes are always placed on the ground. Although this method can solve the problem of basic capabilities of the control plane, it is not suitable for the condition of relatively limited distribution of ground stations. When satellite nodes are not in the coverage of the ground station or belongs to a long-distance deep-space communication scenario, it is impossible to deliver the control information to the nodes in time. The transmission time may be several hours to more than ten hours, which will be difficult to adapt to the higher real-time and dynamic requirement of future satellite networks. This paper proposes a satellite network model with a master-slave controller structure, called SADR model. Taking the earth-moon communication scenario as an example, the control plane is a two-stage structure. The master controllers are placed on the ground to undertake heavy storage, analysis of the node status of the entire network, complex routing calculations, and mode switching control functions. In addition, this type of node usually has a higher basic performance than the normal satellite node, so it can also ensure a higher work efficiency when implementing the controller function. The slave controller nodes mainly undertake the new nodes discovery, nodes status collection and sent to the master controller. It obtains the routing and forwarding rules from the master controller nodes and sent to the data plane nodes. The schematic diagram of the SADR model is shown in the Fig. 1 below.

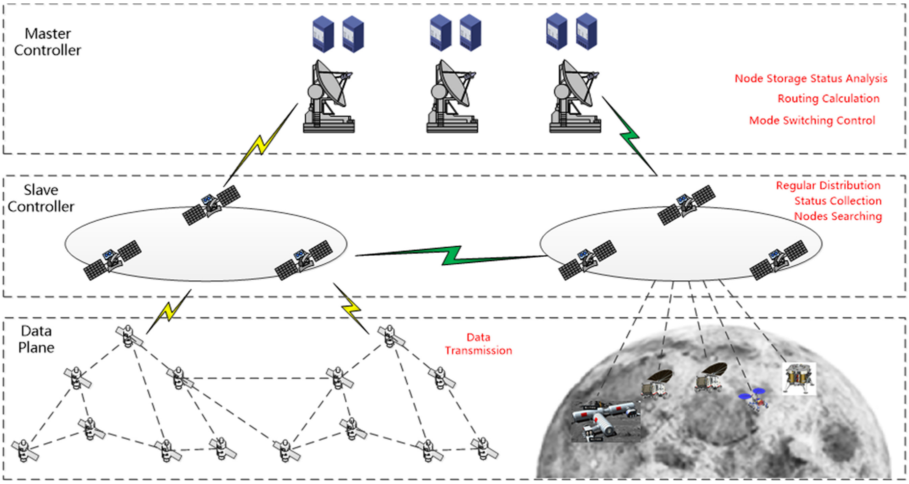

**Fig. 1.** SADR model figure

## 4 Dynamic Routing Algorithm Based on Real-Time Status of Deep Space Network Nodes

The current space network routing method mainly improves the path length and topology maintenance, and less considers the limited resources of space nodes and the limited service capacity, which makes it difficult to ensure the efficiency of data transmission and flexible management of the network. Based on the above-designed deep space network model with a two-stage control structure, this paper intends to design routing mechanism from the following aspects: Firstly, it designs a heuristic intelligent dynamic routing algorithm for the characteristics of deep space networks. According to the performance status of deep space network nodes, it finds the optimal path to avoid node overload; then, it uses a global perspective to optimize the algorithm iteratively, which can improve the convergence time of the algorithm.

### 4.1 Design Goals

When the nodes in the deep space network move in the space, the type of user traffic and the size of application data they serve will change. If these nodes are in one or several important transmission links in the hotspot area, it may cause communication data blocking on these nodes. Given a graph G (V,E) and the connection request from the source node to the destination node, the goal for routing is to find an optimal path with minimum cost from source to the destination, which meets the QoS command of users. In the deep space network, because the node capacity is severely limited, we need to focus on how to make the node load be in a reasonable range, so that the whole network can run stably and efficiently. Therefore, it is particularly important to choose the nodes with strong basic performance to complete routing functions for the realization of QoS routing in satellite networks. The goal of SADR routing algorithm is to find a better path from the source to the destination by combining the short delay path and the basic performance of the node.

(1) Limit of transmission delay: $delay(p(s,d)) \le D$
(2) Available bandwidth ratio limit: $\varepsilon_{ij} = (C_{ij} - R_{ij})/C_{ij} \ge B$
(3) Link disruption limit: $\omega_{sd} = disruption(p(s,d)) \le N$

Among them, s and d are the source node and the destination node, i and j are the deep space network nodes, $R_{ij}$ is the data transmission rate on the link (i, j), $C_{ij}$ is the bandwidth of the link (i, j), and $R_{ij}$ can represent the used bandwidth of link (i, j). $\varepsilon_{ij}$ can represents the degree of congestion, the smaller the value, the higher the degree of congestion. D, B, and N are set constants, which represent the basic performance requirements for guaranteeing user service QoS.

### 4.2 SADR Algorithm

M. Dorigo et al. [9–12] proposed the ant algorithm, which is a heuristic algorithm to simulate the behavior of ant colonies. The algorithm introduces a positive feedback parallel mechanism, which has strong robustness, excellent distributed computer capability, and easy integration. It can have a better result for the complex problem of multi-element composition in a reasonable time. The principle of the algorithm is that when ants move, they will release a volatile substance called pheromone on the path they travel.

The probability of other ants in the colony choosing this path is proportional to the size of the pheromone. For deep space network scenario, a path with better link conditions will pass more ants, so that more pheromone will be left on this path. At the same time, more ants will be attracted from the more pheromone on the path through this path, thus forming a positive feedback effect.

SADR designs multi-condition QoS dynamic routing mechanism for deep space network. The probability of ant k selecting the next hop node j at node i is defined as follows:

$$p_{ij}^{k} = \frac{[\mu_{ij}] \times [\eta_{ij}]^{\alpha} \times [\varepsilon_{ij}]^{\beta} \times [\omega_{ij}]^{\gamma}}{\sum\limits_{x \in N(i)} [\mu_{ix}] \times [\eta_{ix}]^{\alpha} \times [\varepsilon_{ix}]^{\beta} \times [\omega_{ix}]^{\gamma}} \tag{1}$$

$\mu_{ij}$ is the pheromone on the link (i, j), N(i) is the collection of all neighbor nodes of node i, $\eta_{ij} = 1/d_{ij}$, $d_{ij}$ represents the delay from node i to node j, $\varepsilon_{ij} = (C_{ij} - R_{ij})/C_{ij}$ represents the ratio of available bandwidth from node i to node j, $\omega_{ij} = 1/n_{ij}$, $n_{ij}$ represents the number of link interruptions from node i to node j. $\alpha, \beta, \gamma$ indicates the importance of delay, available bandwidth ratio and link interruption to user QoS. SADR will choose the node with shorter delay, larger available bandwidth, smaller number of link interruptions and higher pheromone strength as the basis of next hop routing algorithm. In addition to the above parameters, the basic performance parameters of space network can also include packet loss rate, energy support capability of satellite nodes, etc., which can be flexibly selected and adjusted according to different application environments.

Pheromone plays a very important role in path selection. It changes with the process of searching the destination node. The higher the pheromone strength is, the more ants will be attracted to pass through the node. Pheromone intensity will be updated in several stages.

(1) Pheromone local update

After the ant completes a node selection, the node is placed in the visited node set, and then the pheromone is updated locally.

$$\mu_{ij} \leftarrow (1 - \theta)\mu_{ij} + \Delta\mu_{ij} \tag{2}$$

$$\Delta\mu_{ij} = \mathrm{A} \times [\eta_{ij}]^{\alpha} \times [\varepsilon_{ij}]^{\beta} \times [\omega_{ij}]^{\gamma} \tag{3}$$

$\Delta\mu_{ij}$ means that in the process of searching the next node this time, the pheromone is updated according to the QoS status of the node. $\theta$ means that the pheromone volatilization parameter ($0 \leq \theta \leq 1$). A is a constant, which controls the increase of local pheromone update.

In the next hop node selection, it is necessary to make sure that the node is not in the visited node set to avoid the appearance of routing ring, and then determine the selection probability of the next hop node according to the size of pheromone, and select the next hop node according to the probability.

(2) Pheromone Global Update

When the complete path from the source node to the destination node is completed, the pheromone of all nodes on the path is updated globally. The global update method is as follows.

If $\mathrm{T}(P_{sd}) \leq D$ and $(i,j) \in P_{sd}$

$$\mu_{ij} \leftarrow (1 - \varphi)\mu_{ij} + \Delta\mu_{ij}^{'} \tag{4}$$

$$\Delta\mu'_{ij} = B \times [\eta_{ij}]^{\alpha} \times [\varepsilon_{ij}]^{\beta} \times [\omega_{ij}]^{\gamma} \tag{5}$$

If $(i,j) \notin P_{sd}$,

$$\mu_{ij} \leftarrow (1 - \varphi)\mu_{ij} \tag{6}$$

For deep space communication scenario, information transmission delay is one of the most important indicators. Only when the delay of the whole communication link is within a reasonable range, communication can be efficient and reliable. D is the end-to-end delay requirement. T($P_{sd}$) is the delay for ants to complete the complete path selection. $\varphi$ is the pheromone global attenuation parameter ($0 \leq \varphi \leq 1$). B is a constant, and it controls the increase of pheromone global update. For the nodes that are not on the ant path, the updating of pheromone is the attenuation of pheromone.

(3) Extra incentive mechanism

For the ants that complete the whole path selection, SADR algorithm will calculate the QoS state value of the path, which is defined as:

$$\overline{QV(P_{sd})} = \Big(\sum_{ij \in P_{sd}} QV(P_{ij})\Big)/node\_num$$

$$QV(P_{ij}) = [\eta_{ij}]^{\alpha} \times [\varepsilon_{ij}]^{\beta} \times [\omega_{ij}]^{\gamma}$$

*QV* is the QoS value of a node according to the QoS calculation model. SADR will give extra pheromone rewards to the path that has completed end-to-end communication and the average QoS value of the path is the best.

If $\overline{QV(P_{sd})} \geq \max(\overline{QV(P_{sd})})$, $(i,j) \in P_{sd}$

$$\mu_{ij} \leftarrow \mu_{ij} + \Delta\mu''_{ij} \tag{7}$$

$$\Delta\mu''_{ij} = C \times [\eta_{ij}]^{\alpha} \times [\varepsilon_{ij}]^{\beta} \times [\omega_{ij}]^{\gamma} \tag{8}$$

$QV(P_{sd})$ is the complete path QoS value, C is a constant, which controls the increase of pheromone QoS value.

For deep space network, due to the characteristics of long delay, high dynamic and high packet loss rate, in addition to the nodes and links that meet the delay requirements and have good QoS, the path with less link hops should be selected as far as possible to further ensure the reliability of data transmission on the path, reduce the cost of the whole network system. SADR gives extra reward to the path with less hops.

If $NH(P_{sd}) \leq \min(NH(P_{sd}))$, $(i,j) \in P_{sd}$

$$\mu_{ij} \leftarrow \mu_{ij} + \Delta\mu'''_{ij} \tag{9}$$

$$\Delta\mu_{ij}''' = K/NH(P_{sd}) \tag{10}$$

$NH(P_{sd})$ is the complete hop number of the ant, K is a constant, and controls the increase range of pheromone.

It can be seen from the above that SADR has both local update and global update mechanism. For the complete path from the source node to the destination node with fewer hops and a better QoS state, more pheromone rewards are given. In this way, subsequent traffic will pass this path. When the algorithm described in this paper establishes the QoS state description model, only three of the most typical and commonly used QoS parameters are selected. In actual applications, the required QoS parameters can be adjusted according to requirements.

### 4.3 SADR Algorithm Description

The goal of SADR is to learn from the ant algorithm and periodically find the optimal path between the source and the destination to meet the user's QoS requirements. Each time a node is selected, the node is added to the set of visited node set. At the same time, a lifetime is set for the path-finding ants. If the destination node is not reached or there is no way to choose during the lifetime, it is considered that the path searching fails. If the destination node is reached during the lifetime, it is considered that the path searching is successful. Each time the ants that completes the path search will compare the corresponding values generated by the previously completed ants in terms of path QoS status, hop count, etc., to continuously obtain a better path, and finally obtain the approximate optimal value under certain conditions.

SADR is mainly divided into two phases: dynamic routing lookup update and routing table distribution. Firstly, in the initialization stage, there is a set of default topological connection relationships to make the entire satellite network maintain data communication in the initial state or emergency state, even if it is not a perfect routing mode. And then, it acquires state information of the deep space network nodes by the slave controller and summarizes the state information to the master controller. The Master controller performs dynamic QoS route calculation according to the SADR algorithm. Because of the constantly moving of satellite nodes, and the changing of space environment, the path found in the previous stage may not be a high-quality path or even a usable path after a certain time interval. Therefore, it is necessary to set an update cycle, and in each update cycle. And finally, in the routing table distribution stage, the master controller distributes the calculated routing table to the slave controller, and then the slave controller forwards the received routing table to nodes covered.

## 5 Performance Evaluation

This section verifies the performance of end-to-end QoS value and delay with DQA. For different space routing algorithms, the end-to-end delay of satellite nodes is a basic network performance indicator, which can explain the rationality of the network architecture. And the end-to-end QoS status value can reflect the current QoS status of the node and link on the selected path.

The experiment in this section sets the scenario as a combination of lunar surface network and near-Earth space network. The lunar surface network is composed of 3 lunar relay satellites and 30 lunar nodes. The lunar node has 4 communication links. The near-Earth network consists of 3 relay satellites and 6 orbital planes, 11 satellites on each orbital plane, for a total of 66 low-orbit satellites. The nodes also have 4 inter-satellite links (Figs. 2 and 3).

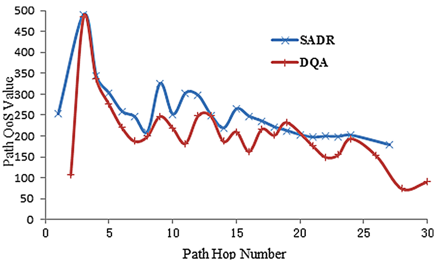

**Fig. 2.** QoS value for end-to-end

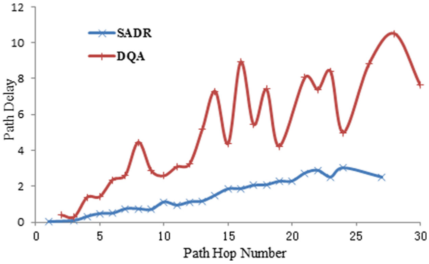

**Fig. 3.** Delay for end-to-end

## 6 Conclusion

SADR is a QoS routing algorithm for deep space networks based on SDN architecture. The algorithm is composed of the following parts: 1) SADR dynamic routing lookup process, it acquires state information of the deep space network nodes by the slave controller and summarizes the state information to the master controller. The Master controller performs dynamic QoS route calculation according to the SADR algorithm. 2) SADR routing table distribution stage, the master controller distributes the calculated routing table to the slave controller, and then the slave controller forwards the received routing table to nodes covered. Finally, the simulation results show that SADR has better performance in end-to-end path QOS state value and end-to-end average delay.

**Acknowledgement.** This work is supported by the 'The National Key Research and Development Program' of China (No. 2018YFB1800301).

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