A Dijkstra Algorithm Based Multi-layer Satellite Network Routing Mechanism

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Abstract. As the basis of satellite communication network, routing mechanism is a hot topic in satellite network. However, due to the dynamic network topology, high propagation delay and limited resource of satellite network, many great challenges have emerged in designing routing mechanism for it. In this paper, we propose a satellite network routing mechanism based on Dijkstra algorithm for multi-layer satellite network. By considering QoS requirements, service pricing, life cycle and load balance together, we first design an evaluation index, which is used to evaluate the effectiveness of the alternative route. Then we utilize the Dijkstra algorithm to select the best path for satellite network. Finally, we evaluate the proposed mechanism on the model of multi-layer satellite network and verify it from many aspects. Evaluation results show that our routing mechanism is feasible and effective.

Keywords: Multi-layer satellite network · Dijkstra algorithm · Routing mechanism

1 Introduction

With the development of wireless communication technology, satellite network has become a new type of Internet that achieves global communication seamless connection. It can supplement the lack of ground network. However, because of the increasing demand for multimedia service, satellite network's main service gradually changes from traditional voice and low-speed data service to Internet and broadband multimedia service. Therefore, building an efficient and reliable satellite network has great economic value.

Satellite network is different from the ground network. The transmission channels of inter-satellite links (ISLs) work in an open environment, which causes dynamic network topology and interference or violation to satellite network. Satellite network routing mechanism directly affects the performance of the satellite network. Dynamic topology, large transmission delay, high error rate, limited resources of nodes and unbalanced distribution of service bring big challenges to satellite network routing.

In recent years, many researchers have studied satellite network routing [1–5]. For example, a routing mechanism based on the periodicity of the satellite network is proposed in [1], and the load balance based routing mechanism is put forward in [4]. But these works just concentrate on partial characteristics of satellite network. By considering QoS requirements, service pricing, life cycle and load balance comprehensively [6], we present a satellite network routing mechanism based on Dijkstra

D.-S. Huang and K. Han (Eds.): ICIC 2015, Part III, LNAI 9227, pp. 586–597, 2015.
DOI: 10.1007/978-3-319-22053-6_61

algorithm. Firstly, we design an evaluation index to evaluate the effectiveness of the alternative route. Then we utilize the Dijkstra algorithm to select the best path for satellite network. Finally, we evaluate the proposed mechanism on the model of multi-layer satellite network and verify it from many aspects.

The remainder of the paper is organized as follows. The related work is presented in Sect. 2. We describe the network model and routing mechanism for multi-layer satellite network in Sect. 3. Section 4 presents our simulation and evaluation results. Our conclusions and future remarks are presented in Sect. 5.

2 Related Work

Currently, research on satellite network routing mechanism has made some progress. According to the problems, satellite routing mechanisms can be divided into five categories [8], mainly based on the constellation period, link switch, QoS requirements, load balance and path-based optimization.

The literature [1] put forward a routing mechanism based on constellation cycle. By using the slot allocation method, dynamic network topology was divided into several time slots, each of which was a static topology for routing. This mechanism demands less for the ability to process, but its adaptability is relatively poor. The literature [2] analyzed life cycle of the path to select path whose lifetime is longer. This routing mechanism meets the certain QoS requirements, but it does not take the fairness of links into account. The literature [3] proposed a routing mechanism based on the QoS requirements. According to various indicators of QoS satisfaction, they chose the best path that meets QoS requirements. This mechanism gets balance in different demands of QoS indicators, so it lacks a comprehensive strategy to optimize the QoS indicators. A routing mechanism based on load balance was studied in [4]. It uses the load as the metric to ensure the flow distribution reasonable, but it increases the expenses of ISLs signaling. The literature [5] considered the path optimization this aspect. According to the network status, they selected the path which is shorter, saves resources and meets QoS requirements. But this mechanism requires very regular network structure.

These researchers just considered partial properties of satellite network to study routing mechanism. In this paper, in order to meet the actual demands, we consider all the above-mentioned characteristics of the satellite network and present a Dijkstra algorithm based satellite network routing mechanism. Through using the QoS requirements, service pricing, life cycle and load balance as the basis for routing, it achieves the purpose of improving the QoS satisfaction, reducing link switch and saving node resource.

3 Model Design

3.1 Network Model

For multi-layer satellite network, the satellite network model reflects the relationship between nodes, determines the number of links of the node, the distance between nodes, and even affects the data transmission path and transmission reliability. According to the characteristics of multi-layer satellite network, we believe that GEO/MEO/LEO satellite network is more representative, and use it as a satellite constellation network structure of this article, as shown in Fig. 1.

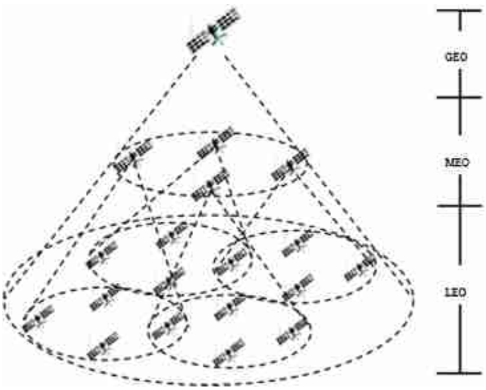

Fig. 1. Three layer satellite network structure

Through a detailed study of the multi-layer satellite network [7], the article identifies the network model by a weighted directed graph representation. As shown in Fig. 2, the weighted directed graph G represents the state of multi-layer satellite network topology; $V = \{v_0, v_1, \cdots, v_{n-1}\}$ denotes the set of satellite nodes and n is the number of satellites; $E(t) = \{e_{ij}\}$ represents the set of weight values, e_{ij} is the distance between the satellite i to j at time t, and $i, j \in [0.1]$.

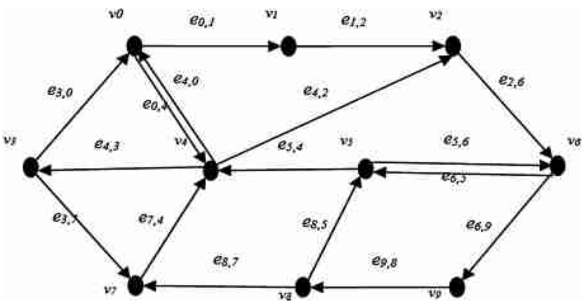

Fig. 2. Example of network model

3.2 Path Effectiveness Evaluation

Effectiveness evaluation is one of the concepts used in economics. It refers to the subjective evaluation of the user for the matching degree of services and demand functions. The article considers the characteristics of ISLs and evaluates comprehensively the QoS satisfaction, service pricing satisfaction, the life cycle fitness and load fitness as the path effectiveness evaluation of alternative paths.

QoS Satisfaction. Due to the QoS requirements of business are generally in the form of interval, this article is based on trapezoidal membership function of fuzzy mathematics to describe the changes of QoS parameters provided by user satisfaction and the service. We use PAL fuzzy enhancement algorithm to describe the user depending on the service level and the effects of parameters on QoS satisfaction.

$L_s \in [L_{Top}, L_{Low}]$ represents the service level that user sets up and the smaller L_s represents the higher service level. This article uses the PAL [10] fuzzy enhancement algorithm, calculated as shown in (1).

$$g(x) = \begin{cases} k_1 \cdot f(x)^2 & 0 \le f(x) \le \tau \\ 1 - k_2 \cdot (1 - f(x))^2 & \tau < f(x) \le 1 \end{cases} \tag{1}$$

$g(x)$ is the trapezoidal membership of QoS parameters.

$$k_1 = \frac{1}{\tau} \tag{2}$$

$$k_2 = \frac{1}{1 - \tau} \tag{3}$$

$$\tau = 1 - \frac{L_s}{L_{Top} + L_{Low}} \tag{4}$$

When the value of τ is different, the function $g(x)$ is as shown in Fig. 3. Clearly, the higher the service level L_s is, the higher value of τ is, and the higher requirement for QoS parameters is.

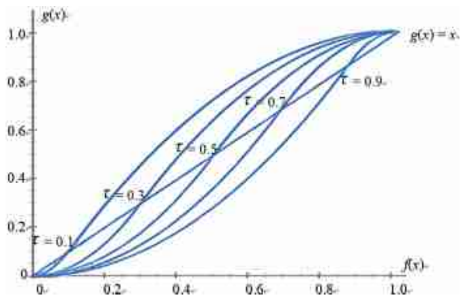

Fig. 3. Function curves of PAL algorithm

We evaluate the QoS satisfaction based on the three important parameters of bandwidth, transmission delay and error rate.

(1) *Bandwidth Satisfaction*

Bandwidth requirement belongs to the maximum and minimum constraint conditions of the QoS requirements. Alternative paths provide the business s with bandwidth which is the minimum value of available bandwidth provided by its sub-links. Assume that the bandwidth of the business s is $[er_s^l, er_s^h]$, then the bandwidth satisfaction SB is calculated as shown in (5).

$$SB = \begin{cases} 0 & bw \le bw_s^l \\ k_1 \cdot \left(\frac{bw - bw_s^l}{bw_s^h - bw_s^l}\right)^2 & bw_s^l < bw \le bw_T \\ 1 - k_2 \cdot \left(1 - \frac{bw - bw_s^l}{bw_s^h - bw_s^l}\right)^2 & bw_T < bw < bw_s^h \\ 1 & bw \ge bw_s^h \end{cases} \tag{5}$$

And,

$$bw_T = \tau \cdot \left(bw_s^h - bw_s^l\right) + bw_s^l \tag{6}$$

(2) *Delay Satisfaction*

Latency requirement is QoS requirements' additive constraint. Time delay of the business s provided by alternative paths is the sum of sub-links' delay. Either in satellite network or conventional ground network, time delay is important parameter for evaluation of routing. End-to-end delay of the satellite network discussed in this paper consists of transmission delay and waiting delay.

Through analyzing ISLs time window with the method in [9], we can get the optional link to guarantee the biggest end-to-end delay dl, calculated as shown in (7).

$$dl = p_0 + (t_n - t_1) + p_n \tag{7}$$

$t_n - t_1$ is the sum of transmission delay and waiting delay of the message from node 0 to node $n-1$ on the path $R = (0, n)$. p_0 represents the time that the message wait for $hop(1)$; p_n is the transmission delay of $hop(n)$.Therefore, ideally, waiting delay is 0, then the end-to-end delay of the path is $dl = p_1 + p_2 + \cdots + p_n$.

Assuming that the demand for the delay of business s is $[dl_s^l, dl_s^h]$, and the delay satisfaction SD is calculated as shown in (8).

$$SD = \begin{cases} 1 & dl \le dl_s^l \\ 1 - k_2 \cdot \left(1 - \frac{dl_s^h - dl}{dl_s^h - dl_s^l}\right)^2 & dl_s^l < dl \le dl_T \\ k_1 \cdot \left(\frac{dl_s^h - dl}{dl_s^h - dl_s^l}\right)^2 & dl_T < dl < dl_s^h \\ 0 & dl \ge dl_s^h \end{cases} \tag{8}$$

And,

$$dl_T = dl_s^h - \tau \cdot \left(dl_s^h - dl_s^l\right) \tag{9}$$

(3) *Error Rate Satisfaction*

Error rate demand belongs to the multiplicative constraints of QoS demands. Alternative path is related to the error rate of service and sub-links provided by business. Satellite network is easy to be interfered by natural or human factors, so the importance of error rate in satellite network routing is more outstanding.

$er(h)$ represents the error rate of $hop(h)$, and the error rate of the path $R = (0, n)$ is calculated as shown in (10).

$$er = 1 - \prod_{h=1}^{n} (1 - er(h)) \tag{10}$$

Assuming that the error rate demand of business s is $[er_s^l, er_s^h]$, and the error rate satisfaction SE is calculated as shown in (11).

$$SE = \begin{cases} 1 & er \le er_s^l \\ 1 - k_2 \cdot \left(1 - \frac{er_s^h - er}{er_s^h - er_s^l}\right)^2 & er_s^l < er \le er_T \\ k_1 \cdot \left(\frac{er_s^h - er}{er_s^h - er_s^l}\right)^2 & er_s^l < er \le er_T \\ 0 & er_T < er < er_s^h \end{cases} \tag{11}$$

Service Pricing Satisfaction. Combining with limited power resource and the market pricing mechanism, we argue that the satellite network service pricing is decided by the power cost and service level. sc is the service pricing of the path $R = (0, n)$.

In (12), pb is the service pricing, P_i is the sending power and α is the adjustment coefficient, $\alpha \in (0, 1)$.

$$\mathrm{sc} = pb \cdot (1 + \alpha \cdot \ln(\sum_{i=0}^{n-1} P_i)) \cdot \left(1 + \frac{L_{Low} - L_s}{L_{Low} - L_{Top}}\right) \tag{12}$$

We evaluate satisfaction service pricing SP through drop half parabolic distribution function, calculated as shown in (13).

$$SP = \begin{cases} \left(\frac{ap_s - sc}{ap_s}\right)^{\beta} & sc \le ap_s \\ 0 & sc > ap_s \end{cases} \tag{13}$$

ap_s is the acceptable unit price for business s and β is the adjustment coefficient.

Life Cycle Fitness. In route choice, the life cycle of the path cannot be ignored. Together with the path's available bandwidth, it determines the amount of data that can be transferred in the life cycle. The life cycle of path $R = (0, n)$ is decided by the minimum value of each link time window's period, calculated as shown in (14).

$$lf = \min(t_h' - t_h) \tag{14}$$

In the daily time, the user cannot describe all the time needed by the business. Therefore, we introduce the threshold value lf_{th} of the path's minimum life cycle, and use half of normal distribution function to evaluate life cycle satisfaction SL of the path, calculated as shown in (15).

$$SL = \begin{cases} 0 & lf \leq lf_{th} \\ 1 - e^{-\gamma \bullet (\frac{lf}{lf_{th}} - 1)^2} & lf > lf_{th} \end{cases} \tag{15}$$

γ is the adjustment coefficient and $\gamma > 0$.

Load Fitness. In this paper, we use the channel bandwidth and power utilization ratio to evaluate satellite node load. The load rate of its node i is calculated as shown in (16).

$$\eta_i = \eta_i^w + \eta_i^p - \eta_i^w \cdot \eta_i^p \tag{16}$$

η_i^p and η_i^w, respectively, represent power load rate and channel bandwidth load rate of satellite node, $\eta_i \in [0, 1]$,$\eta_i \geq \eta_i^p$,$\eta_i \geq \eta_i^w$.

We consider the maximum value of load rate η_i of the path $R = (0, n)$ as the load rate η of the path. Correspondingly, its load fitness SW is calculated as shown in (17).

$$SW = \begin{cases} 1 - \eta & \forall i \in [0, n-1], \\ & W_i \leq W_{available}^i \wedge P_i \leq P_{available}^i \\ 0 & \text{Otherwise} \end{cases} \tag{17}$$

W_i and P_i, respectively, represent the channel bandwidth and power that nodes need in the path $R = (0, n)$. $W_{available}^i$ and $P_{available}^i$, respectively, are residual channel bandwidth and the power of the nodes.

Efficiency Computing. The article introduces the weight coefficient matrix $\mathbf{\Lambda} = [\lambda_1\, \lambda_2\, \lambda_3\, \lambda_4]$, followed by the relative importance of the QoS satisfaction, service pricing satisfaction, life cycle and load fitness in the routing selection, and $\mathbf{\Lambda} = [\lambda_1\, \lambda_2\, \lambda_3\, \lambda_4]$. Path evaluation matrix is $\mathbf{E} = [SQ\, SP\, SL\, SW]^T$. Routing efficiency of alternative paths RU is as shown in (18).

$$RU = \mathbf{\Lambda} \cdot \mathbf{E} \tag{18}$$

3.3 Algorithm Design

Mathematical Model. The article aims to maximize path effectiveness to find the best path, meanwhile meets the QoS requirements and the existence of links.

$$\begin{aligned} & \max(RU) \\ s.t. \quad & lf \geq lf_{th} \\ & sc \leq ap_s \end{aligned} \tag{19}$$

Algorithm Description. According to the evaluation index of the path in this paper, we can get that the path length RL increases with the hops, which guarantees the condition that the length of each hop in Dijkstra algorithm is nonnegative. Therefore, we propose a Dijkstra algorithm based satellite network routing mechanism, and define the length of path RL as shown in (20).

$$RL = \begin{cases} \frac{1}{RU} & \text{constraint conditions of the mathematical model} \\ +\infty & \text{Otherwise} \end{cases} \tag{20}$$

Specific steps show as below.

Input: Satellite network $G = (V, E(t))$, all the parameters of satellite nodes in the network, the QoS requirements and service level L_s of the business.

Output: The optimal path.

Step1: Initialize set $S = \emptyset$ and $T = \emptyset$, set source node V_s and destination node V_d;

Step2: Put the source node V_s into set S, then put the rest nodes into set T.

Step3: Calculate link distance between the nodes in the set T and source node V_s. If there is no link satisfied with visibility and QoS requirements, set the distance $+\infty$.

Step4: Take the node V_n from the set T, which is nearest to the node in the set V_s, into the set S. And remove V_n from the set T.

Step5: Call the path length calculation function, then using V_n as the intermediate node, calculate the distance between V_i and the source node V_s.

Step6: If the new distance is less than the original distance, update the distance from V_i to V_s and record the path, then go to step 7.

Step7: If nodes in set T have been traversed, go to step 8. Otherwise, go to step 5.

Step8: If set T is empty, go to step 9. Otherwise, go to step 4.

Step9: Ends.

4 Performance Evaluation

In this paper, the simulation example is multi-layer satellite network including 15 satellite nodes. As shown in Table 1, the constellation structure includes: 3 GEO, 3 MEO and 9 LEO.

In order to measure the performance of satellite network routing mechanism proposed, the article evaluates it mainly through satellite network capacity adopting the

Table 1. Use case of satellite constellation structure

Orbit parameters	GEO	MEO	LEO
Semi-major axis (km)	42166	27878	8378
Eccentricity ratio	0	0	0
Orbit inclination (°)	0	55	55
RAAN (°)	16E, 136E, 256E	0E, 120E, 240E	0E, 120E, 240E
Argument of perigee (°)	0	0	0
True anomaly (°)	0	0E:0, 120E:120, 240E:240	80, 200, 320
Number of satellites	3	3	9
Number of planes	1	3	3

method of the Hybrid adaptive genetic algorithm [11] based on the golden ratio. The network capacity limit results are shown in Fig. 4 and each strategy's capacity limit of variance between time slots is shown in Table 2.

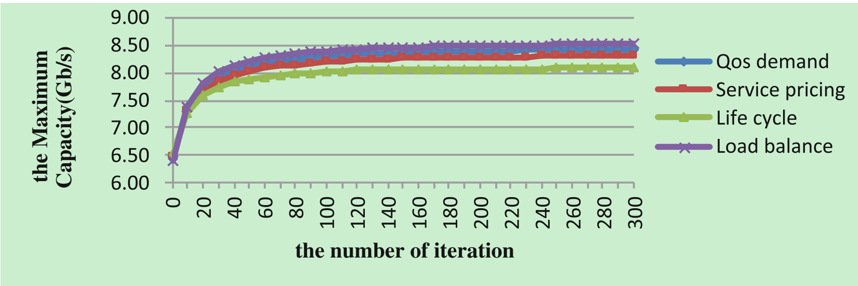

Fig. 4. The maximum capacity with different routing strategies

Table 2. The variances of maximum capacity with different routing strategies

Routing strategy	QoS demand	Service pricing	Life cycle	Load balance
Network capacity variance	0.25	0.32	0.58	0.14

We can see that putting emphasis on load balance, satellite network capacity [12] limit is higher and less volatile. While an emphasis is on the use of life cycle, the capacity limit is low and volatile. The reason is that routing mechanism focused on load balance chooses the path mainly on available resources of nodes, so the path is more diverse. Figure 5 denotes the number of nodes' ISLs and the total number of ISLs. 1–3 represent GEO satellites, 4–6 represent MEO satellites, and 7–15 represent LEO satellites. Obviously, with an emphasis on load balance, the average number of ISLs is larger. Besides, the available resources of each node are relatively balanced. So it is more rational to allocate the limited resources.

Figure 6 shows the comparison of each strategy, the corresponding strategy's variance of capacity lower limit in each time slot is shown in Table 3. Clearly, the

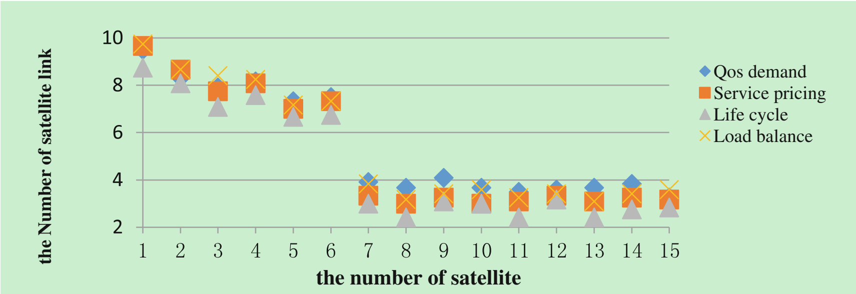

Fig. 5. The number of link in each satellite with different routing strategies

capacity lower limit is more volatile while putting an emphasis on life cycle of network, but it has a higher capacity lower limit. However, while the average number of links is larger, the routing strategy with an emphasis on load balance still gets the similar capacity lower limit with one whose key is on service pricing, because of its rationality of the resources allocation.

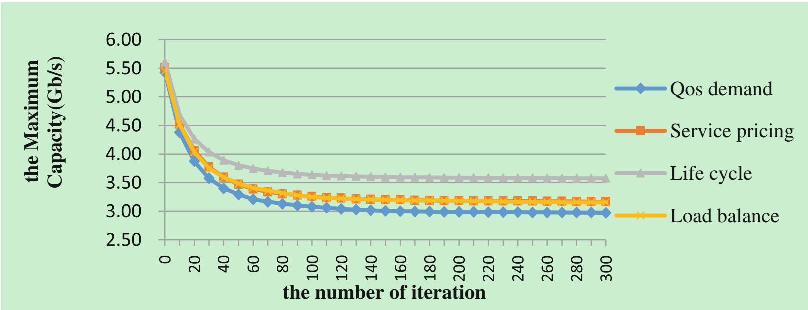

Fig. 6. The minimum capacity with different routing strategies

Table 3. The variances of minimum capacity with different routing strategies

Routing strategy	QoS demand	Service pricing	Life cycle	Load balance
Network capacity variance	0.55	1.00	1.50	0.72

In addition, the network capacity limit's difference between the minimum and maximum by using the routing strategy whose emphasis is on the life cycle. But its nodes change the moving position, which will cause large changes in resource utilization of each node, then the stability of satellite network based on this routing strategy will be worse. The satellite network routing focused on load balance can not only increase network capacity, but also help to increase the stability of the satellite net-work itself.

5 Conclusions and Future Remarks

In this paper, a satellite network Dijkstra algorithm based routing mechanism is presented and we verify the proposed routing mechanism. The mechanism uses QoS requirements, service pricing, life cycle and load balance as the basis to select the route and achieves to improve the QoS satisfaction, node resource conservation and reduce link switch. The evaluation results show that the mechanism of our design is feasible, effective, and better performance. The efficiency of this routing mechanism should be further improved. The practical of this routing mechanism and further improvement are the focus of our future research work.

Acknowledgment. This work is supported by the National Science Foundation for Distinguished Young Scholars of China under Grant No. 61225012 and No. 71325002; the Specialized Research Fund of the Doctoral Program of Higher Education for the Priority Development Areas under Grant No. 20120042130003; Liaoning BaiQianWan Talents Program under Grant No. 2013921068.

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