

A Routing Algorithm Based on SDN for On-Board Switching Networks

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A new routing algorithm for MPLS (Multi-Protocol Label Switching, MPLS) traffic engineering in SDN-based (Software Defined Network, SDN) satellite switching networks is presented in this paper. LSP (Label Switched Path, LSP) link initial weights are defined as composite functions consisting of link transmission delay, residual bandwidth and BER (Bit Error Rate, BER). Based upon ISL (Inter-Satellite Link, ISL) handoff, LSP link stability function is defined. Next, LSP link criticality function is defined by the frequency of ISL used to establish LSP. The LSP link selection probability function is designed based on the three functions mentioned above. The proposed routing algorithm is able to implement dynamic routing from the source to the destination of multiple LSPs, which can balance the load of network traffic. Some numerical simulations are made to test the validity and capability of the proposed routing algorithm.

Keywords: SDN, satellite communication networks, on-board switching, routing algorithm, MPLS

1. INTRODUCTION

SDN (Software Defined Network, SDN) technology has been widely researched over the past decades and it is becoming one of main satellite network communication technologies [1]. Moreover, satellite communications are the primary means to solve global network coverage in the future. The characteristics of SDN technology, such as separation between control layer and forwarding layer and editable software-defined routing policy, can be thoroughly utilized in satellite communication network. Furthermore, SDN technology can improve the utilization of satellites platform payload, the utilization of satellite channel and QoS (Quality of service, QoS) supporting capabilities. The routing calculation functions of SDN-based satellite on-board switching network are set on SDN controller. On-board switches not only receive and store the flow table issued by SDN controllers, but also report link-state information to SDN controllers. Routing calculation functions set on SDN controllers can avoid the load limit of on-board system and make it possible to employ a high computational complexity routing algorithm on SDN controllers. In addition, due to the concentrated calculation of the whole network, the routing topology and load condition of the whole network can be perceived on SDN controllers.

Because of the unbalanced distribution of satellite data traffic, data flow will pro-

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duce some congested nodes, which will increase delay and decrease throughput. Therefore, satellite network routing algorithms employed on SDN controllers need to support traffic load balancing to avoid link congestion or node congestion. In order to solve the problems mentioned above, some algorithms have been put forward such as CSPF (Constraints Shortest Path First, CSPF) and WSP (Widest Shortest Path, WSP) [2-4]. However, those algorithms have only taken into account some functions in terms of balancing network traffic, improving network efficiency and reducing network delay, but have left out the effects of ISL handoff on network routing topology due to computational complexity constraints. Besides, MPLS (Multi-Protocol Label Switching, MPLS) traffic engineering needs to establish LSP (Label Switched Path, LSP) based on the TCP (Transmission Control Protocol, TCP) protocol, however, the highly dynamic topology of satellite constellation system is unable to maintain stable TCP connections [5]. Therefore, LSP, RSVP (Resource Reservation Protocol, RSVP) and other protocols must be manipulated if MPLS traffic engineering [6] is used in satellite constellation system.

Referring to [2-4], the authors only took into account one or two characteristics of satellite network, but not took into account all characteristics comprehensively, like transmission delay, flow imbalance, BER and ISL handoff *etc*. They also ignored the problem that protocols must be manipulated if MPLS traffic engineering is used in satellite constellation system. In this paper, a routing algorithm for SDN-based satellite on-board switching system is proposed. The characteristics of satellite network and SDN technology have been taken into full consideration in this method. MPLS-based traffic engineering protocols is directly employed on SDN controllers, and transmission delay, residual bandwidth, BER, the stability and criticality of the ISL are described as the initial weight for path computation. The experimental results show that the proposed algorithm improves the overall performance of satellite networks and can dynamically change the flow of satellite constellation system through the implementation of traffic engineering.

The following parts of this paper are organized as follows. In Section 2, the network architecture of SDN-based satellite communication is introduced. The proposed routing algorithm is introduced in detail in Section 3. In Section 4, the results of numerical simulation conducted to test the validity of the proposed algorithm are also provided. Conclusions are summarized in the final section.

2. NETWORK ARCHITECTURE

SDN-based satellite communication network may consist of user layer, forwarding layer and control layer. The user layer includes various satellite communications ground terminals. The forwarding layer is mainly composed of LEO (Low Earth Orbit, LEO) constellation communication system. Compared with other on-board systems, the forwarding layer reduces switching units and user management units and increases the control agent modules of OpenFlow [1] protocol, which can implement flow caching, adaptive forwarding and link-state advertisement [7].

The control layer consists of satellite ground stations with network management function and operation control function [8]. SDN controllers are added to conventional satellite center stations in order to integrate SDN controllers with satellite center stations' systems including operating, network management and control systems *etc*. Besides, it

implements network topology discovery, service configuration, routing calculation, label distribution and other functions. The network architecture is shown in Fig. 1.

The space segment of SDN-based satellite communication network mainly consists of LEO constellation. The LEO constellation includes $(N_L \times M_L)$ LEO satellites, which distributes on N_L orbital planes and each orbital plane includes M_L LEO satellites. LEO satellite constellation functions as the access layers, which is responsible for the transmission and exchange of data. Here, the LEO satellites are numbered by (i, j) , where the parameter i represents orbit number and the parameter j represents the number of different LEO satellites on the same orbital plane ($i = 1, 2, \dots, M_L; j = 1, 2, \dots, N_L$). In general, each satellite has four ISLs, standing for two links between two satellites on the same orbital plane and the other two links between two satellites on two adjacent orbital planes. Irrespective of attitude deviation and orbit errors, the distance, elevation and azimuth angle of two adjacent satellites on the same orbital plane hardly change during the process. The relative distance and azimuth angle of two satellites on different orbital planes change more significantly so that two adjacent satellites on different orbital planes cannot establish continuous ISL. A network topology in which LEO constellation remains constant in an interval time is usually called as a snapshot of network topology [9].

The basic model of satellite network for LEO constellation can be expressed as the $G(V, E, W(t))$. $V = (V_1, V_2, \dots, V_n)$ is a finite set of representing nodes in the networks; $E \in (V \rightarrow V)$ stands for communications links between node i to node j ($i \in V, j \in V$); $W(t) = (W_{i,j}(t))$ represents the cost function from node i to node j in interval time $[t_1, t_2]$, which is generally determined by distance, available bandwidth, transmission delay and other factors, and $W_{i,j}(t)$ is a periodic function of T , which is the cycle time of satellite time-varying network topological model [9] or the cycle time of a “snapshot”.

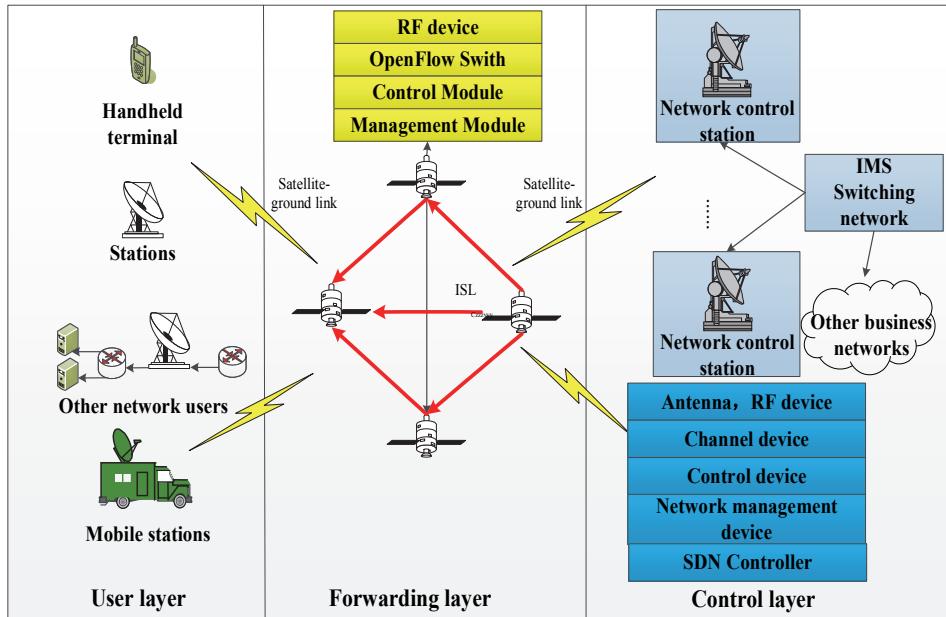


Fig. 1. The architecture of SDN-based satellite communication network.

3. ROUTING ALGORITHM

SDN-based on-board network deploys routing algorithm centrally on SDN controllers. SDN controller establishes a virtual node for each LEO satellite node, which receives and stores link status advertisement reported by satellite nodes. SDN controllers set up virtual MPLS satellite network through each virtual node, label and integrate routing calculation results into the flow table of OpenFlow protocol, and then send them to LEO satellite nodes. The ISL initial weights $I_{i,j}(t)$ for virtual MPLS satellite network are composite functions of link transmission delay, residual bandwidth and BER. Then Dijkstra algorithm is employed to calculate N LSPs from the source node S to the destination node $D(S, D)$. Thereafter, we calculate the initial weight function $m_k(t)$ of each LSP by using the weight $I_{i,j}(t)$ of $ISL(S_i \rightarrow S_j)$. According to the orbit feature and the network topology snapshot of the LEO satellite network, we can calculate remaining lifetime $T_k(S_j \rightarrow S_i)$ of each $ISL(S_i \rightarrow S_j)$. Then we calculate the link stability function $w_k(t)$ of N LSPs between the source node S to the destination node $D(S, D)$. On the basis of the number and the frequency of each $ISL(S_i \rightarrow S_j)$ used in the network to establish LSP, we can calculate LSP link criticality function $g_k(t)$. Finally, we calculate LSP link selection probability function $LSP_{(S \rightarrow D)}(t)$ according to LSP link initial weight function $m_k(t)$, LSP link stability function $w_k(t)$ and LSP link criticality function $g_k(t)$. Thus, this method allows service distribution between the source node S to the destination node $D(S, D)$ to select the LSP with the lower criticality and the longer remaining lifetime to the greatest extent so as to reduce the handoff and balance network traffic, which will fulfill the efficient utilization of satellite networks.

3.1 LSP Link Initial Weight Function

Based on the residual bandwidth, transmission delay and BER of the ISL, the initial weights of each $ISL(S_i \rightarrow S_j)$ can be defined as follows:

$$I_{i,j}(t) = \alpha \cdot \frac{C_{\max}}{C_{i,j}(t)} + \beta \cdot \frac{D_{i,j}(t)}{D_{\min}} + \gamma \lg \left(\frac{F_{i,j}(t)}{F_{\min}} \right). \quad (1)$$

$C_{i,j}(t)$ is the residual bandwidth of $ISL(S_i \rightarrow S_j)$ and C_{\max} is the maximum residual bandwidth of all ISLs. The largest initial weight value of network residual bandwidth is 1, so the smaller residual bandwidth is, the greater weights will be. $D_{i,j}(t)$ is the transmission delay of $ISL(S_i \rightarrow S_j)$ and D_{\min} is the minimum transmission delay of all ISLs. $F_{i,j}(t)$ is the BER of $ISL(S_i \rightarrow S_j)$, F_{\min} is the minimum BER of all ISLs and $\lg(F_{i,j}(t)/F_{\min})$ is an initial weight value of the BER on $ISL(S_i \rightarrow S_j)$. α , β , γ are the link weight adjustment factor.

The initial weights of $ISL(S_i \rightarrow S_j)$ can be obtained by Eq. (1). The shortest path between the source node S to the destination node $D(S, D)$ as the critical path LSP_1 can be found by Dijkstra algorithm. Then, we can calculate N LSPs (N is generally less than 4) between the source node S to the destination node $D(S, D)$ by using Dijkstra algorithm. The Metric value is the sum of the initial weight $I_{i,j}(t)$ of each $ISL(S_i \rightarrow S_j)$ on the LSP. It can be presented as follows:

$$m_k(t) = \sum_m I_{i,j}(t)_m, \quad (m = 1, 2, \dots, M). \quad (2)$$

M is the total number of LSP_k . $m_k(t)$ is used as an initial reference by service for routing among N LSPs. Irrespective of the remaining time and the link criticality of the LSP, based on the routing priority principle of small Metric value, all traffic will be distributed to the critical link LSP_1 . In order to avoid network handoff and balance network load, the proposed algorithm also considers the stability and the criticality of the LSP to form LSP link selection probability function so that the network can dynamically distribute service over multiple LSP, which can thus reduce the impact of network handoff on service interruption, achieve service dynamic allocation and improve network utilization.

3.2 LSP link Stability Function

In LEO satellite communications systems, link stability refers to the ability to maintain ISL unblocked to provide the best data transmission. ISL between two satellites in an orbit period may have handoff several times in one orbital period [10]. LSP link stability function can be determined by the definition of ISL lifetime $T_k(S_j \rightarrow S_i)$ and residual lifetime $T(S_j \rightarrow S_i)$.

In a LEO constellation system cycle, ISL between the satellite node S_i and the satellite node S_j has handoff N times. If at the time of $t_{S_j \rightarrow S_i}^{\text{ON}}$, S_j flies into the sight line of S_i , the $ISL(S_i \rightarrow S_j)$ between them will be established; and if at the time of $t_{S_j \rightarrow S_i}^{\text{OFF}}$, S_j flies out of the sight line of S_i , the $ISL(S_i \rightarrow S_j)$ should be interrupted. The $ISL(S_i \rightarrow S_j)$ lifetime $T_k(S_j \rightarrow S_i)$ is the duration from $t_{S_j \rightarrow S_i}^{\text{ON}}$ to $t_{S_j \rightarrow S_i}^{\text{OFF}}$, which can be expressed as:

$$T_k(S_j \rightarrow S_i) = t_{S_j \rightarrow S_i}^{\text{OFF}} - t_{S_j \rightarrow S_i}^{\text{ON}}. \quad (3)$$

At the time t of the LEO orbital period, the residual lifetime $T(S_j \rightarrow S_i)$ of $ISL(S_i \rightarrow S_j)$ is defined as:

$$T(S_j \rightarrow S_i) = t_{S_j \rightarrow S_i}^{\text{OFF}} - t; (t_{S_j \rightarrow S_i}^{\text{ON}} \leq t \leq t_{S_j \rightarrow S_i}^{\text{OFF}}). \quad (4)$$

$T(S_j \rightarrow S_i)_{\min}$, the minimum residual lifetime of each $ISL(S_i \rightarrow S_j)$ of the LSP_k is the minimum residual lifetime of the LSP. If an orbital period of the LEO constellation system is T_{tol} , then the LSP link stability function is defined as:

$$w_k(t) = T(S_j \rightarrow S_i)_{\min}/T_{tol}. \quad (5)$$

3.3 LSP Link Criticality Function

When a user initiates a service request to the SDN controller, the SDN controller will calculate N LSPs for the user. Each LSP link consists of several $ISL(S_i \rightarrow S_j)$. If C_{sd} is the set of all the LSPs calculated by SDN controllers in the network and it contains all the $ISL(S_i \rightarrow S_j)$ that have been used to establish LSPs in the network. If the ISL criticality function is $g_{i,j}(t)$,

$$\begin{aligned} &\text{If } (S_i \rightarrow S_j) \notin C_{sd}, \text{ then } g_{i,j}(t) = 0; \\ &\text{If } (S_i \rightarrow S_j) \in C_{sd}, \text{ then } g_{i,j}(t) = L(t)/Z(t). \end{aligned}$$

$L(t)$ is the number of MPLS labels that have been distributed by the $ISL(S_i \rightarrow S_j)$ at the time of t , and $Z(t)$ is the total number of the LSPs established in C_{sd} .

The proposed algorithm takes the maximum value $L_{\max}(t)$ of each $ISL(S_i \rightarrow S_j)$ $L(t)$ of the LSP_k as the basis to calculate the LSP_k link criticality function $G_k(t)$, which can be expressed as:

$$g_k(t) = L_{\max}(t)/Z(t). \quad (6)$$

3.4 LSP Link Selection Probability Function

Firstly, we normalize LSP link initial weight, link stability and link criticality function, and then determine the weight of each index, and finally form LSP link selection probability function.

(1) The LSP link normalized initial weight function can be written as:

$$M_k(t) = e^{-q_1 \frac{m_k(t)}{m_{\max}}} \quad (7)$$

where q_1 is the parameter of function normalization, $m_k(t)$ is the initial weight function of the k th LSP link, and m_{\max} is the maximum initial weight value of all the LSPs. The lower the value of $M_k(t)$ is, the higher Metric value of the LSP link will be, then the LSP has lower possibility to be selected to transmit data flow.

(2) The LSP link normalized stability function can be written as:

$$W_k(t) = e^{-q_2 w_k(t)} \quad (8)$$

where q_2 is the parameter of function normalization, $w_k(t)$ is the link stability function of the k th LSP. The lower the value of $w_k(t)$ is, the worse stability of the LSP link is, then it is more possible to have handoff and the LSP has the lower possibility to be selected to transmit data flow.

(3) The LSP link criticality function can be normalized as:

$$G_k(t) = e^{-q_3 g_k(t)} \quad (9)$$

where q_3 is the parameter of function normalization, $g_k(t)$ is the link criticality function of the k th LSP. The lower value of $G_k(t)$ means the higher criticality of the LSP, and then it has the lower possibility to be selected to transmit data flow.

(4) Determining the weight of each function

The LSP link selection probability function is determined by the LSP link initial weight function, stability function, criticality function and the weight of each function. The LSP link selection probability function can be written as:

$$LSP_{(S \rightarrow D)}(t) = \omega_1 M_k(t) + \omega_2 W_k(t) + \omega_3 G_k(t) \quad (10)$$

where ω_1 , ω_2 and ω_3 is the weight of each function respectively. If the priority is $M_k(t) > W_k(t) > G_k(t)$, which is indicated by $X_1(t) > X_2(t) > X_3(t)$, then the relative importance of the indexes is represented as $r_k = \omega_{m-1}/\omega_m$ [11]. It can be expressed as:

$$\omega_m = \left(1 + \sum_{k=2}^M \sum_{i=k}^M r_i \right) - 1 \times \prod_{j=m+1}^M r_j. \quad (11)$$

Based on the importance of each function, the parameter r_k can be set as shown in Table 1. The LSP link selection probability function can set a different r_k value in each AS (Autonomous System, AS) according to service operation. Meanwhile, r_k value can be adjusted dynamically according to network load and QoS guarantee.

Table 1. Assignment table of the relative importance of the parameters r_k .

| $X_{m-1}(t)/X_m(t)$ | Same important | Slightly important | Significantly important | Greatly important | Extremely important |
|---------------------|----------------|--------------------|-------------------------|-------------------|---------------------|
| r_k | 1 | 1.2 | 1.4 | 1.6 | 1.8/2 |

4. NUMERICAL SIMULATION

4.1 Simulation Models and Parameter Setting

By using STK (Satellite Tool Kit, STK) software [12], we set up a LEO constellation model with 5 orbital planes, 6 satellites in each orbit making a total of 30 satellites, and orbit altitude of 1375 km. Within the polar region of north and south latitude 75° to 90°, ISL between two satellites located on different orbit planes is disconnected, while ISL between two satellites on the same orbit plane always remains connected. Specific parameters are listed in Table 2.

Table 2. Specific parameters of the constellation model.

| Parameters | Value | Parameters | Value |
|---------------------------------|---------|--|-------|
| Number of constellation orbit | 5 | Number of satellites in each orbit | 6 |
| Orbital inclination | 86.4° | Phase factor | 0° |
| Number of ISLs within the orbit | 2 | Orbit height | 1375 |
| ISL bandwidth | 200Mbps | Number of ISLs between adjacent orbits | 2 |

The STK software is also used to simulate satellite network topology parameters, namely environment characteristic data of satellite network (including the number of satellite nodes, link handoff time, transmission delay, location and distance relationship, *etc.*). Further, the network model of constellation system is constructed to form the network topology, link transmission delay and snapshots switching cycle. The satellite node distribution is shown in Fig. 2.

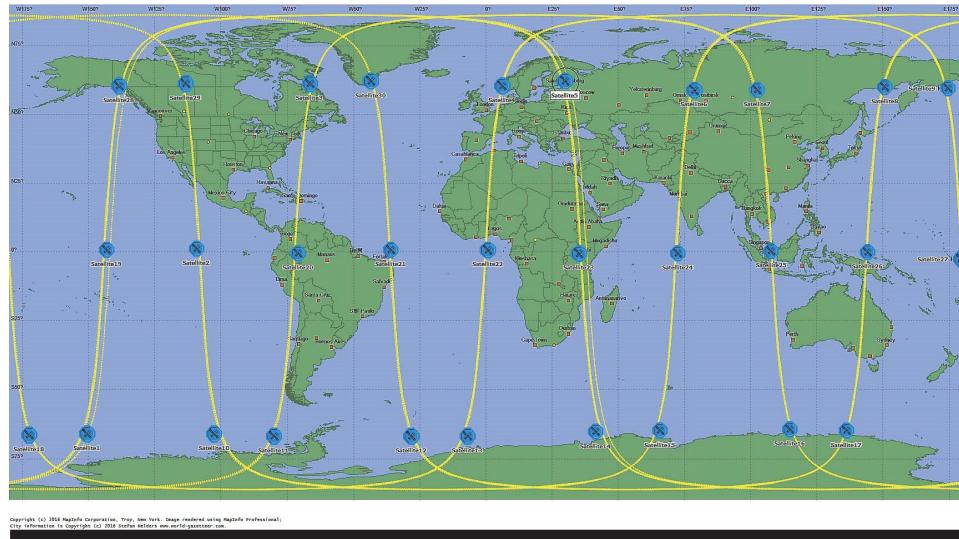


Fig. 2. The network node distribution of OPNET simulation system.

For simulation, an orbit period of the LEO constellation system form 8 snapshots and each snapshot corresponds to a network topology. The network topology and link handoff cycle and other parameters are imported into OPNET [13] where our proposed routing algorithm is also deployed. The parameters of the proposed routing algorithm in this simulation are set as: $\alpha = 1$, $\beta = 1$, $\gamma = 0.1$; $r1 = \omega_1/\omega_2 = 1.2$, $r1 = \omega_1/\omega_3 = 1.6$.

4.2 Performance Analysis

To assure the proposed routing algorithm performs properly under complicated and extreme circumstances, certain numerical simulations are conducted. The link between satellite nodes Sat-node-2 (source) and Sat-node-33 (destination) is simulated, and the packet loss rate and throughput metrics between this node pair are monitored (2, 33). IP packet should reach in the Poisson distribution, satellite status should update at regular intervals, and a satellite network running time is set as 12 hours.

The First Numerical Simulation

We set 30 (S, D) node pairs randomly in the simulated network environment to establish business connections all sending data from the source to the destination. Then we run the CSPF (Open Constraints Shortest Path First) [14], WSP (Widest Shortest Path) [15] and our proposed algorithm respectively. With the link load increased, the average packet loss ratio (as in Fig. 3) and throughput metrics (as in Fig. 4) are compared among algorithms.

CSPF defines the link weights with the inverse ratio of the link bandwidth or the link residual bandwidth. The route computing depends entirely on the link bandwidth.

WSP leads the service to the link with a large bandwidth, while minimizing the length of the transmission path. This algorithm calculates the source and the destination node links above the bandwidth requirement, and then selects the shortest link.

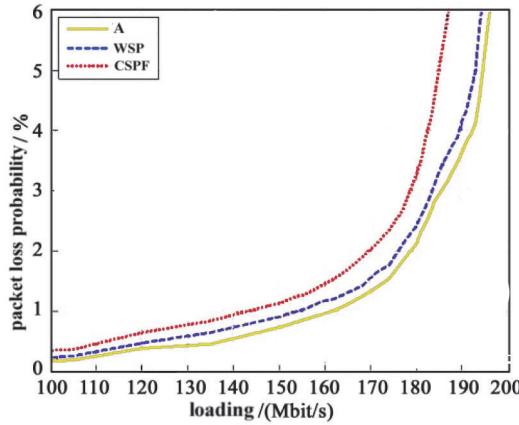


Fig. 3. The packet loss rates curve calculated by different algorithms.

As shown in Fig. 3, when loading is greater than 120Mbps, the packet loss rate of the proposed algorithm (A) is consistently the lowest among three algorithms. For example, in the region of loading between 140 ~ 180Mbps, A is lower than WSP for an average of 0.3%, and lower than CSPF for an average of 0.84%. Additionally, a sharp rising of the packet loss rate curve is observed for all three algorithms once loading reaching 180Mbps. These results show that the performance of our proposed routing algorithm (A) excellent in link stability.

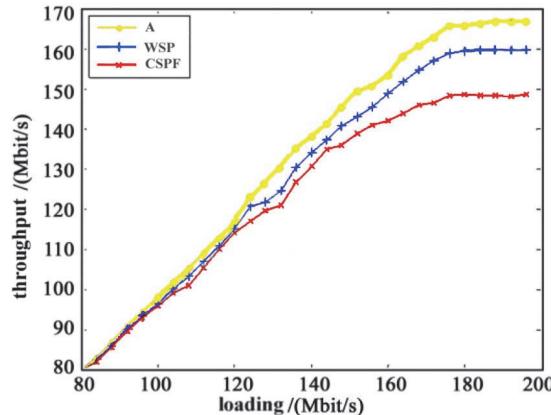


Fig. 4. The throughputs curve calculated by different algorithms.

In comparing the throughputs of A, WSP and CSPF, no obvious difference is observed when loading lower than 120Mbps. However, with loading rises above 120Mbps, the throughput performance of A is gradually but significantly better than those of WSP and CSPF, reaching the largest difference of 10Mbps and 30Mbps than WSP and CSPF respectively (Fig. 4). This figure demonstrates that the throughput of our proposed routing algorithm (A) has strong network load balancing ability resulting in higher level of throughput when network loading increases.

The Second Numerical Simulation

A data packet is sent from satellite source node Sat-node2 to destination node Sat-node-33 every second. Subsequently, CSPF and our routing algorithm (A) are run on the simulation system. The transmission delay of these two algorithms within 1 hour is counted respectively.

As in Fig. 5, the average delay of both routing algorithms is between 120-160ms, with (A) algorithm slightly higher than CSPF. But at the moment of ISL handoff or network topology changes, CSPF delay jumps suddenly for about 20ms than the normal delay. This clear end-to-end delay jitter is caused by route recalculation and convergence, which is not observed with our proposed algorithm (A).

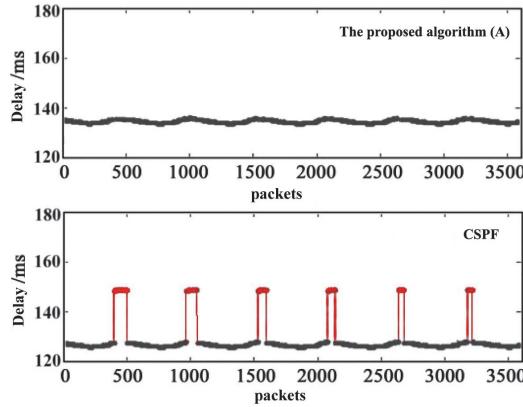


Fig. 5. The delay curves calculated by CSPF routing algorithm and the proposed routing algorithm.

5. CONCLUSIONS

We have presented a new routing algorithm based on SDN satellite on-board switching networks. The deployment of a centralized routing algorithm on SDN controller enables more rational network traffic allocation and enhances QoS supporting capability. During the packet routing process, the proposed algorithm integrates multiple parameters including delay, bandwidth, BER, handoff and load *etc.*, resulting in better balanced network flow, improved network utilization and reduced loss and delay jitter by the ISL handoff. Compared with currently available algorithms, the proposed algorithm exhibits superior performance in terms of packet loss ratio, throughput, average transmission delay and delay jitter.

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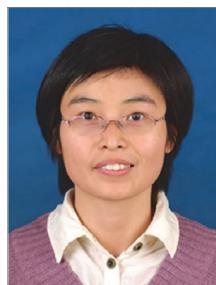
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