Reliability analysis of software-defined satellite network based on control delay

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Abstract. At present, there are few studies about the link failure and reliability of software defined satellite network (SDSN). However, the inter-satellite links (ISLs) may break down because of the long distance between the satellites, the high relative moving speed and the easy interference of the wireless channel. At the same time, most researches on controller deployment in SDSN only consider the transmission delay but ignore the processing delay. To solve these problems, considering the failure probability of intersatellite link, the failure probability model of ISLs is designed, the queuing delay and processing delay are added into the delay model, and the software defined satellite network reliability analysis model based on control delay is established. This model can describe the reliability of the network against link failure. The simulation results show that the model is consistent with the actual situation and can provide some reference value for controller deployment in SDSN.

1. Introduction

There are many problems in the traditional satellite network, such as the coexistence of various protocols, poor network expansibility and high cost of satellite nodes. Introducing the software defined network (SDN) into the satellite network is widely seen as a solution to these problems. Through the separation of control and forwarding and the centralized control of the controller, the switch can only assume the forwarding function, which can reduce the equipment cost, enhance the network scalability and realize the fast response to the network demand[1-2].

The construction of control layer is the key to the application of SDN in satellite network. More and more experts begin to study this problem, but there is still little research on the reliability of the controller deployment. In addition, the research on reliable deployment of ground SDN wide area network controller has been relatively mature, from which we can draw lessons:

The centrality of nodes is described with graph theory and the deployment of controllers are completed based on the reliability of control delay in [3]. However, the modeling of control delay is too simple and the link is considered to have the same failure probability. A multi-controller placement algorithm is proposed in [4]. The mean cumulative delay is defined by comprehensively considering primary path delay and backup path delay, but the link failure probability is neglected. Literature [5] established the probability model of link failure and optimized the deployment controller based on reliability and load. However, only propagation delay was considered. Jie Lu, et al [6] optimized the controller deployment location by using the control path failure probability, control delay and load standard deviation, and designed the controller deployment algorithm by using the clustering idea. In this paper, only propagation delay is considered.
Due to the high relative motion speed between satellite network nodes and time-varying topology, ISLs are greatly affected by distance, environment and other factors, and the failure probability of ISLs is different. Existing reliability research on controller deployment of ground network cannot be directly used in satellite network, so the reliability analysis method suitable for satellite network needs to be improved according to the characteristics of satellite network. Based on the definition of control delay and link failure cost, the SDSN performance and reliability analysis model is established in this paper. The queuing delay and processing delay are taken into account when defining the control delay. The simulation results show that the model is consistent with the actual situation.

2. Architecture of software defined satellite network
Considering the difficulties and high cost of building satellite earth stations around the world; the processing and forwarding capacity of geosynchronous orbit (GEO) satellites cannot adapt to the rapidly increase of the number of low orbit (LEO)satellites and satellite network business; and the large delay of GEO satellite communication to earth, etc[2,7-10]. We choose to place the super controllers in network control center/network management center (NCC/NMC), deploy the regional controllers on GEO, and set the slave controllers on software defined low earth orbit (SD-LEO) [10]. This architecture controls the entire network by utilizing the powerful computing power and sufficient storage space on the ground. GEO satellites maintain a stable connection with the ground stations, and the insufficient computing and storage capacity of GEO is supplemented by slave controllers.

The whole SDSN network is divided into several control domains according to the number of GEO satellites and their coverage areas. Each control domain contains a regional controller, multiple slave controllers and many SD-LEO. Each control domain is divided into several subdomains, in which the slave controller manages the SD-LEO belongs to it. The following analysis of control delay and link failure costs is based on one control domain in the network with its slave controller and SD-LEO as examples. The same analysis method can also be applied to other control areas in the network.

3. Reliability analysis model of software defined satellite network
This paper deals with the dynamic satellite network topology by using the time slice partition idea. A cycle of satellite orbit is divided into several time slices, and the network topology and service are relatively stable in each time slice. The topology of SDSN control domain in one time slice can be expressed as \(G=(V,E)\), where \(V\) represents the set of nodes, network node is represented by \(v_i\), \(E\) represents the set of links, and ISL is represented by \(e_{ij}\). The number of SD-LEO is \(N\), and the number of slave controllers is \(M\). The set of slave controllers is \(C=\{c_1,c_2,…,c_M\}\), The set of SD-LEO is \(S=\{S_1,S_2,…,S_N\}\). The shortest distance between two nodes is denoted by \(d(G)_{ij}\). Network traffic can be expressed as a function of time, and the flow request rate of the \(n'\)th SD-LEO in one time slice can be expressed as \(\lambda(t)\). Matrix \(X(G)_{ij}\) is used to describe the connection relationship between slave controller and SD-LEO in SDSN control domain, the value of its elements are shown in formula (1).

\[
x_{ij} = \begin{cases} 
1, & \text{if SD-LEO was controlled by } c_i \\
0, & \text{others}
\end{cases}
\]

3.1. Control delay between slave controllers and switches
The control delay \(AT(t)\) between SD-LEO and slave controllers can be divided into three parts: queuing delay \(Q(t)\), processing delay \(P(t)\) and propagation delay \(T(t)\). Queuing delay refers to the delay caused by packets queuing on the input port of the controller; Processing delay refers to the delay caused by the controller to process packets; Propagation delay refers to the delay caused by packet propagation between satellite nodes.

Queuing delay and processing delay is related to the request rate of SD-LEO in the control subdomain and the remaining processing capacity of slave controller. When the controller has sufficient processing capacity, in order to simplify the operation, we can assume that the queuing delay and processing delay of all SD-LEO in the network to the slave controller are approximately
equal. The transmission delay is related to the length of ISL between SD-LEO and slave controller. The flow request to be processed by the \( i \)’th slave controller per unit time is set as \( L(t)_i \). \( T(t)_i \) is the average transmission delay between SD-LEO and slave controller in a control subdomain. \( AT(t) \) is the average control delay of the entire control domain.

\[
L(t)_i = \sum_{j=1}^{N} \hat{a}(t)_j x(G)_j \\
T(t)_i = \frac{\sum_{j=1}^{N} (\hat{a}(t)_j x(G)_j \hat{d}(G)_j)}{c/L(t)_i} \\
AT(t) = \frac{\sum_{i=1}^{M} \left[ L(t)_i (Q(t)_i + P(t)_i + T(t)_i) \right]}{\sum_{i=1}^{M} L(t)_i}
\]

### 3.2. Failure probability analysis of inter-satellite link

ISLs in satellite networks can be divided into two types: inter-plane intersatellite links and in-orbit intersatellite links, among which the in-orbit intersatellite links are relatively stable, while in-orbit intersatellite links are usually closed when the satellite passes near the pole (the absolute value of the satellite latitude is greater than 60°) due to the interference problem [11]. So, the failure probability of unit length of inter-plane ISLs should be higher than that of intra-plane ISLs.

**Definition 1:** ISL failure probability \( P(e_{ij}) \). \( P(e_{ij}) \) is related to the length of ISLs. In order to facilitate calculation, it can be simplified into a proportional relationship. ISL failure probability per unit length is \( P(e_{ij})_{\text{unit}} \). inter-plane ISLs and intra-plane ISLs have different \( P(e_{ij})_{\text{unit}} \) values. Take the unit length to be equal to 10^3 km.

\[
p(e_{ij})_{\text{unit}} = \begin{cases} 
\min(0.005 \cdot n, 1), & \text{intra - plane ISLs} \\
\min(0.006 \cdot n, 1), & \text{inter - plane ISLs}
\end{cases} \\
P(e_{ij}) = \begin{cases} 
\min\left(\frac{d_{ij} \cdot p(e_{ij})_{\text{unit}}}{x_{ij}}, 1\right), & x_{ij} = 1 \\
1, & x_{ij} = 0
\end{cases}
\]

### 3.3. Node reliability

**Definition 2:** Eigenvector centrality \( E(v_i) \) reflects the centrality of neighboring nodes of the node. \( \alpha \) is a standardized constant. \( \beta \) reflects the influence of neighboring nodes on the centrality of the node. \( y_{ij} \) is the adjacency matrix of \( G \). \( \lambda_i \) is the degree of the node \( v_i \). \( B(v_i) \) is defined as the number of nodes whose control delay lower than the limited value when the node is used as a slave controller. the maximum control delay is \( \sigma \).

\[
D(v_i) = \frac{\lambda_i}{N - 1} \\
E(v_i) = \sum_{v_{ij}} (\alpha + \beta D(v_j)) y_{ij} \\
B(v_i) = \frac{\sum_{v_{ij}} 1 - \min\left(\frac{AT(t)}{\sigma}, 1\right)}{\max(B(v_j))}
\]

**Definition 3:** Node reliability \( R(v_i) \). \( R(v_i) \) is determined by \( B(v_i) \) and \( E(v_i) \). The value can represent the reliability of the node. The larger the \( R(v_i) \), the stronger the node's ability to cope with link failure in the network, and the more suitable it is to deploy a slave controller. \( \lambda \) is the weight coefficient.

\[
R(v_i) = \lambda E(v_i) + (1 - \lambda) B(v_i)
\]
3.4. Link failure cost

By default, at most one link in the network fails at a time. After the failure of link $e_{ij}$, the network topology changes and the control delay changes accordingly. At this time, the network topology is represented by $G-e_{ij}$.

**Definition 4**: link failure cost $\delta(e_{ij})$. $\delta(e_{ij})$ represents the value added of the average control delay in the control domain when link failure occurs. Set the network control delay to $AT(t)'$ after link failure, then:

$$AT(t)' = AT(t)_{e_{ij} \rightarrow G-e_{ij}}$$ (11)

$$\delta(e_{ij}) = AT(t)' - AT(t)$$ (12)

**Definition 5**: deployment plan failure cost $\delta(t)$. $\delta(t)$ is the sum of link failure probability multiplied by link failure cost of all directly connected links [3]. The parameter can represent the network's bearing capacity to link failure. The smaller this value, the stronger the network's ability to cope with link failure and the higher its reliability.

$$\delta(t) = \sum_{e_{ij} \in \delta} \delta(e_{ij})P(e_{ij})$$ (13)

4. Simulation and Analysis

4.1. Simulation environment

In the experiment, Matlab 2016b was used to simulate the algorithm and analyze the experimental results. The satellite orbit simulation was carried out using STK11.01. The topology parameters of the LEO satellite network were adjusted based on Iridium[12].

The simulation parameters are set as follows: differentially select the value of SD-LEO flow request rate $\lambda(t)_n$, and set its value range to 100kB/s~500kB/s to simulate the satellite network traffic characteristics. $\alpha=0$, $\beta=1$, $\lambda=0.5$. The queuing delay and processing delay of all SD-LEO controllers in the network are set to 4ms and 6ms respectively.

4.2. The impact of slave controller number on network performance

This experiment explores the impact of the number of slave controllers deployed on network performance and reliability. This experiment is carried out under the same business traffic and topology, $n$ was taken as 20. K-means method is used to calculate the deployment location and control domain division based on the network shown in Fig.1. Results are shown in Fig.2.

It can be seen that with the increase of the number of controllers deployed in the network, the network control delay and the failure cost of deployment scheme are reduced, and the simulation results are consistent with the actual situation. However, due to the high deployment cost of slave controllers, network performance is generally not improved by simply increasing the number of slave controllers, but by pursuing a balance between deployment cost and network performance and reliability.
4.3. The impact of controller deployment location on the network performance

This experiment was carried out under the same control subdomain partition, the slave controllers are deployed at different locations, and the network control delay and deployment scheme failure cost are analyzed. The network multi-domain partition is shown in Figure 4. Three plans are used for comparison. The slave controller deployment at \{4,10,16,22\} in deployment plan 1, \{7,9,17,19\} in deployment plan 2, \{1,5,21,25\} in deployment plan 3. The reliability of selected nodes is shown in Figure 5. The node reliability of plan 2 is the highest, while that of plan 3 is the lowest.

The control delay and failure cost of the three deployment plans are shown in Figure 6. By analyzing the failure cost of the three deployment plans, it can be seen that selecting the node with high node reliability can effectively improve the network reliability. Through the comparisons of plan 1, 2 and 3, we can see that the controller deployment location plays an important role on the performance and reliability of the network, the optimization deployment location may improve network performance and reliability at the same time, planned deployment can obtain better effect than random deployment. The comparison between plan 1 and 2 shows that the network performance and reliability cannot be improved indefinitely. Under normal circumstances, it is necessary to find a balance between the network performance and reliability.

4.4. Influence of domain partition on network performance

The control delay and deployment failure cost of different schemes are compared in this experiment (AMDA [13], K-means [14], ILP [15]). The domain partitioning results obtained by the three different methods are shown in Figure 6. Different graphs represent different control subdomains in this figure. The comparison between plan 1 and 2 shows that the network performance and reliability cannot be improved indefinitely. Under normal circumstances, it is necessary to find a balance between the network performance and reliability.
partition can improve network performance and reliability. By comparing AMDA and ILP, we can see that the improvement of network performance is often accompanied by the decline of network reliability, so it is necessary to select an appropriate domain partition according to the actual demand.

5. Conclusion
In this paper, the difference of ISLs’ failure probability in SDSN is considered, and the queueing delay and processing delay are added into network delay model, and the analysis method of performance and reliability of SDSN is established. At the same time, the consistency between this model and the theoretical results is proved by the simulation experiment.

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