DCTG: Degree Constrained Topology Generation Algorithm for Software-defined Satellite Network

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Abstract

With the increasing number of satellites, the problem of satellite networking becomes more and more important. However, due to the limited link resources of satellite nodes, it is difficult to comprehensively consider the limited number of satellite node connections in the existing network. In this paper, we define the degree of satellite as the number of link connections for satellite nodes. In the software-defined satellite network, we put forward the node model and link model under degree constraints. Besides, we propose a heuristic algorithm for satellite network topology generation based on link weight based on the software-defined satellite network under the constraint of degree. Simulation results show that the heuristic algorithm has better average link bandwidth, average link rate and average link delay than the traditional degree-constrained shortest path algorithm.

Keywords: Degree Constrained, Software-Defined Satellite Networks, Topology Algorithm

1 Introduction

The software-defined satellite network [8][10] has significant advantages over the traditional satellite network. The centralized management and control architecture is conductive to the unified management of the whole network. The controller has a global view of the network, which can uniformly process routing calculation and resource allocation. The software-defined satellite network separates the control plane and the forwarding plane of the satellite network through network entities such as controllers and repeaters, and realizes the decoupling of the control logic and the forwarding function, effectively solving the problem of tight processing resources on the satellite.

In the satellite network, the communication between satellite nodes is mostly by means of laser link. However, the satellite laser communication system is composed of relatively independent modules. The modular function affects the overall integration of the hardware. On the relatively compact satellite nodes, independent modules have certain constraints on the number of satellite laser links. The limited number of link connections puts forward higher requirements for the design of the satellite network topology. The existing satellite topology research mainly focuses on the topology design under the optimal strategies such as the shortest distance, the maximum resource utilization, and the longest link connection time. Unfortunately, in software-defined satellite networks, there is little consideration of the topology design with a limited number of node link connections to meet the actual hardware conditions of different types of satellite nodes with different network functions.

The rest of this paper is organized as follows: In section 2, we review related works about software-defined satellite networks and topology generation algorithms. In section 3, we mathematically model

Journal of Internet Services and Information Security (JISIS), volume: 9, number: 4 (November, 2019), pp. 49-58
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the degree constrained software-defined satellite network. In section 4, we propose a heuristic algorithm DCTG for generating satellite network topology based on link weight. In section 5, we evaluate the performance of the proposed heuristic algorithm. In section 6, we make a summary and discuss future work.

2 Related Work

Recently, combined with software-defined satellite networks to integrate ocean, land and space networks into a satellite-terrestrial network is one of the main research trends. For example, Zhu *et al.* [15] proposes a software-defined satellite network architecture that uses the idea of software-defined networks for satellite networks, and provides a detailed description of the advantages and challenges of software-defined satellite networks. Bao *et al.* [5] puts forward a new type of satellite network architecture called OpenSAN, which separates the forwarding node and the control node in the satellite node, and realizes the decoupling between the data layer and the control layer. However, the above research focuses more on the architectural design of the network, and does not elaborate on the design of network topologies.

The existing research on satellite network topology can be divided into two categories, either within single-layer satellite network topology or within the multi-layer satellite network topology. The former is to design the LEO/MEO/GEO (Low/Medium/Geosynchronous Earth Orbit) single-layer satellite network topology without considering the inter-layer links. Xiao *et al.* [16] proposed an LEO layer satellite network capacity model, and proposed a reverse inter-satellite link topology strategy to reduce link load. In order to reduce the number of repeated inter-satellite links, Hussein *et al.* [7] presented a topology method based on energy perception. Dong *et al.* [6] proposed a hybrid topology architecture based on the GEO orbit distributed satellite cluster network; And the latter is about the design of multi-layer satellite network topology. In order to establish an inter-layer link and an intra-layer topology that meets the requirements, the multi-layer satellite network topology design needs to consider the characteristics between the orbit. In the structure of the IGSO/MEO two-layer satellite network, considering the beam coverage of laser beam, Yan *et al.* [17] put forward an inter-layer link establishment strategy which is high-orbit-centric. Ma *et al.* [11] took the dynamics of satellite network topology into consideration, proposed a two-layer satellite network topology that can optimize network time slice. Li *et al.* [18] designed a new zero phase factor LEO/MEO double-layer optical satellite network under the strict requirements of optical satellite communication for ATP (Acquisition Tracking and Pointing).

Although the above research have expounded the topology design of the single-layer and multi-layer satellite networks from different perspectives, all of them have not considered the scarcity of satellite resources, and the limited number of satellite laser transmitting/receiving modules, which is difficult to apply in laser satellite communication networks. Therefore, we propose a satellite network topology which can satisfy the limited number of link connections.

In this article, we propose a heuristic algorithm based on link weights for degree constrained software-defined satellite network topology. It aims to comprehensively consider the various characteristics of the software-defined satellite network link, and to generate a satellite network topology with good transmission performance.

3 Network Modeling And Problem Formulation

In this section, we will introduce the network modeling and the problem formulation.

3.1 Network Modeling

Based on Graph theory, we model the software-defined satellite network as an undirected graph $G = \{V, E, W\}$. V and E represent the vertex of satellite nodes and potential satellite links in the degree constrained software-defined satellite network, respectively. W is a matrix of w_{ij}, representing the comprehensive performance of the overall network.

3.1.1 Satellite Model

The node number, degree constraint, node function and satellite cluster in the software-defined satellite network are some of the main factors we consider. Therefore, based on these factors, we can build a model of $Sat = \{number, degree, function, cluster\}$ for satellite nodes in a software-defined satellite network.

Sat represents the satellite node in the software-defined satellite network; *number* and *degree* represent the number and degree constraints of the satellite node, respectively; *function* is the function carried by the satellite node in the software-defined satellite network, such as control function or forwarding function; *cluster* represents the group of satellite nodes in the software-defined satellite network, which can be divided into LEO/MEO/GEO orbital groups according to orbital altitude, or satellite groups arranged according to specific functional requirements.

3.1.2 Link Model

The link model in software-defined satellite network can be represented as follows:

$$Link = \{L\_node, s\_time, e\_time, weight, type\}$$

L_node is a binary variable, which indicates the satellite node of two endpoints of the satellite link; *s_time* and *e_time* represent the start and end times of the potential inter-satellite links in the software-defined satellite network, respectively. Due to the time-varying and dynamic characteristics of the satellite network, the state of the inter-satellite link will switch frequently. We define the start and end time of the two satellites from the visible to invisible time period as the *s_time* and *e_time* of the link; *weight* indicates the weight of the link, which is a parameter that comprehensively characterizes the link quality between two satellite nodes; *type* refers to what type of link this link belongs to. In software-defined satellite network, satellite links can be divided into three types, namely, the control layer link, the forwarding layer link, and the control-forwarding layer link.

For the link weight w_{ij} between two nodes in the software-defined satellite network, we consider five parameters (bandwidth b_{ij}, average link distance d_{ij}, delay t_{ij}, loss rate l_{ij} and transmission rate r_{ij}) that mainly affect the transmission quality of the each link. The comprehensive evaluation index w_{ij} of the link weight is as follows.

$$w_{ij} = \alpha \cdot b_{ij} + \beta \cdot \frac{1}{d_{ij}} + \gamma \cdot \frac{1}{t_{ij}} + \delta \cdot \frac{1}{l_{ij}} + \varepsilon \cdot r_{ij} \qquad (\alpha + \beta + \gamma + \delta + \varepsilon = 1) \tag{1}$$

The influence factors characterizing the different characteristics of the link can be obtained by the following method [13].

$$\hat{X} = \frac{X - X_{min}}{X_{max} - X_{min}} + \rho, \qquad X \in \{b_{ij}, d_{ij}, t_{ij}, l_{ij}, r_{ij}\} \tag{2}$$

$$\theta_X = \frac{\sigma_{\hat{X}}}{\mu_{\hat{X}}} \tag{3}$$

Equation (2) indicates the maximum-minimum normalization of the five parameters. Equation (3) represents the degree of influence of the parameter, $\sigma_{\hat{X}}$ and $\mu_{\hat{X}}$ represent the standard deviation and the mean of the parameter $\hat{X}$, respectively. The specific values of the influence factors α, β, γ, δ and ε can be calculated by the equation (4).

$$\alpha(\beta,\gamma,\delta,\varepsilon)=\frac{\theta_{b_{ij}}(\theta_{d_{ij}},\theta_{t_{ij}},\theta_{r_{ij}},\theta_{l_{ij}})}{\theta_{b_{ij}}+\theta_{d_{ij}}+\theta_{t_{ij}}+\theta_{l_{ij}}+\theta_{r_{ij}}} \tag{4}$$

3.2 Problem Formulation

In the software-defined satellite, we divide the satellite node vertex set V into the control node vertex set V^c and forwarding node vertex set V^f, $V = V^c \cup V^f$ and $V^c \cap V^f \neq \varnothing$. In order to facilitate the exchange of control information, the control nodes are connected in pairs. In the following work, we represent the software-defined satellite network topology generation problem under the degree constraint as an ILP optimization problem. The goal of the optimization model is to maximize the link weight of the overall satellite network under the premise of satisfying degree constraints.

Objective:

$$max \sum_{(i,j)\in V} x_{ij}\cdot w_{ij} \tag{5}$$

Constrains:

$$\sum_{i} x_{ij}=2,\sum_{i,j} x_{ij}=N^c,\forall(i,j)\in V^c \tag{6}$$

$$\sum_{(i,j)\in V^f} x_{ij}\leq \sum_{i\in V^f} D_i-(\sum_{i\in V^c} D_i-2N^c) \tag{7}$$

$$\sum_{j\in V} x_{ij}\leq D_i \tag{8}$$

$$x_{ij}\in\{0,1\},\forall(i,j)\in V \tag{9}$$

Equations (6) ensure that the control layer nodes are connected in pairs; Equation (7) constrains the number of control layer links; Equation (8) imposes degree constraints on nodes in the software-defined satellite network; Equation (9) gives constraints on satellite link values.

4 Algorithm

Based on the degree constrained software-defined satellite network model, we propose a heuristic degree constrained topology generation (DCTG) algorithm. The core of the algorithm is to generate a topology that maximizes the link weight of the overall network according to the link weight without violating the degree constraint.

Before using the algorithm to generate the topology, the data need to be preproced in the following two steps. Firstly, Obtain the link information, calculate link weight w_{ij}, and generate link weight matrix W. Secondly, Generating a matrix M that sorts w_{ij} from large to small and contains satellite node information.

The pseudocode of the DCTG algorithm is shown in Algorithm 1. The set P and Q represent the temporary vertex set and the final vertex set of the generated topology, respectively. The matrix T is composed of x_{ij} and represents the connection matrix of all nodes in the generated topology. D_i, D_j are temporary variables that characterize satellite node degree constraints. D_{loop} represents the degree of the constraint of the nodes forming the loop in the set P. We use the D_{loop} constraint to avoid the existence of independent loops in the resulting topology.

Algorithm 1 Degree Constrained Topology Generation Algorithm.

Input: The link weight w_{ij} of Software-defined Satellite Networks, Satellite constraint degree D_i ;
Output: The topology matrix T of Degree constrained Software-defined satellite network;

Initial set P and Q, Initial matrix T, Initial constant k, D_i, D_j = 0;
while k $\leq$ len(M) **do**
  choose M[k] which represent link x_{ij};
  if d_{ij} == INF **then**
    continue;
  else
    if both $D_i, D_j \neq 0$ **then**
      if i or j not in set P **then**
        $D\_i = D_i - 1$, $D\_j = D_j - 1$;
        put i or j in set P;
      end if
      if no loop in set P **then**
        update set Q use set P, update D_i, D_j use D_i, D_j;
        put link x_{ij} in matrix T;
      else
        if D_{loop} in all the loop node == 0 **then**
          update set P use set Q;
        else
          update set Q use set P, update D_i, D_j use D_i, D_j;
          put link x_{ij} in matrix T;
        end if
      end if
    else
      continue;
    end if
  end if
  k += 1;
end while

5 Simulation Results

In order to verify the feasibility and effectiveness of the DCTG algorithm, we use the GEO/MEO/LEO three-layer satellite network constellation in [14] as the experimental constellation, including 3 GEO satellites in the same orbit, 10 MEO satellites in two orbits and 66 LEO satellites in six orbits. The constellation parameters and inter-satellite link parameters are shown in Table 2, Table 3 [9]. We use Systems Tool Kit (STK) [3] software to simulate the 24-hour movement of the satellite nodes to obtain link information. The simulation track of the GEO/MEO/LEO three-layer satellite network is shown In Figure 1.

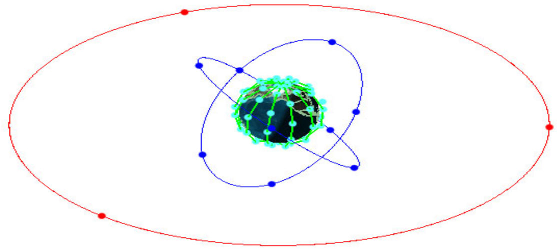


Figure 1: The Orbit Simulation of Software-defined Satellite Network

Table 1: The Orbit Parameters of Software-defined Satellite Network

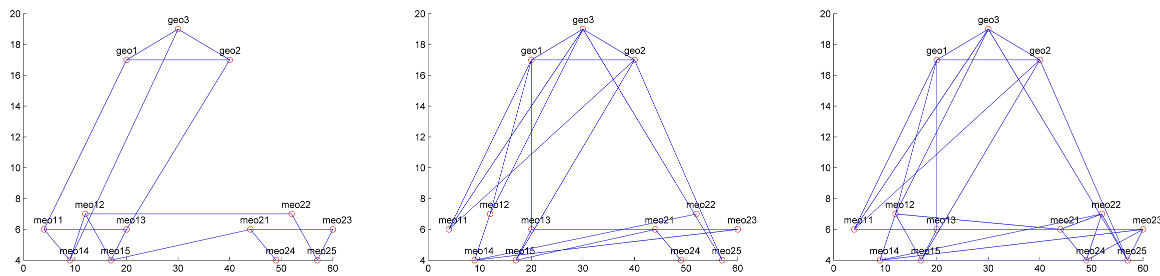
Orbit	Orbit height	Orbit inclination	Number of satellites
GEO	36000 KM	0	1*3
MEO	10390 KM	45	2*5
LEO	780 KM	90	6*11

Table 2: The Link Parameters of Software-defined Satellite Network

	GEO				MEO				LEO			
	b_{ij} *(Mbps)*	t_{ij} *(ms)*	l_{ij} *(%)*	r_{ij} *(Mbps)*	b_{ij} *(Mbps)*	t_{ij} *(ms)*	l_{ij} *(%)*	r_{ij} *(Mbps)*	b_{ij} *(Mbps)*	t_{ij} *(ms)*	l_{ij} *(%)*	r_{ij} *(Mbps)*
GEO	2K	250	5	1K	500	145	3	300	/	/	/	/
MEO	500	145	3	300	1K	85	1.5	655	500	50	0.5	300
LEO	/	/	/	/	500	50	0.5	300	500	15	0.15	300

We used the OpenStack [2] platform to simulate 79 satellite nodes ($N = 79$), and simulated the satellite nodes with the Linux virtual machine of Ubuntu 16.04 [4] operating system. Due to the good coverage of GEO satellites, we deployed the controller on the GEO layer satellite ($N^c = 3$). The MEO/LEO satellite is used as the forwarding node ($N^f = 69$). Between the control node and the forwarding node, we use the Openflow [12] protocol. The forwarding node uses the Delay-Tolerant Networking [1] protocol for communication. The average link length of satellite visibility information invariant slot is chosen as the d_{ij}, the adjustment parameter ρ is set to 0.1, and the values of the five influencing factors α, β, γ, δ and ε are calculated to be 0.31, 0.26, 0.07, 0.05 and 0.31, respectively.

Firstly, the DTCG algorithm under different constraints is analyzed. Figure 2(a) and Figure 2(c) represent the software-defined satellite network topology between the GEO layer and the MEO layer satellite when the control node and the forwarding node constraint degree D_i are 3 and 5, respectively. Figure 2(b) shows the topology of the GEO and MEO layer network when the control node constraint degree D_i is 5 and the forwarding node constraint degree D_i is 3. It can be seen from the three given pictures that the DTCG algorithm proposed in this paper can dynamically adapt to scenarios with the same or different constraint degrees of satellite nodes in the software-defined satellite network. The DCTG algorithm is capable of generating the required topology that is consistent with the degree of satellite node constraints. From another point of view, as the degree of satellite node constraint increases, the satellite network topology is constantly changing, and the number of layers and the number of connections and connections in the layers have changed significantly. In Figure 2(a) with the constraint degree of 3, it can be seen that the number of inter-layer links is only three, and the intra-layer links are relatively simple; as the node constraints increase, In Figure 2(c), the node constraint degree is 5, the number of inter-layer links is increased to nine, and the intra-layer links become complicated. As the constraint degree of nodes increases, the number of potential links selected by the DTCG algorithm increases. The network topology generated by the DTCG algorithm becomes more complex, but the stability of network topology increases, which can effectively avoid the failure of the whole network topology caused by single node and single link fault.



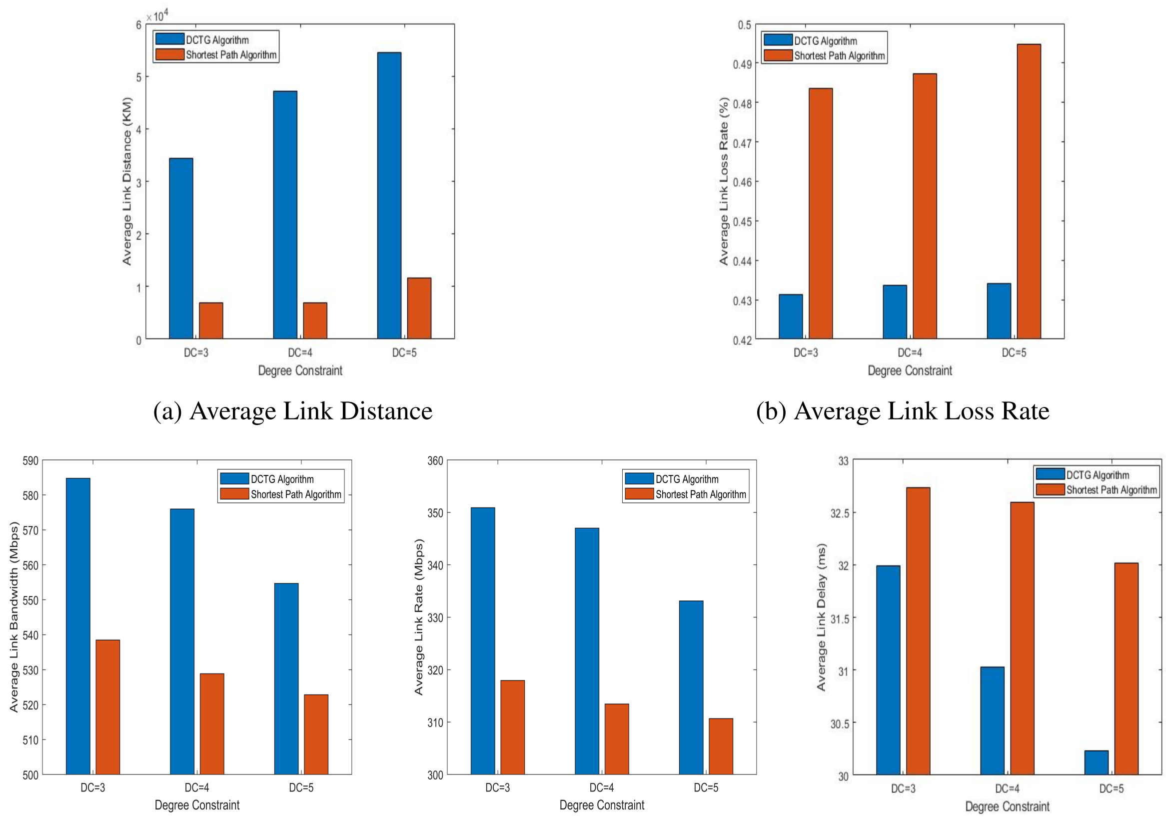
(a) $D_i = 3$ (b) $D_{N^c} = 5, D_{N^f} = 3$ (c) $D_i = 5$

Figure 2: The topology generated by the DCTG algorithm

In Figure 3(a) to 3(e), we compare the DTCG algorithm with the degree constrained shortest path algorithm. DCTG algorithm and degree constrained shortest path algorithm is analyzed from five aspects of average link distance, average link packet loss rate, average link bandwidth, average link transmission rate and average link delay when all GEO, MEO, and LEO satellite nodes have constraint degrees of 3, 4 and 5. The average link distance, loss rate, bandwidth, transmission rate, and delay means the total link distance, loss rate, bandwidth, transmission rate and delay of the network divided by the number of links in the generated topology.

It can be seen from Figure 3(a) and Figure 3(b) that as the degree of constraint of the satellite node increases, the average link length and average link loss rate of the topology generated by the DTCG algorithm and the degree constrained shortest path algorithm are increasing; Figure 3(c), Figure 3(d) respectively represent the average link bandwidth and the average link transmission rate of the topology generated by the DTCG algorithm and the degree constrained shortest path algorithm under different constraints. With the increase of node constraint degree, the values of the two corresponding parameters also decrease. This is because the DTCG algorithm and degree constrained shortest path algorithm are both based on the greedy algorithm to make the optimal topology link selection. As the node degree constraint increases, the non-optimal link corresponding to each satellite node will also be selected. The quality of satellite link will be reduced as a result. Figure 3(e) is different from the above, the average link delay decreases as the degree of node constraint increases. This is because the selection of inter-layer links tends to be fixed with the increase of node constraint degree. Most newly added links belong to intra-layer links, which are mainly reflected in the increase in the number of connections in LEO layer. The increase in the number of low-delay links in LEO layer will inevitably reduce the average link delay of the overall network topology.

The performance difference between the DCTG algorithm and the degree constrained shortest path algorithm are compared horizontally from five aspects of average link distance, average link bandwidth, average link transmission rate, average link loss rate, and average link delay. It can be seen from the Figure 3(a) that the DCTG algorithm does not perform as well as the degree constrained shortest path algorithm in the performance of the average distance of the link. Under different constraint degrees of satellite nodes, the average link distance of topology generated by DCTG algorithm is significantly higher than the degree constrained shortest path algorithm. DCTG algorithm compared to the degree constrained shortest path algorithm, not only concerns the link from link distance feature, and comprehensive consideration to other kinds of link parameters such as link bandwidth, link delay and so on.



(a) Average Link Distance (b) Average Link Loss Rate

(c) Average Link Bandwidth (d) Average Link Rate (e) Average Link Delay

Figure 3: $D_i = 3,4,5$, The performance between DCTG and Shortest Path algorithm

DCTG algorithm sacrifices some of the link distance performance, but has better considerations for other link parameters, which can be reflected from Figure 3(b) to Figure 3(e). Figures 3(b) and Figure 3(c) show the average link loss rate and the average link bandwidth, respectively. It can be seen intuitively that the DCTG algorithm is superior to the degree constrained shortest path algorithm in terms of average link bandwidth and average link rate. Similarly, as can be seen in Figure 3(d) and Figure 3(e), DCTG algorithm can outperform the degree constrained shortest path algorithm in terms of average link rate and average link delay.

The DCTG algorithm proposed in this paper can adapt to the scenario of the same and different satellite node degree constraints. The generated network topology can improve the stability of the network and avoid the failure of the whole network topology caused by single node and single link fault. In addition, the DCTG algorithm comprehensively considers the link characteristics. Compared with the degree constrained shortest path algorithm, the performance of other link characteristics is significantly improved at the expense of the average link distance. When the influence factors such as β, γ, δ and ε are both set to 0, DCTG algorithm is equivalent to the degree constrained shortest path algorithm.

6 Conclusion

In this paper, we propose a heuristic algorithm for satellite network topology generation based on link weights for degree constrained software-defined satellite network topology. It comprehensively considers the various characteristics of the software-defined satellite network link. The simulation results show that the proposed heuristic algorithm has better average link bandwidth, average link rate and average link delay than the traditional degree constrained shortest path algorithm.

In the future research work, we will combine artificial intelligence, neural network and spatial network on the basis of this paper, and analyze the techniques such as spatial routing and spatial resource allocation under dynamic changes of degree constraints.

Acknowledgments

This paper is supported by National Key R&D Program of China under Grant No. 2018YFA0701604, NSFC under Grant No. 61802014, No. U1530118, and National High Technology of China ("863 program") under Grant No. 2015AA015702. Huachun Zhou is the corresponding author of this paper.

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