SN-VNE: A Virtual Network Embedding Algorithm for Satellite Networks

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***Abstract*—Network virtualization is a significant technology for the future network development. Many research results of it have already been proposed. However, almost all of these research is based on terrestrial networks to establish a network model. These terrestrial-based research cannot adapt to the extremely limited re-sources and high dynamics of satellite networks, and obviously cannot meet the demands of satellite networks for the network virtualization services. The inter-satellite link only establishes a connection when it carries a task. This establishment of inter-satellite links consumes the energy of the satellite. To reduce energy consumption of satellite network, this paper establishes a satellite network model and proposes a virtual network embedding (SN-VNE) algorithm. By considering link establishment state in node mapping and link mapping, we moderately map virtual links to the established physical connections. Our experiments prove that SN-VNE can reduce the number of link establishments in the mapping of virtual links. This reduction can save the energy consumption of satellite networks.**

***Index Terms*—Energy consumption, network virtualization, satellite network, virtual network embedding, virtual network establishment.**

I. Introduction

Network virtualization [1]–[3] is an important network technology that has emerged in recent years. It enables multiple network architectures or network applications to share the same physical network resources and provides users with various customized services. Virtual network embedding (VNE) algorithms are the core technology of network virtualization. When service providers (SPs) create heterogeneous networks, they will generate virtual network requests. Then infrastructure providers (InPs) choose an optimal virtual network embedding algorithm allocates appropriate physical resources for virtual network requests to improve the virtual network requests acceptance rate and overall network performance [4], [5].

VNE is an NP-hard problem. It needs to solve many problems such as resource constraints, admission control, online requests and topology diversity. Though there are many re-searches on this algorithm, it is still a very challenging issue. The baseline algorithm is a classical algorithm of the VNE algorithm [6]. It decouples the VNE algorithm into two independent parts, which are the node mapping and the link mapping phases. The node mapping phase adopts a greedy algorithm, while link mapping phase uses the shortest path algorithm. What's more, literature [6] proposes to split a virtual link into multiple physical links based on the support of virtual link segmentation for the physical network. And Chowdhury et al. [7] modeled the VNE problem as a mixed mathematical programming problem. Houidi et al. [8] proposed a distributed VNE algorithm. This algorithm is implemented through the exchange and cooperation of the underlying nodes in the network without a centralized controller.

In addition, there are a variety of VNE algorithms [9]–[14], but most of them are based on terrestrial network models, and when make strategic choices they only consider how to avoid network bottlenecks. Therefore, they cannot adapt to the nonfixed physical network topology of satellite networks.

However, satellite network needs network virtualization technology to meet task requirements. At present, with the development of space technology, the number of satellites has increased dramatically, and the space missions carried on satellite networks have become increasingly complex and varied, such as ground observation, manned spaceflight, navigation, deep space exploration, space communications, and data relay and so on. In the future, space network access services will be popularized to the general public. But when the satellite network is facing multiple services, it still adopts a completely closed model from the physical layer to the application layer. When they want to support a service, a complete set of systems needs to be constructed, and the service construction model is rigid and inefficient. Therefore, the satellite network urgently needs to use appropriate network virtualization technology, make full use of its centralized control features, and virtualize multiple levels of resources such as transmission, network, and computational storage capabilities to support multitask dynamic reconstruction capabilities in the upper-layer.

Different from terrestrial networks, the embedding of virtual networks on satellite networks requires face an addition-al number of restrictions:

- The dynamic of the satellite network. The underlying physical topology of satellite networks generally changes periodically. In high latitudes, due to the relative speed between satellites on different orbital planes is too fast, the connection between satellites will be disconnected. There are also nonperiodicity changes in underlying physical topology of satellite networks. The connection between the two satellites has a certain requirement on the relative position of the two satellites, but the position of the satellite itself is unstable, resulting in the between the satellites. And these link disconnections will cause reconfigurations of virtual network requests originally carried on the failed links.
- The scarcity of resources on the satellite. A satellite is expensive to construct, and its resources such as computation, storage, and bandwidth are limited, while a satellite has to take on a variety of space tasks. Therefore, the onboard resources that VNE can use are not as abundant as ground nodes, and the VNE algorithms that are too complicated and require frequent interaction may not be applied to satellite networks.
- The special constraints of satellite networks. There are some differences between satellite networks and terrestrial networks, and some factors overlooked by the terrestrial networks may have a significant effect on satellite networks. For example, by default, the detection of network status information of the terrestrial network is real-time, but for satellite networks, it needs to go through a distance between satellites and ground, resulting in a huge delay; the link between nodes in the terrestrial network can be considered as fixed, while in the satellite network, each satellite has the ability to connect with several satellites around it, but the link is only established when the link of the satellite will be in use. What's more, the antenna alignment requires a certain amount of time to deflect the angle when the link is establishing and will consume a certain amount of energy and create a large amount of delay.

In a word, ignoring the special constraints of satellite networks can seriously affect the performance of satellite networks.

This paper proposes SN-VNE—a virtual network fast embedding algorithm for satellite networks, which aims to reduce the probability that unestablished link is mapped and the total time caused by the antenna deflection, thus reducing the overall energy required for spatial virtual network request mapping and the user space service latency. At the same time, in order to prevent established links from becoming a network bottleneck, certain load balancing measures are taken by SN-VNE. In Section 2, the problem of VNE and the performance evaluation model based on satellite network are introduced. In Section 3, the network model and SN-VNE algorithm are proposed. Section 4 analyzes the simulation results of SN-VNE algorithm are evaluated. And Section 5 makes a summary and indicates the next research direction.

II. Virtual Network Embedding

A. Virtual Network Embedding Problem

In the satellite network virtual network embedding, the underlying physical network is represented by a weighted directed graph $G^S = \{N^S, L^S, W_N^S, W_L^S\}$, where N^S and L^S represent the set of nodes and links of the physical network, W_N^s and W_L^s represent the attribute set of the nodes and links in the physical network. The set of node attributes includes the CPU remaining resources $CPU\left(n^s\right)$. The set of link attributes include available bandwidth resources $Bw_L\left(l^s\right)$, transmission delay $Delay(l^s)$, link establishment time $Buildtime(l^s)$, and link establishment status $Status(l^s)$. The link establishment status $Status(l^s)$ is a binary function. If the link establishment status is already established, the value is 1; if not, the value is 0. It is given by the following

$$Status(l^s) = \begin{cases} 1 & Link\ is\ unestablished \\ 0 & Link\ is\ established \end{cases} \tag{1}$$

The virtual network is represented as $G^V = \{N^V, L^V, C_N^V, C_L^V\}$, where N^V and L^V represent the set of nodes and links of the virtual network, respectively, C_N^v and C_L^v represent the constraint sets of virtual network nodes and links. The virtual network request is represented as $V_i = \{G^v, t_s, t_e\}$, in which t_s indicates the time when the virtual network starts, and t_e indicates the time when the virtual network ends. When the virtual network requests arrive, the ground controller allocates the physical resources for the virtual network, and when the virtual network requests leave, the ground controller recovers the physical resources allocated to the virtual network.

$$M : G^v \ \rightarrow \ G^s$$

VNE is the process of allocating physical resources that satisfy the constraints of the virtual network requests in the underlying physical network, defined as

$$NodeMapping : M_N : \{N^v, C_N^v\} \rightarrow \{N^s, W_N^s\}$$

$$LinkMapping : \ M_L : \{L^v, C_L^v\} \rightarrow \{L^s, W_L^s\}$$

Both node mapping and the link mapping must satisfy their own constraints. When the two parts of the process are done successfully, the virtual network can be mapped to the physical network.

B. Performance Evaluation Standard

Evaluating the performance of a VNE algorithm generally has the following standards. This paper introduces the concept of resource occupancy time to better evaluate the performance of VNE in satellite networks.

1) Revenue:

Revenue reflects the sum of the values of the CPU and link bandwidth that successfully mapped to the physical network. It is defined as follows:

$$Revenue\left(M\left(G^v\right)\right)=\left(\sum_{l^v\in L^v} Bw_L\left(l^v\right)\right.\\ \left.+\alpha_R\sum_{n^v\in N^v} CPU\left(n^v\right)\right)\left(t_e-t_s\right), \tag{2}$$

α_R is a weight parameter for adjusting bandwidth and CPU.

2) Cost:

Cost reflects the total consumption of the CPU and bandwidth used by the physical network to support the virtual network. It is defined as follows:

$$Cost\left(M\left(G^v\right)\right)=\left(\sum_{l^v\in L^v} Hop\left(l^v\right)Bw_L\left(l^v\right)\right.\\ \left.+\alpha_C\sum_{n^v\in N^v} CPU\left(n^v\right)\right)Time\left(G^v\right). \tag{3}$$

$\mathrm{Hop}\left(l^v\right)$ is the number of the physical links occupied by a virtual link, and α_C is a weight parameter for adjusting bandwidth and CPU.

$\mathrm{Time}\left(G^v\right)$ is the total time for the virtual network to occupy the physical resources, including the physical link establishment time and the virtual network lifetime:

$$Time\left(G^v\right)=\sum_{l^s\in M_L'\left(L^v\right)} Buildtime\left(l^s\right)+\left(t_e-t_s\right). \tag{4}$$

$M_L'\left(L^v\right)$ is a set of links that need to be established in the physical link mapped by the virtual network.

3) R/C:

R/C reflects the efficiency of the virtual network embedding algorithm for the utilization of the physical resources, it is defined as follows:

$$R/C=\frac{\sum Revenue\left(M\left(G^v\right)\right)}{\sum Cost\left(M\left(G^v\right)\right)}. \tag{5}$$

4) Request acceptance ratio:

The virtual network request acceptance ratio reflects the capacity of a VNE algorithm to accommodate virtual network requests and is defined as follows:

$$AcceptanceRatio=\frac{Sum\left(V'\right)}{Sum\left(V\right)}. \tag{6}$$

$\mathrm{Sum}\left(V'\right)$ is the total number of virtual network requests successfully mapped, and Sum(V)is the total number of virtual network requests arrived.

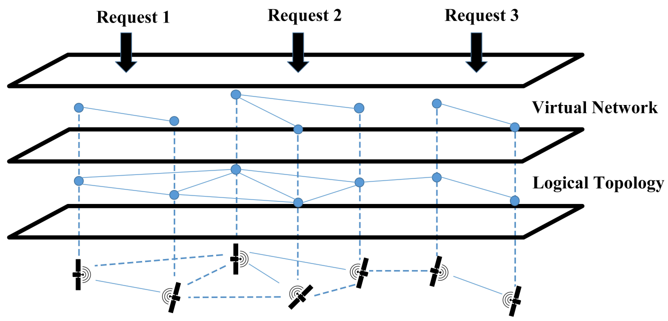

Fig. 1. Structure of SN-VNE

5) Energy consumption:

Energy consumption reflects the total energy consumed by satellite networks during the construction of virtual networks for a period of time. For we cannot directly simulate the energy consumption, we assume that the energy consumption is proportional to the settling time. In this paper energy consumption is given by

$$EnergeConsumption=\sum Buildtime\left(G^v\right), \tag{7}$$

where the $Buildtime\left(G^v\right)$ is defined as:

$$Buildtime\left(G^v\right)=\sum_{l^s\in M_L\left(L^v\right)} Buildtime\left(l^s\right). \tag{8}$$

III. Virtual Network Embedding For Satellite Network

A. Network Model

In view of the large number of energy consumption and delays caused by link establishment in satellite networks, this paper proposes a virtual network fast embedding algorithm for satellite networks: SN-VNE. This algorithm adds a logical topology layer between the physical network layer and the virtual layer. The logical topology layer is the abstraction of the resources and the link state in the satellite network. The node and link mappings in the SN-VNE algorithm must perform resource allocation based on the logical topology.

The node abstraction of the logical topology layer is responsible for integrating the CPU and the remaining bandwidth of link connected with this node into a logical weight $W_{logic}\left(n^s\right)$, which is defined as follows:

$$W_{\mathrm{logic}}\left(n^s\right)=CPU\left(n^s\right)+\alpha_{\mathrm{logic}}^n Bw_N\left(n^s\right),$$

α_{logic}^n is a parameter that adjusts the weight of the CPU and bandwidth. The remaining bandwidth of the direct link $W_{logic}\left(n^s\right)$ is the sum of the remaining bandwidth of all established links connected with this node directly,

$$Bw_N\left(n^s\right)=\sum_{l^s\in L'}\left(Bw_L\left(l^s\right)S\left(l^s\right)\right),$$

$$S\left(l^s\right)=\left\{\begin{array}{ll}1 & Status\left(l^s\right)=0\\ \mu & Status\left(l^s\right)=1\end{array}\right.,$$

L' is the set of all links whose endpoint is this node and μ is a parameter between 0 and 1.

In the link abstraction, the link bandwidth $Bw'(l^s)$ and the $Buildtime'(l^s)$ is integrated into the logical distance $D_{logic}(l^s)$, where $Bw'(l^s)$ is the normalized bandwidth of the links of the network, it is expressed as follows:

$$Bw'(l^s) = \frac{MaxBw_L(l^s) - Bw_L(l^s)}{\max\limits_{l^s \in L^s} MaxBw_L(l^s)},$$

$MaxBw_L(l^s)$ is the maximum bandwidth of the link l^s and the link establishment time $Buildtime'(l^s)$ is expressed as:

$$Buildtime'(l^s) = \frac{Buildtime(l^s)}{\max\limits_{l^s \in L^s} Buildtime(l^s)} Status(l^s).$$

And we define $D_{logic}(l^s)$ by:

$$D_{\text{logic}}(l^s) = Delay(l^s)\,(1 + \alpha_{\text{logic}}^{l} Bw'(l^s) + \beta_{logic}^{l} Buildtime'(l^s)).$$

α_{logic}^{l} and β_{logic}^{l} are parameters that adjust the weight of the building time and bandwidth.

B. SN-VNE Algorithm

The SN-VNE overall adopts two-step mapping: node mapping and link mapping, both of which are mapped according to the logical topology. The node mapping uses the greedy algorithm with the logical weight $W_{logic}(n^s)$ as the optimization goal. The link map extracts the available links whose residual resources are larger than the demand resources of the virtual network, and then uses the shortest path algorithm to perform mapping on the available links of the logical topology. At this time, the shortest path algorithm will select the path with the smallest logical length. If the mapping is successful, the logical topology is updated; if the mapping fails, the request is put into the waiting queue. When the number of failures exceeds the preset remapping threshold parameter, the request is directly rejected. The specific algorithm is described in Table I.

IV. Performance Evaluation

A. Simulation Environment And Parameter Settings

In order to comply with the satellite network environment, the number of physical network nodes in this paper is set to 50 and the number of links is about 240. The bandwidth of links and CPUs of physical network nodes is distributed uniformly from 50 to 100, and the establishment time of the links is a uniform distribution of 0.3 time windows to 0.5 time windows. The performance of VNE focuses on the hop count of the link. We set the transmission delay of all links to 1.

Each virtual network node has a uniform distribution between 2 and 5, and the link connection probability between two virtual nodes is 0.5. The bandwidth of the virtual links and CPU of virtual nodes is uniformly distributed from 0 to U_M,

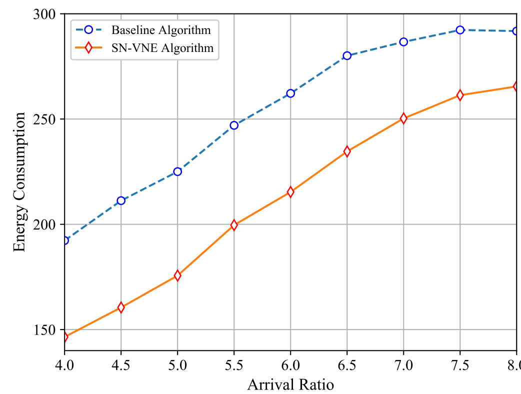

Fig. 2. Energy consumption within 50 time windows

Algorithm 1: ALGORITHM OF SN-VNE

Input: Physical network G_S, virtual network G_V
Output: Mapping results
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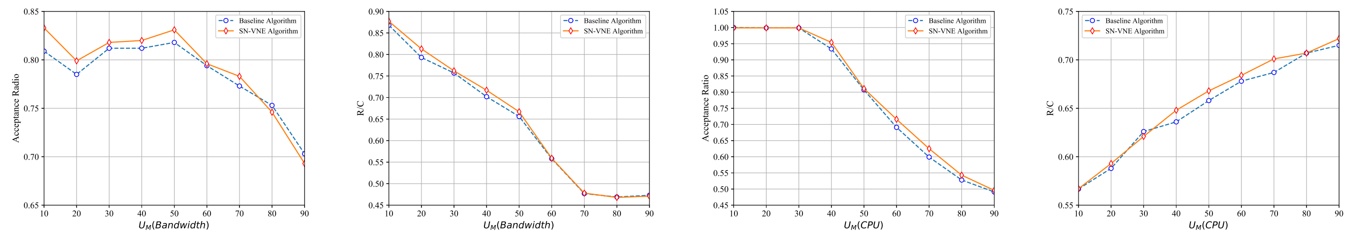
1  Initialize the logical topology
2  Virtual Network Request Collection V (Sort by priority)
3  for v_i ∈ V do
4      for n^v ∈ N^v do
5          Select the node based on the logical topology
6          if Step 5 fails then
7              Deny the request or send it to the waiting queue
8              break
9          else
10             Map the virtual node to the physical node
11         end
12     end
13     for l^v ∈ L^v do
14         Select the path based on the logical topology
15         if Step 14 fails then
16             Deny the request or send it to the waiting queue
17             break
18         else
19             Map the virtual link to the physical link.
20         end
21         Update logical topology.
22     end
23 end
```

and the U_M is changed from 10% to 90% of the maximum value of the physical resources, each time increased by 10%.

The arrival rate of the virtual network conforms to the Poisson distribution whose mean value varies from 4 to 8, and the lifetime of the virtual networks are the exponential distribution with an average of 10 time windows. Since this paper aims to simulate the performance of the algorithm in the interval time between two topology changes, this simulation



(a) (b) (c) (d)

Fig. 3. Average performance for varying BW and CPU of virtual networks: (a) Acceptance ratio with varying bandwidth, (b) R/C with varying bandwidth, (c) Acceptance ratio with varying CPU, (d) R/C with varying CPU

will use the data of 50 time windows. The remapping threshold of the virtual network is set to 3 times.

This simulation will use three performance indicators to evaluate the performance of the algorithm. They are the R/C based on the satellite network, virtual network acceptance ratio and the sum of the energy required to establish the link within the 50 time windows introduced in the second chapter.

B. Simulation Results

We configure the SN-VNE and baseline algorithm into a simulated satellite network environment. We use the concept of "Snapshot" which is an idea used to solve the problem of satellite network dynamics. Snapshot routing algorithms decompose dynamic topology of satellite network into several static topologies.

The environment in which we simulate is a snapshot of satellite network. In this environment, the location of the nodes and the connection relationships between the nodes is fixed, but there is no link is established between the nodes at the initial of the network. After a virtual network is allocated with physical resources, it must wait for physical links to be established before running its services.

In result 1) and 2), α_C and α_R are set to 1 and α^n_{logic}, α^l_{logic}, β^l_{logic} and μ is set to 0.5. And in result 3), β^l_{logic} will be changed and the bandwidth of the virtual links and CPU of virtual nodes is uniformly distributed from 0 to the half of the maximum value of the physical resources. The simulation results are as follows.

1) ***SN-VNE can significantly reduce the energy required for virtual network establishment****:* As shown in fig.2, the energy required to establish the inter-satellite links generated by the SN-VNE algorithm is significantly less than the classical baseline algorithm. This shows that the SN-VNE can significantly reduce the link's setup time in the mapping. The main reason is that SN-VNE improves the K shortest path algorithm in the process of link mapping, integrates the remaining resources of the link and the establishment state into a logical distance, so that the unestablished link has a relatively larger logical distance. What's more, the links with less residual resources or a larger setup time will also get a larger logical distance. In this way, when the shortest path is selected based on the logical distance, the probability of selecting paths which are not established or have a large setup time will be reduced. SN-VNE may greatly decreases the virtual network setup time and reduces the energy consumption of the satellite network virtual network mapping.

2) ***With a reasonable parameter configuration, SN-VNE has a similar performance of the R/C and acceptance ratio with baseline algorithm****:* As shown in fig.3, SN-VNE has a slight improvement compared to the classical baseline virtual network mapping algorithm in terms of R/C and request acceptance rate performance. This is because SN-VNE reduces the setup time. After the satellite network allocates physical resources for the virtual network, it needs to establish the physical resources. This not only means that the user needs to wait for an additional period of time, but also means that the virtual network occupies the physical resources for an additional period of time but does nothing. SN-VNE reduces the setup time and accelerates the replacement of virtual networks.

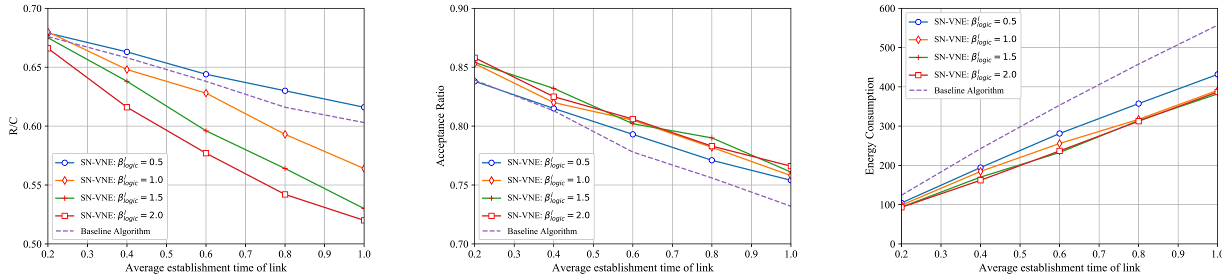
However, the SN-VNE increases the mapped probability of the established link, making the path selected by the mapping is not the path with the smallest number of hops. In other words, when the same virtual network is mapped, SN-VNE will occupy more resources per unit time.

In general, SN-VNE takes the cost of more resources occupation per unit time, reduces the total time the resources are occupied.

3) ***Excessive*** $\beta^{\mathbf{l}}_{\mathbf{logic}}$ ***does not have much effect on reducing energy consumption, but instead increases R/C significantly****:* β^l_{logic} indicates the degree of influence of the link setup time on the link mapping decision in the SN-VNE. The bigger of β^l_{logic} makes a greater tendency to choose a link that has been established. As we can see in fig.4, SN-VNE can significantly reduce the energy required for virtual network establishment when β^l_{logic} is 0.5 or 1, but has no performance improvement in energy consumption when β^l_{logic} is larger than 1. On the contrary, the increase of β^l_{logic} will cause a faster falling of R/C, even if β^l_{logic} is exceed 1.

V. Conclusion

This article abstracts the satellite network resources to builds a logical topology layer to properly increase the probability that the established link is mapped. With a similar performance of the R/C and acceptance ratio, SN-VNE shortens the virtual network setup time, reduces the energy consumption of virtual



(a) (b) (c)

Fig. 4. Effect of β^l_{logic} and average establishment time of link: (a) R/C, (b) Acceptance ratio, (c) Energy consumption

network creation and improves the overall performance of the satellite network.

The network environment in this simulation is a network with a fixed topology, and it mainly simulates the performance of the algorithm within two variation intervals of the satellite network. The next work plans to build a more realistic dynamic satellite network environment, to study the long-term performance of the SN-VNE in a periodically changing network, and study the influence of various weight parameters on the performance of the algorithm. At present, there is not much research on VNE algorithm for the satellite networks. This paper currently considers the energy consumption of virtual network and load balancing of resources. In addition to the study of supplementary algorithms, the next step also plans to consider additional satellite network special constraints.

ACKNOWLEDGMENT

The authors deeply appreciate the reviewers for their considering and dealing with this paper. This work is supported by the ”Stereoscopic Coverage Communication Network Verification Platform for China Sea” (Project Number: PCL2018KP002) and the ”Research and Application of Software-Defined Content Distribution System for Broadband Beijing” (Project Number: Z151100000315078), the ”Research and verification of 5G Fixed and Mobile Convergence System based on NFV-SDN Architecture” (Project Number: 2018ZX03001019-003) and the ”Key Technologies and Demonstrations of the Future Integrated Identification Network” (Project Number: 2015AA015702).

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