Reviewer Comments and Responses from Authors

First of all, we greatly appreciate for the editor and the reviewer for carefully reading the manuscript and giving constructive comments and suggestions, which definitely improves the quality of this paper. Based on the comments, we have carefully revised the letter and try to describe clearer. Revised portions are marked in underline in the letter. The responds to the reviewer's comments are as follows:

1. **This paper is lack of detail explanation of various factors and mathematical formulation. Please add following explanation:**

- Why do authors define as Equation (2)?

Author reply: Thanks for your comments. To mapping the virtual network over elastic optical network, the spectrum continuity and contiguity of elastic network should be considered. We first define the continuity factor to measure the spectrum continuity of substrate links. However, the substrate link with good spectrum continuity does not mean having the adequate spectrum resources. As is shown in Fig.1, the continuity factor in Fig.1.(a) is the same with that in Fig.1.(b), which means the spectrum continuity resources are the same. Obviously, the available frequency slots in Fig.1.(b) is more concentrated than that in Fig.2.(a). That is say, the spectrum contiguity in Fig.1.(b) is much better than that in Fig.2.(a). To measure the spectrum contiguity, the contiguity factor is defined.

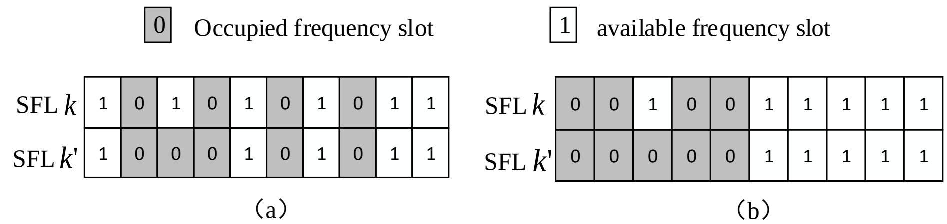

Fig.1. The different aggregation degree of available frequency slots

In [1], authors use spectrum consecutiveness factor to measure the spectrum contiguity. In this letter, contiguity factor is used to measure the spectrum contiguity. Contiguity factor is defined as the aggregation degree of available frequency slots, shown in equation (1). In equation (1), the sum of adjacent elements' difference in continuity vector we defined is used to measure the aggregation degree of available frequency slots. The larger the difference is, the less concentrated the available frequency slots will be. To calculate conveniently, reciprocal is used.

$$CG_{k,k'} = \frac{1}{\sum_{i=2}^{N} \left| \delta_i^{k,k'} - \delta_{i-1}^{k,k'} \right|} \tag{1}$$

The contiguity factor of node v^s is shown in equation (2), which measures the spectrum contiguity of all links connected to node v^s.

$$CG_{v^s} = \frac{\sum_{k,k' \in K^{v^s}, k' \neq k}^{K^{v^s}} \left\{ \frac{1}{\sum_{i=2}^{N} \left| \delta_i^{k,k'} - \delta_{i-1}^{k,k'} \right|} \right\}}{K^{v^s} \cdot (K^{v^s} - 1)/2} \quad (2)$$

As is shown in equation (2), the contiguity factor of node v^s can be used to measure the spectrum contiguity of substrate links which are connect to node v^s. Thus, we define contiguity factor as equation (2).

- The formulation of node availability rank is multiplication of various values. Why do authors define so?

Author reply: Thanks for your comments. In this letter, we defined various factors for virtual network mapping over elastic optical network. To take the various factors into consideration, weighting method and multiplication are the two most common methods [1] [2]. The weighting method has strong subjectivity and personal feelings. Moreover, multiplication of various factors is easy to achieve, which is simple and effective. Thus, in the letter, node availability is defined, which is multiplication of various factors.

- Why can the formulation of path node influence reduce the blocking probability?

Author reply: Path node influence factor is defined to measure the change of node availability rank. During the link mapping stage, k-shortest paths are found at first. Then we choose the one with the lowest path node influence factor to map the virtual link. That is to say, the link mapping stage has the small influence on the resources of substrate nodes. When the future virtual network request is coming, the substrate nodes still have enough resources to be mapped. Thus, the path node influence factor can reduce the blocking probability of the future virtual network requests.

- Please add explanation of the state transition probability and mathematical formulation for update of the pheromone in detail.

Author reply: Thanks for your advice. We have clarified the state transition probability and update of the pheromone clearer as follows:

Update of the pheromone: During iteration, the ant which has the minimum objective function value can leave the pheromone. Before next iteration, the pheromone from virtual node i to substrate node j at time $(t+\left|V^V\right|)$ is calculated as follows:

$$\tau_{ij}(t+\left|V^V\right|) = (1-\rho)\cdot\tau_{ij}(t) + \Delta\tau_{ij}^{\min} \quad (3)$$

where $\rho \in [0,1]$ is information evaporation coefficient. $\Delta\tau_{ij}^{\min}$ represents the pheromone increment that the ant with the minimum objective function value leaves. It is defined as follows:

$$\Delta\tau_{ij}^{\min} = \frac{Q}{L} \tag{4}$$

$$L = \min \sum_{e^v \in E^V} \sum_{e^s \in E^S} \xi_{e^s} \cdot (N - \sum_{i=1}^{N} s_{e^s,i}^{e^v}) + \sum_{e^v \in E^V} \sum_{i=1}^{k} INF_{k_i}^{e^v} \tag{5}$$

where Q is a constant and L is the objective function, shown in section 3.2.

The state transition probability: Ant colony optimization is one of the most efficient meta-heuristic algorithms, which is used in the letter. In the ant colony optimization, the pheromone and expected heuristic information are key factors, which have important impact on performance. According to the pheromone $\tau_{ij}(t)$ and heuristic information η_{ij}, ants move from current state to next adjacent state. In this letter, the state transition probability is defined as follows:

$$p_{ij}^{m}(t) = \begin{cases} \dfrac{\left[\tau_{ij}(t)\right]^{\alpha} \cdot \left[\eta_{ij}(t)\right]^{\beta}}{\sum_{s \subset allowed_m} \left[\tau_{ij}(t)\right]^{\alpha} \cdot \left[\eta_{ij}(t)\right]^{\beta}}, j \in allowed_m \\ 0, else \end{cases} \tag{6}$$

where $p_{ij}^{m}(t)$ is the state transition probability. In equation (6), $allowed_m = \{C - tabu_k\}$, where C is a set of substrate nodes which satisfy the constraints. $tabu_k$ is a tabu list. $\tau_{ij}(t)$ is the pheromone from virtual node i to substrate node j at time t . α and β are information heuristic factor and expected heuristic factor, which represent the importance of the pheromone and the heuristic information respectively. $\eta_{ij}(t)$ is the expected degree from virtual node i to substrate node j and $\eta_{ij}(t) = a_j$.

2. **This paper is also lack of simulation conditions, for instance, physical topology simulated. Please add it.**

Author reply: Thanks for your advice. We have added the simulation conditions in the letter. The simulation parameters in the substrate network topology with 14 nodes and 21 substrate fiber links are shown in Table Ⅰ. The computing capacity in each substrate node obeys uniform distribution and the bandwidth capacity in each substrate link is 150. Virtual optical

Table Ⅰ. Simulation parameters

Parameters	*Value*
Number of substrate nodes	14
Number of substrate fiber links	21
Computing capacity in substrate node	[300,400]
Bandwidth capacity in substrate link	150
Computing request in virtual node	[1,3]
Bandwidth request in virtual link	[1,5]
Number of virtual nodes in VON	[2,5]

network requests arrive by Poisson process with an average rate λ . The number of virtual nodes in each VON is generated randomly and the virtual link is connected with a probability p .

3. Minor mistakes:

In Section 2.2.

The VON can be mapped onto the substrate network when when it…

> The VON can be mapped onto the substrate network when it…

In Section 3.1.

Continuity factor and contiguity factor can be used to measure the spectrum contiguity and contiguity.

> Continuity factor and contiguity factor can be used to measure the spectrum continuity and contiguity.

Author reply: Thank you very much for your advices about the minor mistakes of our manuscript. We have corrected them one by one and examined the whole manuscript to ensure that there is no minor mistake any more.

Reference

[1] S. Shakya, N Pradhan, X Cao, Z Ye and C Qiao: Virtual Network Embedding and Reconfiguration in Elastic Optical Networks. GLOBECOM (2014) 2160-2165.

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ELectronics EXpress

IEICE Electronics Express, Vol.*, No.*, 1–8

Resource and load aware mapping algorithm for elastic optical network

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Abstract: To improve the efficiency of network, virtualization has developed by sharing the same physical network's resources for different users and applications. As one of the substrate networks, elastic optical network (EON) is expected to be used for the virtualization due to its flexibility and effectiveness. In this letter, we propose a virtual network mapping algorithm called resource and load aware algorithm based on ant colony optimization (RL-ACO), which considers the load jointly with spectrum continuity and spectrum contiguity during the node mapping stage. The variation of node availability rank is defined in the process of link mapping which helps to decrease the blocking ratio of virtual network requests. Simulation results show that RL-ACO not only reduces the blocking probability and the occupied frequency slots, but also balances the link load.

Keywords: EON, virtualization, load, spectrum continuity, spectrum contiguity

Classification: Optical systems

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1 Introduction

The sustained growth of data traffic with a huge amount of emerging applications requires a high efficiency and flexible basic network, such as video conference, high-definition television, and cloud computing [8]. To accommodate to the diversity of infrastructure network, researchers have proposed network virtualization as a solution [1]. Through the network virtualization, multiple heterogeneous networks can coexist on the same physical infrastructure by sharing the resources, such as CPU resources [10]. Meanwhile, the traditional wavelength division multiplexing (WDM) networks cannot satisfy the current network requirements due to the increasing traffic demand [7]. Elastic optical networks (EONs) employing the orthogonal frequency division multiplexing (OFDM) technology distribute data on low data rate subcarriers and can allocate spectrum flexibly [2][9]. Based on the concept of network virtualization, multiple virtual optical networks (VONs) share physical resources in the same substrate network. A VON is composed of several virtual nodes and virtual links. The substrate nodes provide computing resources for virtual nodes and the substrate fiber links (SFLs) offer bandwidth resources to virtual links. The process of constructing VONs is called virtual optical network embedding (VONE) [3].

Although the VONE problem over WDM networks has been lucubrated [4], the VONE problem over EONs is still in the preliminary research stage [5]. It is necessary to consider spectrum continuity constraint and contiguity constraint of the VONE problem over EONs, which is different from the virtual network mapping over WDM networks. In [5], the authors formulated a virtual network mapping problem for both static and dynamic traffic. In [3], the authors proposed two heuristic algorithms with a layered-auxiliary-graph. In [6], spectrum consecutiveness and alignment of SFLs connected to the substrate node are regarded as the node resources. However, only considering the spectrum consecutiveness and alignment can lead to the over load of some region in the network and cause the increase of blocking probability because the link load is not taken into account. A SFL with a heavy load will not be chosen although its consecutiveness and alignment satisfy the requirement. When other resources are the same, the SFL with a slighter load is preferred to be mapped. Hence, the link load has significant impact on network performance. To reduce the blocking probability and balance the load of substrate networks, the link load should be considered jointly with spectrum continuity and contiguity.

In this letter, we propose a virtual network mapping algorithm over EON based on ant colony optimization (ACO). Substrate nodes are ranked according to the joint link load and spectrum resources. The change of node availability rank is minimized when mapping virtual links.

2 Network model

2.1 Problem descriptions

VON is modeled as an undirected graph $G^V(V^V, E^V)$, where V^V represents the set of virtual nodes and E^V represents the set of virtual links. The computing requirement of virtual node v^v is denoted as $c(v^v)$ and the bandwidth requirement of virtual links e^v is denoted as $b(e^v)$. Likewise, the substrate physical network is denoted as $G^S(V^S, E^S)$, where V^S is the set of substrate nodes and E^S is the set of substrate fiber links (SFLs). Each substrate node v^s has the computing resources of $c(v^s)$ and each substrate fiber e^s link has the bandwidth capacity of $b(e^s)$. In addition, the degree of virtual nodes is denoted as $d(v^v)$ while the degree of substrate nodes is denoted as $d(v^s)$.

2.2 Constraint

The VON can be mapped onto the substrate network when it satisfies the node and link mapping constraints. *Node mapping*: a virtual node v^v can be mapped onto a unique substrate node v^s when satisfying the $c(v^v) \leq c(v^s)$ and $d(v^v) \leq d(v^s)$. *Link mapping*: a virtual link e^v can be mapped onto the spectrum path which contains one or several SFLs when satisfying the $b(e^v) \leq b(e^s)$.

3 Virtual network mapping algorithm

In this section, we propose a heuristic algorithm called resource and load aware algorithm based on ant colony optimization (RL-ACO), which sorts the substrate nodes according to the node availability rank (NA-Rank) and considers the path node influence factor (PNI Factor).

3.1 Node availability rank

In order to consider the link load jointly with spectrum resources, several empirical metrics are defined as below.

Assume that the number of SFLs connected to the substrate node v^s is K^{v^s} and the spectrum allocation state of the SFLs k and k' connected to the node v^s is shown in Fig.1.

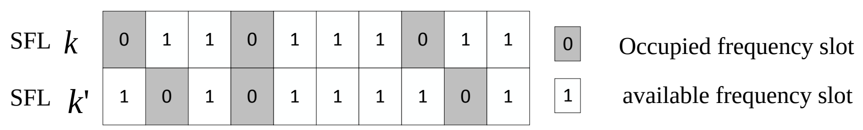

Fig. 1. The spectrum allocation state of the SFLs k , k'.

Definition 1: Continuity vector is defined as $\delta_{k,k'} = \underset{i=1,\cdots,N}{vect}\{s^{v^s}_{k,i} \& s^{v^s}_{k',i}\}$, where N is the total frequency slot number of each SFL. If the frequency slot i in link k is available, $s^{v^s}_{k,i} = 1$. Otherwise, $s^{v^s}_{k,i} = 0$. Then a vector of length N will be obtained. This vector is defined as continuity vector. The continuity vector in Fig.1. is $\delta_{k,k'} = (0, 0, 1, 0, 1, 1, 1, 0, 0, 1)$.

Definition 2: Continuity factor is defined as $CN_{k,k'} = sum\{\delta_{k,k'}\}$, which represents the sum of elements in vector $\delta_{k,k'}$. The continuity factor of node v^s is shown below:

$$CN_{v^s} = \frac{\sum\limits_{k,k' \in K^{v^s}, k \neq k'}^{K^{v^s}} \{CN_{k,k'}\}}{K^{v^s} \cdot (K^{v^s} - 1)/2} \tag{1}$$

The continuity factor is used to measure the spectrum continuity of SFLs. However, the substrate link with good spectrum continuity does not mean having the adequate spectrum resources. As is shown in Fig.2, the continuity factor in Fig.2.(a) is the same with that in Fig.2.(b), which means the spectrum continuity resources are the same. Obviously, the available frequency slots in Fig.2.(b) is more concentrated than that in Fig.2.(a). That is to say, the spectrum contiguity in Fig.2.(b) is much better than that in Fig.2.(a). To measure the spectrum contiguity, the contiguity factor is defined.

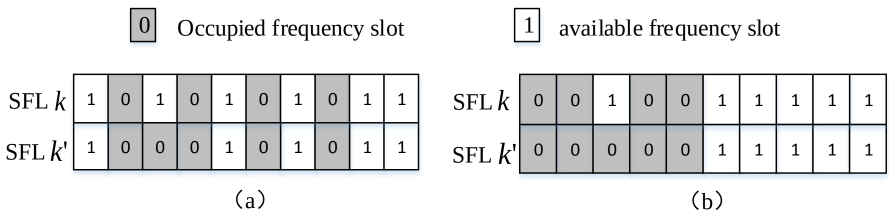

Fig. 2. The different aggregation degree of available frequency slots.

Definition 3: Contiguity factor is defined as $CG_{k,k'} = \frac{1}{\sum_{i=2}^{N} \left| \delta_i^{k,k'} - \delta_{i-1}^{k,k'} \right|}$, where $\delta_i^{k,k'}$ is the element of $\delta_{k,k'}$. The contiguity factor represents the aggregation degree of available frequency slots. The sum of adjacent elements difference in continuity vector is used to measure the aggregation degree of available frequency slots. The larger the difference is, the less concentrated the available frequency slots will be. To calculate conveniently, reciprocal is used. The contiguity factor of node v^s is shown in Eq.(2):

$$CG_{v^s} = \frac{\sum\limits_{k,k' \in K^{v^s}, k' \neq k}^{K^{v^s}} \{CG_{k,k'}\}}{K^{v^s} \cdot (K^{v^s} - 1)/2} \tag{2}$$

As is shown in equation (2), the contiguity factor of node v^s can be used to measure the spectrum contiguity of substrate links which are connect to node v^s.

Continuity factor and contiguity factor can be used to measure the spectrum continuity and contiguity of the SFLs that connect to the node v^s. The spectrum continuity and contiguity are regarded as the resources of the node

v^s. When an EON request is coming, it is essential to meet the spectrum continuity constraint and contiguity constraint.

Definition 4: Load factor

$$L_{v^s} = \frac{\sum_{k=1}^{K^{v^s}} (N - \sum_{i=1}^{N} s_{k,i}^{v^s})}{d(v^s)} \tag{3}$$

Eq.(3) is the mean of load of all SFLs that connect to the node v^s. The loads of all SFLs can be measured by and a larger load factor means that the load is heavier. In order to consider the link load jointly with spectrum continuity and contiguity of SFLs, the node availability rank (NA-Rank) is defined as follows:

$$a_{v^s} = \frac{c(v^s)}{c(v^s_{\max})} \cdot \frac{CN_{v^s}}{N} \cdot CG_{v^s} \cdot \frac{1}{L_{v^s}+1} \tag{4}$$

where a_{v^s} is the node availability rank of the node v^s. $c(v^s)$ is the computing capacity of v^s. CN_{v^s} is the continuity factor and CG_{v^s} is contiguity factor of node v^s. $c(v^s_{\max})$ and N is to normalize the variables. L_{v^s} is the load factor. To avoid the 0 of denominator, we add 1 to denominator.

3.2 Path node influence factor

When mapping virtual links, we consider the variation of node availability rank. Assume that the virtual link maps onto the spectrum path k_i, which contains one or several SFLs and several substrate nodes, denoted as $l_1, \cdots, l_{n-1}$ and $o_1, \cdots, o_n$, respectively.

Definition 5: Path node influence factor (PNI Factor)

$$INF_{k_i} = \sum_{j=1}^{n} \frac{a_{o_j} - a_{o_j}^{k_i}}{a_{o_j}} \tag{5}$$

Where INF_{k_i} is the PNI Factor of path k_i. a_{o_j} is the NA-Rank of node o_j and $a_{o_j}^{k_i}$ is the NA-Rank of node o_j if the path k_i contains the node o_j. Eq.(5) calculate the variation of node availability rank.

During the link mapping stage, k-shortest paths are found at first. Then the one with the lowest path node influence factor is chosen to map the virtual link. That is to say, the link mapping stage has the small influence on the resources of substrate nodes. When the future virtual network request is coming, the substrate nodes still have enough resources to be mapped. By considering PNI Factor, the blocking probability of the future VON request can be reduced.

Objective:

$$L = \min \sum_{e^v \in E^V} \sum_{e^s \in E^S} \xi_{e^s} \cdot (N - \sum_{i=1}^{N} s_{e^s,i}^{e^v}) + \sum_{e^v \in E^V} \sum_{i=1}^{k} INF_{k_i}^{e^v} \tag{6}$$

where ξ_{e^s} is Boolean variable. If SFL e^s belongs to the spectrum path k_i which the virtual link mapped onto, $\xi_{e^s} = 1$. Otherwise, $\xi_{e^s} = 0$. The aim of objective in Eq.(6) is to minimize the total number of occupied frequency slots of the VON request and the PNI Factor, which impact the blocking probability of the future VON request.

3.3 Ant colony optimization

Max-Min ACO is used to map virtual nodes and virtual links. In Max-Min ACO, the ant which has the minimum objective function value can leave pheromone.

The variables and constants in ant colony algorithm are as follows: M is the number of the ants. $\left|V^V\right|$ is the number of the virtual nodes. $\tau_{ij}(t)$ is the pheromone from virtual node i to substrate node j at time t. $p_{ij}^m(t)$ is the state transition probability, which contains the pheromone $\tau_{ij}(t)$ and heuristic information η_{ij}.

In the ant colony optimization, the pheromone and expected heuristic information are key factors, which have important impact on performance. According to the pheromone $\tau_{ij}(t)$ and heuristic information η_{ij}, ants move from current state to next adjacent state. In this letter, the state transition probability is defined as follows:

$$p_{ij}^m(t) = \begin{cases} \frac{[\tau_{ij}(t)]^\alpha \cdot [\eta_{ij}(t)]^\beta}{\sum\limits_{s \subset allowed_m} [\tau_{ij}(t)]^\alpha \cdot [\eta_{ij}(t)]^\beta}, j \in allowed_m \\ 0, else \end{cases} \tag{7}$$

Where $allowed_m = \{C - tabu_k\}$. C is a set of substrate nodes which satisfy the constraints and $tabu_k$ is a tabu list. α and β are information heuristic factor and expected heuristic factor, which represent the importance of the pheromone and the heuristic information respectively. $\eta_{ij}(t)$ is the expected degree from virtual node i to substrate node j and $\eta_{ij}(t) = a_j$.

During each iteration, the ant which has the minimum objective function value can leave the pheromone. Before next iteration, the pheromone from virtual node i to substrate node j at time $(t + \left|V^V\right|)$ is calculated as follows:

$$\tau_{ij}(t + \left|V^V\right|) = (1 - \rho) \cdot \tau_{ij}(t) + \Delta\tau_{ij}^{\min} \tag{8}$$

where $\rho \in [0, 1]$ is information evaporation coefficient. $\Delta\tau_{ij}^{\min}$ represents the pheromone increment that the ant with the minimum objective function value leaves. It is defined as follows:

$$\Delta\tau_{ij}^{\min} = \frac{Q}{L} \tag{9}$$

where Q is a constant and L is the objective function, shown in section 3.2.

The detailed steps of RL-ACO are shown in Fig.3.

4 Performance evaluation

The performance of the RL-ACO is evaluated in this section. For the benchmark algorithms, we use alignment and consecutiveness-aware virtual network embedding (ACT-VNE) [6], the local resource capacity and the shortest path first fit (LRC-SP-FF) [4], Greedy Algorithm and the shortest path first fit (Greedy-SP-FF), which is widely used in simulations. The simulation parameters in the substrate network topology with 14 nodes and 21 substrate fiber links are shown in Fig.4(a). The computing capacity in each

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Algorithm resource and load aware algorithm based on ACO (RL-ACO)
Input: substrate network G^S, virtual optical network request G^V
Output: node mapping N_M, link mapping L_M
calculate NA-Rank for each v^s in G^S ;
for every generation G = 0 to G_max in do // The number of generation.
    for every ant M = 0 to M_max do // The number of ants.
        erase the tabulist; // Initialize the tabu list.
        Q_s ← randomly sorted the virtual node;
        for i = 0 to |Q_s| − 1 do // Map virtual nodes.
            calculate the probability according to the NA-Rank;
            map virtual nodes and record the used substrate nodes into tabulist;
            if node mapping fails
                mark G^V as blocked;
            end if
        end for
        if G^V is not marked //Map virtual links.
            map virtual links according to PNI Factor;
            if link mapping fails
                mark G^V as blocked;
            end if
            record the mapping result and its objective value;
        end if
    end for
    update pheromone according the mapping result;
end for
```

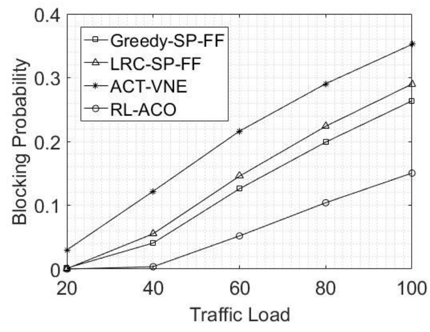
Fig. 3. Pseudo code of RL-ACO.

substrate node obeys uniform distribution and the bandwidth capacity in each substrate link is 150. Virtual optical network requests arrive by Poisson process with an average rate λ. The number of virtual nodes in each VON is generated randomly and the virtual link is connected with a probability p.

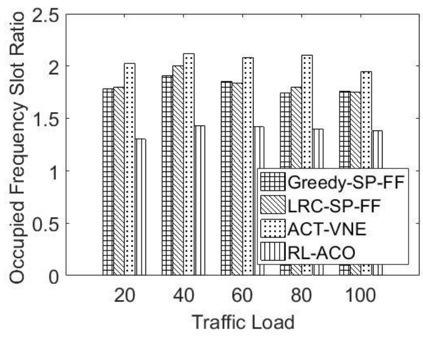
Fig.4(b)(c)(d) show the blocking probability, the occupied frequency slot ratio and the link load balance of RL-ACO, LRC-SP-FF, Greedy-SP-FF and ACT-VNE. In Fig.4(b), it can be seen that the blocking probability of RL-ACO is obviously lower than other algorithms. One reason is that RL-ACO sorted the substrate nodes according to the proposed availability rank, which helps to map virtual nodes. Moreover, the influence of node availability rank is considered when mapping virtual links, which contributes to the success of upcoming VON request. Fig.4(c) shows that RL-ACO occupies the minimum frequency slot resources because the spectrum resources of SFLs are considered during the node mapping stage. It can be concluded that RL-ACO has the most effective use of spectrum resources. Fig.4(d) shows the link load balance obtained from the four algorithms. The variance of loads of SFLs is used to measure the link load balance in Fig.4(d). The results indicate that RL-ACO has the best performance since the load is considered when mapping virtual nodes and virtual links. The ACT-VNE has the maximum variance because only spectrum consecutiveness and alignment are considered in the process of mapping virtual nodes and links.

Parameters	*Value*
Number of substrate nodes	14
Number of substrate fiber links	21
Computing capacity in substrate node	[300,400]
Bandwidth capacity in substrate link	150
Computing request in virtual node	[1,3]
Bandwidth request in virtual link	[1,5]
Number of virtual nodes in VON	[2,5]

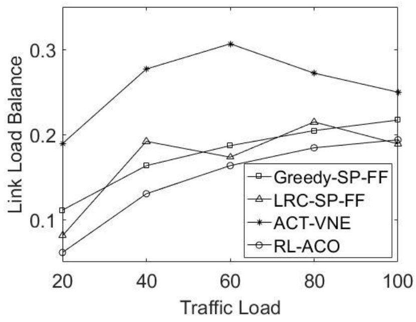
(a)



(b)



(c)



(d)

Fig. 4. (a)Simulation parameters;(b)Blocking probability vs.traffic load;(c)Occupied frequency slot ratio vs.traffic load;(d)Link load balance vs.traffic load

5 Conclusion

This letter proposes a virtual network mapping algorithm over EON based on Max-Min ACO, called resource and load aware algorithm based on ACO (RL-ACO). To improve the successful rate of node mapping and minimize the occupied frequency slots, the node availability rank (NA-Rank) and path node influence factor (PNI Factor) are defined. Max-Min ACO is used for realization. The simulations have shown that the proposed algorithm achieves better performance.

Acknowledgments

This work was supported by the Fundamental Research Funds for the Central Universities Grant No. JB150318, the National Science Foundation of China Grant No. 61472300, No.61334003, the Research Funds of the Science and Technology on Information Transmission and Dissemination in Communication Networks Laboratory and the 111 Project Grant No.B08038.