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Opaque virtual network mapping algorithms based on available spectrum adjacency for elastic optical networks

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Abstract Optical network virtualization enables multiple virtual optical networks constructed for different infrastructure users (renters) or applications to coexist over a physical infrastructure. Virtual optical network (VON) mapping algorithm is used to allocate necessary resources in the physical infrastructure to the VON requests (VRs). In this paper, we investigate the opaque VON mapping problems in elastic optical networks (EONs). Based on the concept of available spectrum adjacency (AvSA) on links or paths, we consider both node resource and AvSA on links for node mapping, and present a link mapping method which chooses the routing and spectrum plan whose AvSA on paths is the largest among all the candidates. Finally, the overall VON mapping algorithm (i.e., AvSA-opaque VON mapping, AvSA-OVONM) coordinated node and link mapping is proposed. Extensive simulations are conducted and the results show that AvSA-OVONM has better performance of blocking probability and revenue-to-cost ratio than current algorithms.

Keywords optical network virtualization, opaque, virtual optical network, mapping algorithm, elastic optical networks (EONs)

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1 Introduction

Network virtualization is regarded as an efficient method to overcome the current Internet ossification problem by allowing multiple heterogeneous virtual networks to coexist on a shared substrate network [1–3]. Meanwhile, elastic optical networks (EONs) based on orthogonal frequency division multiplexing (OFDM) technology are regarded as a promising next-generation approach for allocating bandwidth at the flexible granularity of an OFDM subcarrier [4] rather than at the coarse unit of a wavelength in the fixed-grid wavelength-division multiplexing (WDM) networks [5–7]. Furthermore, extensive literature demonstrate that EONs are emerging as a prospective technology for virtualization in the optical networks from the viewpoint of elastic networking level to sliceable equipment level [8, 9].

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Virtualization in EONs brings many challenges and problems, and attracts much research interest. As one of the essential challenges, VON mapping algorithm is used to map the VON requests (VRs) onto the substrate network by maximizing the resource utilization of the underlying physical infrastructure [10]. Most of the previous studies on VON mapping were targeted for WDM networks. In [11], Peng et al. investigated the impacts of physical layer impairments (PLIs) on VON composition and designed a PLI-aware VON composition mechanism to execute the proper mapping of the VON to the available physical resources. Zhang et al. formulated the problem as a mixed integer linear programming (ILP) model and proposed two greedy heuristics to solve the node mapping and link mapping sub-problems separately in WDM networks in [12]. Zhang et al. focused on the network design problem for VON mapping in WDM networks and presented two heuristic algorithms that jointly considered VON mapping and routing and wavelength assignment (RWA) in [13]. Perelló et al. presented ILP models for opaque and transparent VON mapping in WDM networks in [14] which did not consider node mapping.

Different from WDM networks, the multiple subcarriers for a service have to be allocated in a contiguous manner typically [15]. Due to the additional constraints, the VON mapping algorithms designed for WDM networks cannot be applied to EONs directly, and the problems for EONs involve tremendous difficulties. In [16], Perelló et al. formulated the VON problem for EONs as an ILP problem but without heuristic algorithms. Zhao et al. presented an optimal ILP formulation and two heuristics for both static and dynamic traffic in [17], where multiple virtual nodes could be mapped onto the same physical node, and the virtual link between those virtual nodes would not be assigned subcarriers. Nevertheless, this assumption will lead logic errors on connection when multiple virtual nodes of a VON request share the same physical node, and it makes the algorithm less practical. Gong et al. formulated ILP models and designed algorithms for both transparent and opaque VON mapping over EONs in [18]. The algorithm for opaque VON mapping over EONs is still margin for performance improvements in link mapping stage. A flexible VON provisioning procedure for distance-adaptive EONs was proposed in [19] where the author did not pay much attention to the algorithm itself. In conclusion, there is a lack of VON mapping algorithms designed for EONs, and few algorithms pay much attention to the characteristics of resources allocation in EONs. Aiming at designing a customized VON mapping algorithm for EONs with low blocking probability, this paper deeply investigated the opaque VON mapping problems in EONs, and designed methods for both node mapping and link mapping.

In this paper, we investigate the opaque VON mapping problems in EONs. In opaque VON mapping, the electronic termination capabilities are physically presented at each substrate nodes and opaque transport services are provided from the VON viewpoint as assumed in previous work [14, 18]. Based on the concept of available spectrum adjacency (AvSA) on links, we consider both node resource and the AvSA on links for node mapping which can raise the probability of successful link mapping. Based on the concept of AvSA on paths, we present a link mapping method which chooses the routing and spectrum plan whose AvSA on paths is the largest among all the candidates. This method can weaken the deterioration of spectrum fragment resulting from resource allocation, as well as serves for the future VRs better. Finally, the overall VON mapping algorithm (i.e., AvSA-opaque VON mapping, AvSA-OVONM) coordinated node and link mapping based on AvSA is proposed.

The remainder of this paper is organized as follows. Section 2 describes the VON mapping problem in EONs. AvSA-OVONM for opaque VON mapping in EONs is proposed in Section 3. Section 4 presents and discusses the simulation results. We conclude the paper in Section 5. Abbreviations and formula parameters are listed in Appendix A.

2 Model and problem statement

A VON request is composed of several virtual nodes (VNs) interconnected by virtual optical links (VOLs). Each VN or VOL requires necessary resources allocated by the physical infrastructure. Each VN can be mapped onto any substrate node (SN). Each VOL can be mapped onto any substrate light path (SLP) composed of several substrate fiber links (SFLs). Due to the combination of node and link constraints,

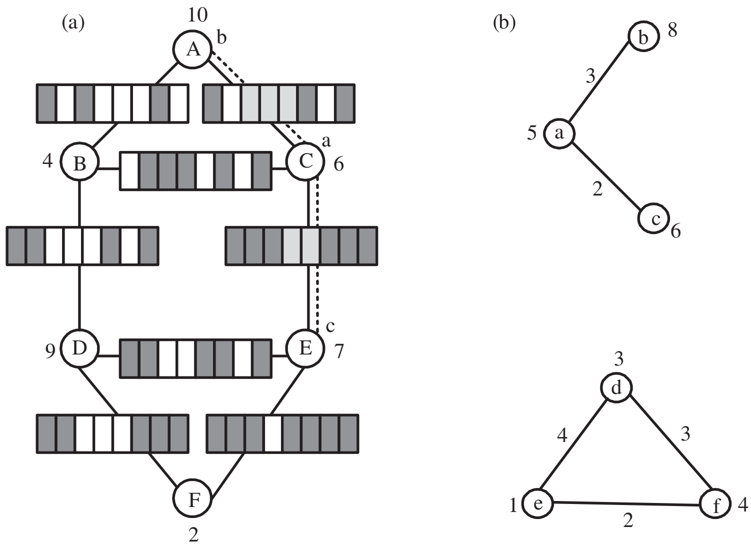

Figure 1 Example of substrate EONs and VRs. (a) A substrate EONs; (b) two VRs.

VON mapping problem is NP-hard.

As described in most literature, the substrate EONs are modeled as an undirected graph G^s=(N^s, L^s), where N^s and L^s refer to the set of SNs and SFLs, respectively. In this paper, computing capacity denoted by C_u^s is considered for node attributes, and bandwidth capacity (there are frequency slots, FSs) for link attributes is denoted by F_l^s. Besides, P^s denotes the set of SLPs in the substrate networks. We also denote a VON request by an undirected graph G^v =(N^v, L^v) , where N^v and L^v refer to the set of VNs and VOLs, respectively. C_v^r represents the computing resource requirement of each VN, and the bandwidth requirement of each VOL is F_l^r.

The VON mapping is defined as a mapping from G^v to a subset of G^s [20], such that the constraints in G^v are satisfied. Naturally, the problem of VON mapping can be decomposed into node mapping and link mapping as follows:

$$\text{Node mapping, } N^v \to N^s; \quad \text{Link mapping, } L^v \to P^s.$$

In node mapping stage, each VN of the VON request is mapped onto a unique SN that has sufficient computing capacity. Then SFLs are set up for VOLs to satisfy the bandwidth requirement in link mapping stage. Routing and spectrum assignment (RSA) in EONs should preserve the spectrum non-overlapping, continuity and contiguous constraints [21]. Moreover, the spectrum conversion and opaque transport services are provided in opaque VON mapping. Therefore, VOLs of the VR can use different contiguous FS-blocks (CFSBs) on the SLPs. The path splitting and different modulation formats are not taken into account.

The Figure 1(a) shows substrate EONs, where the numbers at nodes represent the available computing capacity and the slots on each SFL correspond to its spectrum utilization, the slot in dark color indicates the frequency slot is occupied, otherwise it is available. Two VRs are depicted in Figure 1(b) where the numbers over links represent the required bandwidth and the numbers at nodes indicate the required computing resource. For example, the VNs a, b, c in the first VON request are mapped to SNs C, A, E, and the VOLs (a, b) and (a, c) are mapped onto the SLPs (C, A) and (C, E) with the computing and bandwidth constraints all satisfied. The slot in light color on each SLP indicates the FS is allocated to the VON request. A similar mapping occurs for the second VON request.

3 Opaque VON mapping problems in EONs

In this section, we propose the algorithm AvSA-OVONM for opaque VON mapping in EONs. The proposed algorithm consists of two stage, node mapping and link mapping. The node mapping is based

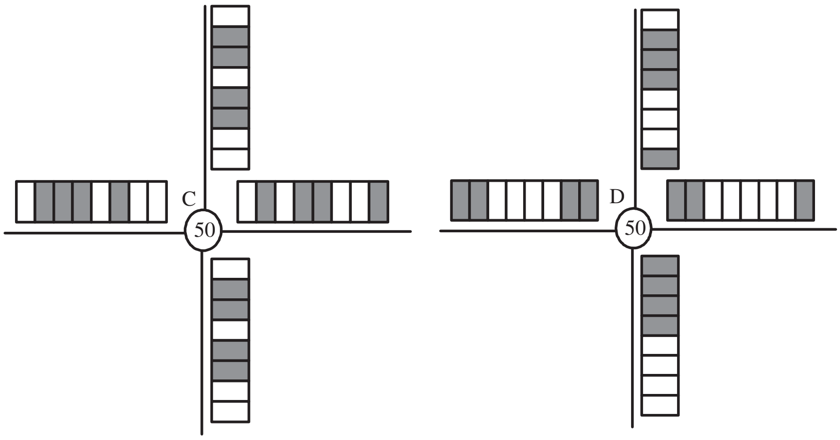

Figure 2 Examples of AvSA.

on the concept of AvSA on SFLs, and the link mapping utilizes K-Shortest-Path (KSP) routing and the AvSA on SLPs.

3.1 Available spectrum adjacency

The available spectrum adjacency, AvSA describes the size of available spectrum resource, as well as the adjacency among available spectrum resource on SFLs or SLPs [21]. The definitions of AvSA on links and paths are as follows:

$$\mathrm{AvSA}(l) = \frac{\sum_{i=1}^{S-1} l(i) \cdot l(i+1)}{B_l} \times \frac{\sum_{i=1}^{S} l(i)}{S}, \tag{1}$$

$$\mathrm{AvSA}(p) = \frac{\sum_{i=1}^{S-1} p(i) \cdot p(i+1)}{B_p} \times \frac{\sum_{i=1}^{S} p(i)}{S}, \tag{2}$$

where B_l and B_p denote the number of available CFSBs in the SFL and the SLP, respectively. The symbol "·" indicates the logical and operator. Boolean variable $p(i)$ equals 1 if the i-th FS is available in all SFLs of the path, otherwise, it is 0. Boolean variable $l(i)$ equals 1 if the i-th FS is available in the SFL, otherwise, it is 0. S is the total number of frequency slots on each SFL.

The AvSA reflects the ability to provide spectrum resources of SFLs or SLPs appropriately. When the size of available spectrum resource is larger, and the adjacency among available spectrum resource is better on SFLs or SPLs, the AvSA is larger. There is an example in Figure 2. The average sizes of available spectrum resource on all SFLs that directly connect to node C and that to node D are the same. However, the adjacency of available spectrum resource on SFLs that directly connect to node C is better than that to node D. Hence, the average AvSA on all SFLs that directly connect to node C is larger than that to node D. Obviously, the probability of successful link mapping is larger when a VN is mapped onto SN D than onto SN C.

3.2 Node mapping

We utilize the AvSA on links to design a greedy node mapping algorithm, AvSA-NM. Here, we come up with two definitions to sort nodes.

Rb_v is the product of computing resource requirement of the VN and total bandwidth requirements of the VOLs.

$$Rb_v = C_v^r \times \sum_{l^v \in L_{dc-v}^r} F_{l^v}^r, \tag{3}$$

where L_{dc-v}^r is the set of VOLs that directly connect to the VN.

Similarly, $R\text{AvSA}_u$ is the product of available computing capacity of the SN and average AvSA on the SFLs,

$$R\text{AvSA}_u = C_u^s \times \frac{1}{|L_{dc-u}^s|} \sum_{l^s \in L_{dc-u}^s} \text{AvSA}(l^s), \tag{4}$$

where L_{dc-u}^s is the set of SFLs that directly connect to the SN, "$|\cdot|$" indicates the operator to get the size of set.

Firstly, calculate the Rb_v for each VN in the VON request. Secondly, compute the $R\text{AvSA}_u$ for each SN in the substrate network G^s. Finally, map the VN with the largest Rb_v onto the feasible SN that also has the largest $R\text{AvSA}_u$ in node mapping. The details of node mapping algorithm AvSA-NM are depicted in Algorithm 1.

Algorithm 1 The node mapping algorithm AvSA-NM

Require: Substrate EONs G^s, VON request G^v;
Ensure: VON node mapping flag NMF;
NMF $\Leftarrow 0$;
Calculate the Rb_v for each VN in G^v, then sort all VNs in descending order of their Rb_v;
Calculate the $R\text{AvSA}_u$ for each SN in G^s, then sort all SNs in descending order of their $R\text{AvSA}_u$;
for each v_k in the order above **do**
  for each unmarked u_k in the order above **do**
    if $C_u^s(u_k) \geqslant C_u^s(v_k)$ **then**
      map v_k onto u_k;
      mark u_k as selected;
      NMF $\Leftarrow 1$;
    end if
  end for
  if NMF $= 0$ **then**
    return NMF;
  end if
end for
return NMF;

The time complexity of the node mapping algorithm is analyzed as follows. $O(N\log N)$ is the time complexity of sorting nodes, where N represents the number of nodes. $O(N)$ is the time complexity of calculating the values for nodes. As for selecting the SN with largest value for each VN, the time complexity is $O(|N^s|)$. Thus, the total time complexity of AvSA-NM algorithm is $O(|N^s|\log|N^s| + |N^v|\log|N^v|)$.

3.3 Link mapping

AvSA-LM algorithm is proposed for link mapping. The algorithm uses the K-Shortest-Path (KSP) for routing, and then for all available CFSBs on each path, it calculates the AvSA(p) under the condition of allocating a certain available CFSB on this path to the VON request. Finally, we choose the routing and spectrum plan whose AvSA(p) is the largest among all the candidates. Algorithm 2 shows the details of the algorithm.

The following is the analysis of the time complexity of the link mapping algorithm. The time complexity of finding the VOLs is $O(\frac{N^v}{2})$. $O(N\log N + L)$ is the time complexity of KSP method, where N represents the number of nodes, and L refers to the number of links. The time complexity of spectrum allocation which finds the path and CFSB plan with the largest AvSA(p) is $O(KS)$, where S is the number of total FSs on each SFL, K is the parameter in KSP method. Therefore, the time complexity of AvSA-LM algorithm is $O(|N^v|(|N^s|\log|N^s| + |L^S|)KS)$.

3.4 Overall VON mapping algorithm

When a VON request arrives, we map VNs onto SNs utilizing AvSA-NM algorithm. Then AvSA-LM algorithm will be executed for link mapping when all VNs are mapped successfully. The VON request

Algorithm 2 The Link mapping algorithm AvSA-LM

Require: Substrate EONs G^s, VON request G^v, $K \Leftarrow 3$;
Ensure: VON link mapping flag LMF;
for each VOL $l_v = (v_a, v_b)$ in G^v **do**
  LMF $\Leftarrow 0$;
  find the selected SNs u_a, u_b for VNs v_a, v_b;
  if find paths from the u_a to u_b in G^s **then**
    for each path **do**
      if find the available CFSBs **then**
        for each CFSBs **do**
          LMF $\Leftarrow 1$;
          compute and store the AvSA(p) assuming to allocate the CFSB on the path to G^v;
        end for
      end if
    end for
    if LMF $\neq 1$ **then**
      return LMF;
    else
      choose the path and spectrum plan with largest AvSA(p);
    end if
  end if
end for
return LMF;

will be served only if both VNs and VOLs are mapped onto substrate EONs, otherwise, it will be marked blocked. The detailed procedures of AvSA-OVONM algorithm are described in Algorithm 3.

From the analysis above, the time complexity of AvSA-OVONM is $O(|N^s|\log|N^s| + |N^v|\log|N^v| + |N^v|(|N^s|\log|N^s| + |L^S|)KS)$.

Algorithm 3 Opaque VON mapping algorithm AvSA-OVONM

Require: Substrate EONs G^s, VON request G^v, $K \Leftarrow 3$;
Ensure: VON mapping flag MF;
$MF \Leftarrow 0$;
apply AvSA-NM for node mapping;
if NMF$\neq 0$ **then**
  apply AvSA-LM for link mapping;
  if LMF$\neq 0$ **then**
    return $MF \Leftarrow 1$;
  end if
end if
mark G^v as blocked;
return MF;

4 Performance evaluation environment

In this section, we describe the performance evaluation environment firstly, then depict the comparison algorithms and performance metrics, and present our main evaluation results and discussion in the end.

4.1 Performance evaluation environment

There are three substrate network topologies with different initial network resource for simulation. We generate VRs with the Poisson traffic model. The number of VNs in each VON request is randomly distributed in a preset range, and the probability that a VN-pair is directly connected equals 0.5. The simulation parameter K equals 3, and the parameters in VRs and substrate topologies are described as follows.

Figure 3 shows a simple six-node topology with ten links. In the substrate topology, the SN's initial computing capacity is 50 units, and the total number of FSs on each SFL is 50. As for the VRs on the

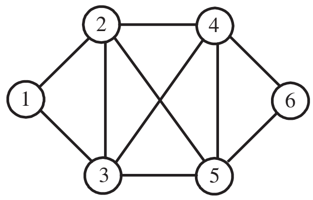

Figure 3 A simple six-node topology.

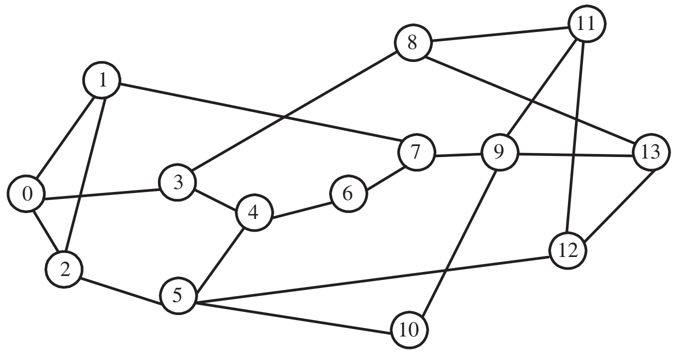

Figure 4 DT topology.

topology, they have a random number of VNs between 2 and 3, each VN requires a random number of computing capacity between 1 and 4, and each VOL requires a random number of FSs between 1 and 3.

A realistic deutsche telecom (DT) topology with 14 nodes and 23 links [22] is depicted in Figure 4. In the substrate topology, the SN's initial computing capacity is 200 units, and the total number of FSs on each SFL is 200. For the VRs, they have a random number of VNs between 2 and 7, each VN requires a random number of computing capacity between 1 and 6, and each VOL requires a random number of bandwidth between 1 and 10.

There is a random topology with 50 nodes and 141 links generated with tools. The SN's initial computing capacity is 200 units, and total number of FSs on each SFL is 200. For the VRs, they have a random number of VNs between 2 and 10, each VN requires a random number of computing capacity between 1 and 20, and each VOL requires a random number of bandwidth between 1 and 20.

4.2 Comparison algorithms and performance metrics

For comparison algorithms, we modify the Baseline algorithm in [20, 23] and adapt it to VON mapping in EONs.

(1) Ba (baseline)-OVONM algorithm: The algorithm uses the node computing capacity as the reference when sorting SNs and VNs in node mapping stage, and it utilizes KSP for routing and First-Fit (FF) for spectrum allocation in link mapping stage.

(2) SAvS (size of available spectrum)-OVONM algorithm: In Node mapping stage, the algorithm sorts SNs by the product of node available computing capacity C_u^s and average SAvS on all SFLs that directly connect to the node, and then sorts VNs by the value of Rb_v as in the AvSA-OVNM algorithm. The algorithm also utilizes the same link mapping procedure as Ba-OVONM algorithm for link mapping.

As for the performance metrics, we consider the request blocking probability (BP) as the major performance metric, which is defined as

$$BP = \frac{MF_{\text{num}}}{\text{Num}}, \tag{5}$$

where MF_{num} and Num represent the number of blocked VON requests and total arrived VON requests, respectively.

As another performance metric, the revenue-to-cost ration (RCR) is defined as follows:

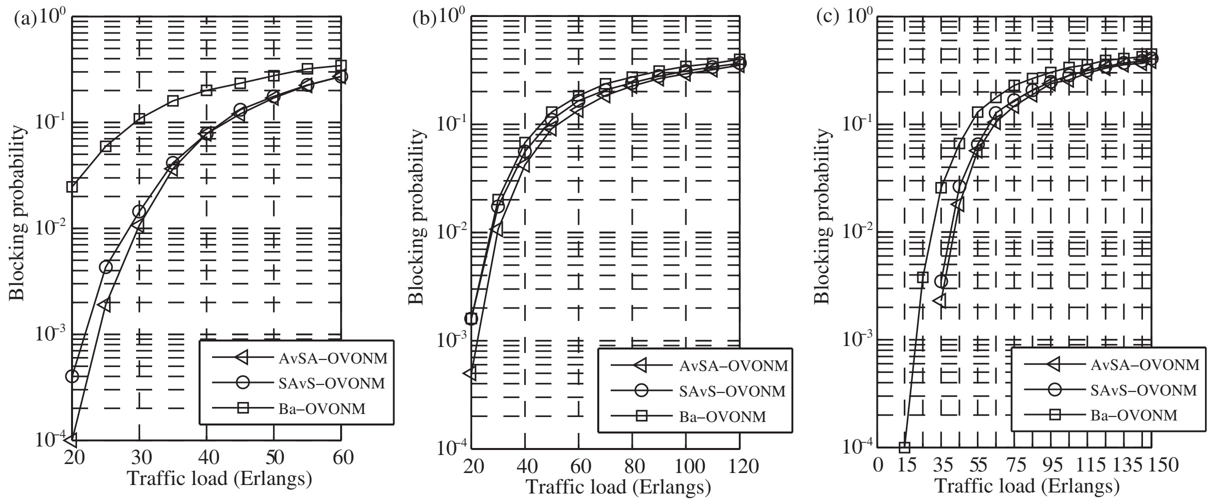

Figure 5 Simulation results on blocking probability performance for opaque VON. (a) Six-node topology; (b) DT-topology; (c) random topology.

$$\mathrm{RCR} = \frac{1}{|MS_{\mathrm{VR}}|}\sum_{\mathrm{VR}\in MS_{\mathrm{VR}}}\frac{\sum_{v\in N_{\mathrm{VR}}^{v}} C_v^r + \sum_{l^v\in L_{\mathrm{VR}}^{v}} F_{l^v}^r}{\sum_{u\in N_{\mathrm{VR}}^{s}} C_u^{as} + \sum_{l^s\in L_{\mathrm{VR}}^{s}} F_l^{as}}, \tag{6}$$

where MS_{VR} represents the set of VRs mapping successfully, respectively. C_v^r is the computing capacity required by VN v. $F_{l^v}^r$ is the bandwidth (FS) required by VOL l^v. C_u^{as} is the computing capacity allocated by SN u, and F_l^{as} is the bandwidth (FS) allocated by SFL l^s. N_{VR}^v and L_{VR}^v refer to the set of VNs and VOLs in VR, respectively. N_{VR}^s and L_{VR}^s refer to the set of SNs and SFLs in the substrate network onto which the VR is mapped successfully.

4.3 Evaluation results and discussion

The blocking probability and the revenue-to-cost ratio performance of three algorithms obtained from the three topologies are depicted in Figures 5 and 6.

As observed from Figure 5, the blocking probability of all three algorithms becomes high and converges to a similar certain value with the increase of traffic load. The reason is that a shared physical infrastructure with limited resources cannot serve overburdened amount of VRs simultaneously whatever mapping algorithm. And the converging value relates to the amounts of total physical resources provided by the substrate network and required resources by the VON. Apparently, Ba-OVONM always provides the worst blocking performance which only considers the node resource in node mapping stage. Compared with the Ba-OVONM, both SAvS-OVONM and AvSA-OVONM reduce the blocking probability. The reason is that they take into account both node and link resources in node mapping stage. Except for node resource, SAvS-OVONM considers size of the available spectrum resource on SFLs for node mapping, but neglecting the adjacency among the available spectrum which is crucial to allocate spectrum resource in EONs. AvSA-OVONM considers node resource and AvSA on links for node mapping, and thus it has a larger probability of successful link mapping than the former two algorithms. Besides, AvSA-OVONM chooses the routing and spectrum plan whose AvSA(p) is the largest among all the candidates in link mapping stage which can decrease the deterioration of spectrum fragment resulting from resource allocation, as well as serve for the future VRs better. Therefore, the AvSA-OVONM has better performance of blocking probability than SAvS-OVONM.

Figure 6 shows the revenue-to-cost ratio performance of three algorithms. Our proposed algorithm always provides the highest ratio among three algorithms in three topologies, which indicates that AvSA-OVONM can serve the VRs by using least substrate resource. This is because the AvSA(p) relates to the length of path. Then AvSA-OVONM will choose a path whose length is shorter and adjacency among the available spectrum is better than the former two algorithms among the K paths. However, in DT

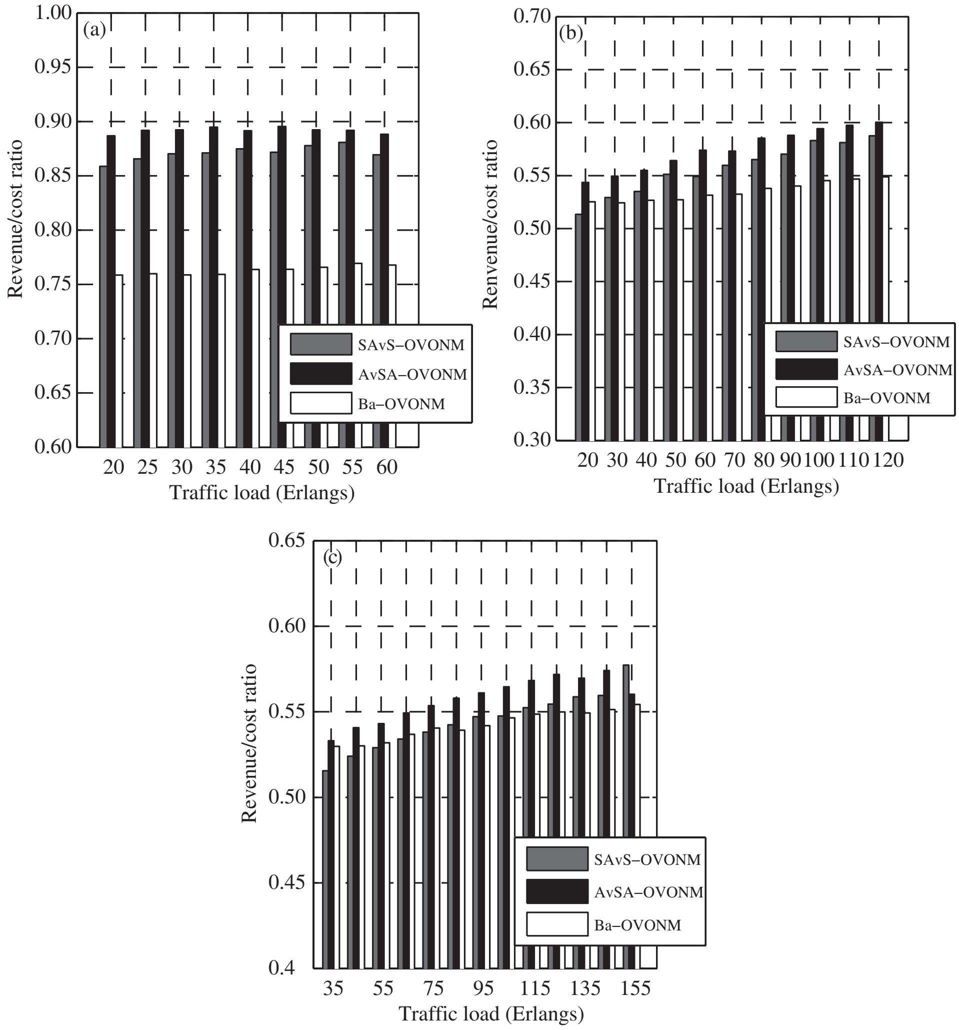

Figure 6 Simulation results on revenue-to-cost ratio performance for opaque VON. (a) Six-node topology; (b) DT-topology; (c) random topology.

topology and random topology, the performance of all three algorithms is not good as that in six-node topology. More resources are needed to map the VRs successfully onto the latter two topologies.

5 Conclusion

In this paper, we investigated the opaque VON mapping problems in EONs. Based on the AvSA which describes size of the available spectrum resource, as well as adjacency among the available spectrum on SFLs or SLPs, the AvSA-OVONM algorithm for opaque VON mapping was proposed. The results of simulation demonstrated that the AvSA-OVONM achieved good blocking probability and revenue-to-cost ratio.

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Conflict of interest The authors declare that they have no conflict of interest.

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Appendix A Abbreviations and formula parameters

Table A1 The main abbreviations in this paper

VON	Virtual optical network
EONs	Elastic optical networks
OFDM	Orthogonal frequency division multiplexing
WDM	Wavelength-division multiplexing
VR	Virtual optical network request
VN	Virtual node
VOL	Virtual optical links
SN	Substrate node
SLP	Substrate light path
SFL	Substrate fiber link
FS	Frequency slot
CFSB	Contiguous FS block
NM	Node mapping
LM	Link mapping
DT	Deutsche Telecom
AvSA	Available spectrum adjacency
Ba-OVONM	Baseline-opaque VON mapping
SAvS-OVONM	Size of available spectrum-opaque VON mapping
AvSA-OVONM	AvSA-opaque VON mapping
AvSA-NM	AvSA-node mapping
AvSA-LM	AvSA- link mapping

Table A2 The main formula parameters in this paper

G^s	Substrate topology of the physical infrastructure
N^s	Set of SNs
L^s	Set of SFLs
C_u^s	Computing capacity of each SN
F_l^s	Bandwidth capacity of each SFL
P^s	Set of SLPs
G^v	Topology of VR
N^v	Set of VNs
L^v	Set of VOLs
C_v^r	Computing resource requirement of each VN
F_l^r	Bandwidth requirement of each VOL
B_l	Number of available CFSBs in SFL
B_p	Number of available CFSBs in SLP
$l(i)$	Boolean variable that equals 1 if the frequency slot is available in SFLs, otherwise, it is 0
$p(i)$	Boolean variable that equals 1 if the frequency slot is available in all SFLs of the path, otherwise, it is 0
S	Total number of FSs on each SFL
l_{dc-v}^r	Set of VOLs that directly connect to the VN
l_{dc-u}^s	Set of SFLs that directly connect to the SN
Rb_v	Value used by sorting VNs
$R\mathrm{AvSA}_u$	Value used by sorting SNs
MF_{num}	The number of blocked VRs
Num	The number of total arrived VRs
MS_{VR}	Set of the VON requests mapping successfully
N_{VR}^v	Set of VNs in VR
L_{VR}^v	Set of VOLs in VR
N_{VR}^s	Set of SNs in substrate network onto which the VR is mapped successfully
L_{VR}^s	Set of SFLs in substrate network onto which the VR is mapped successfully
C_u^{as}	Computing resource allocated by each SN
F_l^{as}	Bandwidth resource allocated by each SFL