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Cross-layer restoration with software defined networking based on IP over optical transport networks

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ABSTRACT

The IP over optical transport network is a very promising networking architecture applied to the interconnection of geographically distributed data centers due to the performance guarantee of low delay, huge bandwidth and high reliability at a low cost. It can enable efficient resource utilization and support heterogeneous bandwidth demands in highly-available, cost-effective and energy-effective manner. In case of cross-layer link failure, to ensure a high-level quality of service (QoS) for user request after the failure becomes a research focus. In this paper, we propose a novel cross-layer restoration scheme for data center services with software defined networking based on IP over optical network. The cross-layer restoration scheme can enable joint optimization of IP network and optical network resources, and enhance the data center service restoration responsiveness to the dynamic end-to-end service demands. We quantitatively evaluate the feasibility and performances through the simulation under heavy traffic load scenario in terms of path blocking probability and path restoration latency. Numeric results show that the cross-layer restoration scheme improves the recovery success rate and minimizes the overall recovery time.

1. Introduction

With the emergence of future Internet services (e.g., high-bandwidth video streaming, large bandwidth medical and financial data, etc.), data center applications have attracted an amount of attention by the service providers and network operators. A large amount of service providers and enterprises are hosting their storage contents and computing resources in data centers to achieve lower delay, higher availability and efficiency at a lower cost [1]. Due to diversity and hugeness of the services, such network-based data center applications have presented the high burstiness and high-bandwidth characteristics. To accommodate these applications in cost-effective, highly-available and energy-effective connectivity channels, IP and optical transport networks can be used into the inter-data center scenario and provide the electrical and spectral resources in a highly dynamic and efficient manner [2–4].

IP networks and optical transport networks are traditional deployed and controlled independently. For example, the IP network runs the IP/MPLS control plane, while the optical network employs the control plane offered by generalized multi-protocol label switching (GMPLS) [5–7]. Little resource information about various networks is shared across any interface/boundary among the networks in either direction. The service demand can be only made across the user-network interface (UNI) between users and networks [8,9]. It leads to the high complexity, expensive cost and much power consumption. Therefore, the future networks tend to be IP and optical integrated to meet the growing requirement of network performance and management capabilities [10].

In addition, a large amount of delay-sensitive services require a high-level end-to-end quality of service (QoS) guarantees [11]. If a link failure occurs in the IP over optical network, the network restoration provided cross IP and optical layers for the dynamic traffic will become much complex [12]. So far, there are a lot of researches about the cross layer protection or restoration in previous IP over WDM network [13–18]. For instance, the authors investigate the survivability issue in IP over WDM networks when a dual-homing architecture is provided in the access network, which can reduce the protection cost in the core network imposed by the proposed architecture in [16]. To restore from an IP layer outage, the researchers build an integrated IP/optical layer restoration architecture which combines transponder-shared mesh restoration at the optical layer with innovative methods of using router line cards and re-configurability [17]. In [18], the authors propose dynamic routing and logical topology remapping schemes to keep a survivable mapping from logical topology to physical topology in

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dynamic traffic scenario, while two different cutset-searching methods are also presented to support the proposed online survivable mapping algorithm.

Traditionally, the aforementioned optical network protection or restoration schemes and mapping are ensured by providing backup or new paths considering optical layer resources. Once cross-layer link (i.e., cross-link which connects IP router and corresponding optical equipment) breaks down, the traffic flow in the link cannot be shifted from the IP router to optical network directly. The traditional schemes using the single optical layer resources can be hard to provide the restoration. It means that the service is difficult to be restored just considering the optical layer resources. The network restoration provided at multiple layers, e.g., IP and optical layers, for dynamic traffic in IP over optical network scenario has not been addressed well. Furthermore, the control of IP networks and optical networks is separately deployed in the traditional architecture. The service request can only be exchanged across the user-network interface between user and network. The availability of comprehensive resource information together with a flexible and cross-layer control system becomes a key issue to enable end-to-end dynamic restoration and high-level performance requirement in case of a failure. On the other hand, as a promising centralized control architecture, the software defined networking (SDN) enabled by OpenFlow protocol has gained popularity by supporting programmability of IP and optical network functionalities [19–21], which can provide maximum flexibility for the operators, make a unified control over various resources and abstract them as unified interface for the joint optimization of functions and services with a global view [22,23]. The SDN relies on the functional separation between control plane and data plane. The control plane is handled by a centralized controller (i.e., OpenFlow controller), while the data plane is performed by node-located agents (i.e., OpenFlow switches). Therefore, from the operators' point of view, it is very necessary to apply SDN/OpenFlow technique to realize the cross-layer restoration in such IP over optical networks environment [24].

In this paper, we propose a novel cross-layer restoration scheme for data center services with software defined networking based on IP over optical network. With the interworking between the centralized controllers in different layers, IP layer and optical layer can coordinate using the restoration scheme. To separate the aggregation services and cross-layer restoration link, the proposed scheme aims at the path restoration optimization for each disrupted service in case of a link failure. The cross-layer restoration scheme can enable joint optimization of IP network and optical network resources, and enhance the data center service restoration responsiveness to the dynamic end-to-end service demands. The feasibility and performances of the proposed scheme are quantitatively evaluated by means of simulations in terms of path blocking probability and path restoration latency compared with conventional cross-layer restoration. Numeric results show that the scheme improves the recovery success rate and minimizes the overall recovery time.

The rest of this paper is organized as follows. Section 2 introduces the software defined networking architecture based on IP over optical network. The cross-layer restoration scheme under this network architecture is proposed in Section 3. We describe the simulation environment and present the numeric results and analysis in Section 4, and last section gives the conclusions.

2. Software defined networking architecture based on IP over optical networks

In the realistic operation environment of network carrier, the IP routers and optical switches are provided by different vendors regularly. For instance, the network operator purchases IP routers from Cisco or Juniper, while buys optical devices of ROADM or OXC from Huawei or ZTE. It causes that the management between routers and optical cross-connect devices of different vendors becomes overly complex due to confidentiality and manageability issues. Therefore, it is important to research the faults occurring on the connection between IP router and optical transport equipment. The cross-layer restoration scheme should be realized in the software defined networking architecture, which can be designed to interact and gather with multiple layers (i.e., IP layer and optical layer) resources in an open control manner. In this section, we first define a general software defined networking architecture for cross-layer restoration based on IP over optical networks. Then the functional building blocks of the controllers and the coupling relationship between them in control plane are presented in detail.

The software defined networking architecture based on IP over optical networks for data center service restoration is illustrated in Fig. 1. In the proposed architecture, the overlapping IP over optical networks can be used to interconnect distributed data centers. It follows that the network architecture mainly consists of two layers: the IP layer network resources and the optical layer network resources (e.g., spectral sub-carriers), as shown in Fig. 1. Note that, the cross-layer link indicates the link between IP layer and optical layer, which means the physical connection which connects IP router and corresponding optical equipment. Therefore, the cross-layer link failure means that a failure occurs on the physical connections which connects router and optical switch, which can cause the traffic flow in the link cannot be shifted from the IP router to optical network directly. The traditional schemes using the single optical layer resources can be hard to provide the restoration. It means that the service is difficult to be restored just considering the optical layer resources. The other link failure indicates the failure appears on the link which connects IP routers or optical devices in one layer. The recovery can be performed in one layer using traditional schemes. For the sake of simplicity, most studies have focused on scenarios where heterogeneous networks are operated by a single OpenFlow controller. Due to the growing extent of network scale and types, the information needed to maintain and operate a single controller is expected to increase rapidly and this will inevitably stress the controller performance. Consequently, the architecture based on a single controller cannot support and meet the scalability and flexibility requirements. Therefore, in this paper, we present the software defined networking architecture in IP over optical network based on two controllers, one is for the IP layer, and the other is for optical network. Note that, the location and placement of the controller are also important which can influence the performance of the

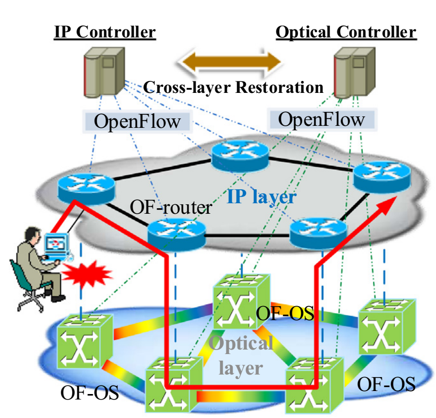


Fig. 1. The architecture of OpenFlow-enabled software defined networking based on IP over optical networks.

centralized controlled network, especially the large-scale network increases [25]. For the sake of simplicity, the placement optimization issue of two controllers will be researched through a large number of simulation and experiments in our future work. Each layer resource is software-defined with OpenFlow and controlled by an optical OpenFlow controller (OOC) and an IP OpenFlow controller (IPOC) respectively in a unified manner. To control the heterogeneous networks with extended OpenFlow protocol (OFP), OpenFlow-enabled optical switch and IP router nodes with OFP agent software are required, which are referred to as OF-OS and OF-router and demonstrated and proposed in [26]. The proposed architecture emphasizes the cooperation among the IP and optical controllers, and it effectively realizes the data center service restoration to use the mixed IP and spectral path achieving joint and global optimization of cross layer resources in case of a link failure. Here, the path provisioning such service uses IP and optical resources through IP network and optical network layers, which is called mixed path (MP). Once received a link failure information from the OOC, the IPOC is responsible for the analyzing it with flow resource status maintained and monitored in the IP layer for service restoration. The OOC exploits optical layer network resources abstracted from the physical network and performs accordingly resilient lightpath provisioning in optical networks. For the sake of simplicity, we use private protocol to exchange information through the interfaces between the OOC and IPOC. Here, we use UDP message to simplify the interworking procedure and reduce the performance pressure of controllers. The cross-layer restoration interacting among two controllers can provide recovery connectivity for the user to guarantee end-to-end QoS.

To achieve the function of the proposed architecture described above, the IP and optical controllers have to be extended in order to support the cross-layer restoration functions. The functional building blocks of two controllers and the basic interactions among them are described in Fig. 2. The optical controller consists of five modules, i.e., network abstraction, failure detection, path computing entity (PCE) and plug-in, restoration control and data base modules. The network abstraction module can abstract the required flexible optical resources, while the failure detection module interworks the information with OF-OS periodically to perceive optical networks through extended OFP. In case of a link failure, the failure detection module discovers it and delivers such failure information to the restoration control. When the failure occurs at cross-layer link on the mixed IP and spectral path, the restoration control module decides to apply cross-layer restoration scheme associated with the IP layer resources. The PCE module can calculate a resilient lightpath, where the various computation strategies are alternative as a plug-in. The information of path is conserved into data base management and updated the results interworking with the IPOC. In the IP OpenFlow controller, flow monitor and estimation module compiles the status of OF-routers via an OpenFlow module in the IP layer. The restoration

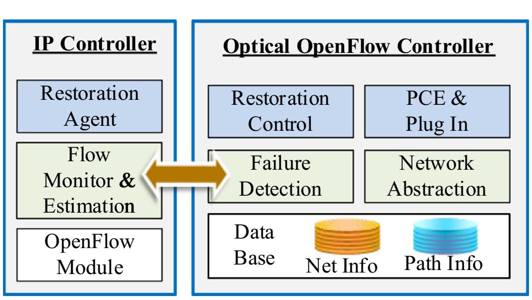


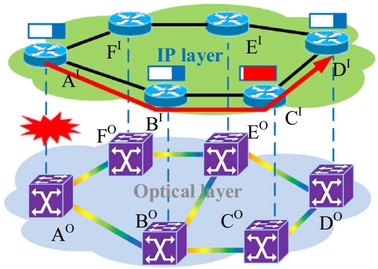
Fig. 2. The functional model of the controllers in software defined networking architecture for cross-layer restoration.

agent can perform cross-layer restoration scheme and decide the IP routing to offload the flow into the optical layer partly using a mixed path. Moreover, the IPOC obtains IP network information periodically or based on event-based trigger through the flow monitor and estimation module. Note that, the IP and optical SDN controllers can be implemented by some existing tools, such as NOX, POX [27], Opendaylight [28], Floodlight [29], and ONOS [30]. In this paper, we develop the controllers based on Opendaylight for simplicity. Also, we consider optical performance monitors as the physical layer technique to detect the cross-layer link failure. Note that the existing OpenFlow messages have the original function. For simplicity, these messages are reused to simplify the implementation in this paper. In fact, in our experiments, we revise and extent the PORT_STATUS message to report the cross-layer link failures status detected by the closest optical switch to the controller. Also, the new messages types will be defined to support new functionalities in the future work.

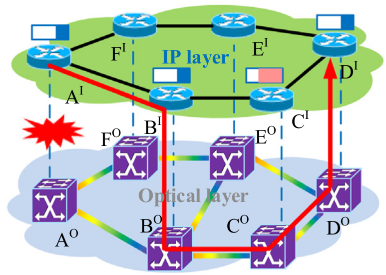
3. Cross-layer restoration scheme

3.1. Problem statement

In the traditional control architecture and strategy, in case of a cross-layer link failure, the traffic flow cannot be shifted from the IP router to optical network. It means that the service is difficult to be restored just considering the optical layer resources. On the other hand, if IP layer resources are used to carry the service, the restoration of such service will consume much energy and cost in the IP network, even the parts of IP router nodes are blocked in the queue especially when the network is loaded heavily. Therefore, we study a novel cross-layer restoration scheme that is essential for the proposed architecture to support the restoration using the mixed path with both IP and optical layer resources. In IP over optical networks, IP network and optical network carrying the data center services have different advantages in various network traffic scenarios. Compared to the optical network, the IP network is more suitable for supplying small granularity service flows due to its flexibility and convenience of packet switching. Under a heavy traffic load scenario, the optical network can offer highly-available, cost-effective and energy-effective connectivity services by provisioning a spectral path. Especially when parts of IP network nodes process the traffic flows busy in the queue, the data center services can be provided through optical bypass partially to take advantage of optical network with large bandwidth. Thus, the path providing such service provisioning uses IP and optical resources through IP network and optical network layers, which is called mixed path. It performs more effective data center service provisioning, i.e., utilizing less resources and enhancing network performance. We use an example to explain the proposal about the restoration, which is shown in Fig. 3(a) and (b). Two 6-node simple networks are considered in overlapping IP over optical network in this example. As shown in Fig. 3(a), a path from source IP node A^I to destination node D^I is used to accommodate the service, where the traffic flow is offloaded into optical layer to optical node A^O and shifted to IP layer from node D^O. It means that the optical node A^O and D^O are the source and destination of related spectral path respectively. When the cross-layer link A^I–A^O breaks down, the traffic flow cannot be shifted from the IP router to optical network in the traditional architecture. To provide the restoration, the new path A^I–B^I–C^I–D^I is rerouted according to the routing table of IP routers only in IP layer network. However, as we can see in Fig. 3 (a), the process of IP node C^I is very busy and almost blocked in the queue. It causes that the other request from node C^I will be blocked and the network performance is degraded. To solve such problem, the cross-layer restoration scheme uses the mixed path with both



(a) Traditional restoration scheme in IP layer.



(b) Cross-layer restoration scheme in IP over optical networks

Fig. 3. Illustration of different schemes for the service restoration when cross-layer link failure occurs.

IP and optical network resources to support the restoration, as shown in Fig. 3(b). The new IP node B^I which is relative idle in the IP layer can be found to offload the traffic, while the corresponding optical node B^O transfers the flow on the new lightpath. The new mixed path A^I–B^I–B^O–C^O–D^O–D^I can enhance the network resource utilization with lower blocking effectively in the proposed scheme.

3.2. Cross-layer restoration procedure with software defined networking based on IP over optical network

Two SDN-based OpenFlow controllers are assumed for each layer in IP over optical networks, containing a networking database storing topology and resources availability information, and a path database storing established paths information. The networking database of the optical OpenFlow controller also contains the cross-layer topology mapping information, which can be described as node pairs (IP node–Optical node). The SDN controllers communicate with the routers or switches by OpenFlow protocol. The cross-layer link failures are detected and reported by the closest optical node (i.e., optical switch) which can inform the OOC through an OpenFlow PORT_STATUS message. The recovery procedures will be triggered by the controller as follow.

In case there is a failure in the link of cross-layer, the providing service will fail to be offered to user. Due to the monitor information using PORT_STATUS message, the OOC receives the information report and finds the cross-layer link failed. Through the stored networking database and path database in the controller, the OOC finds the available nodes attached to the link of cross-layer. With the analysis in optical network layer, the OOC escalates the recovery to IP layer for a possible change of path and forward this request to the IPOC in turn. After the session establishment, the IPOC receives the CORECOVERY request for collaborative recovery from OOC, including the information of cross-layer link failure and corresponding node. Then the IPOC computes the restoration path in the IP layer to provide recovery with weighting mechanism [10] based on the traffic engineering to calculate restoration path, which is called auxiliary graph. When the OOC receives the reply, it can compute the restoration path in the optical layer with Dijkstra's algorithm. The IPOC and OOC can perform the collaborative recovery scheme to set up the restoration path by controlling all corresponding nodes along the computed path by using OpenFlow protocol. For each disrupted path, the occupied resources used by the computed restoration path which is stored in networking database can be updated while computation completed.

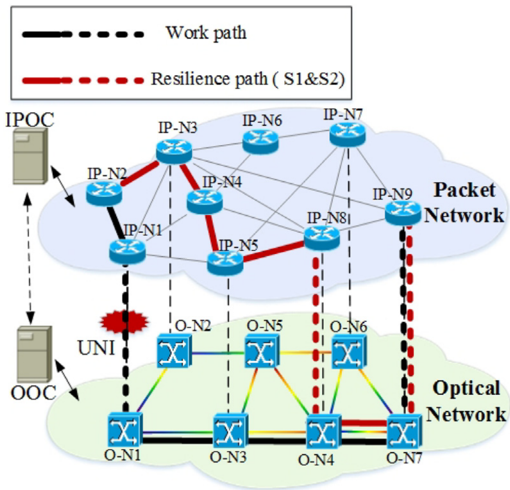
During the aforementioned steps, the restoration paths have to be bypassed with the link of cross-layer. Hence, two SDN-based strategy are hereafter proposed and discussed for cross-layer restoration path computation, i.e., the bundle cross-layer link restoration (BCLR) scheme and the separate cross-layer link restoration (SCLR) scheme.

3.2.1. Bundle cross-layer link restoration scheme

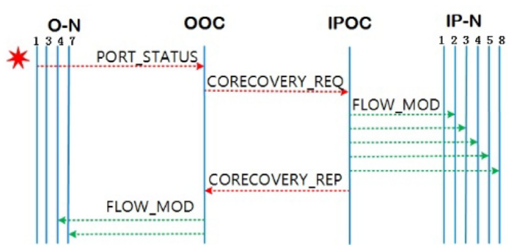
In the bundle cross-layer link restoration scheme, when all the disrupted services can converge to the IP node and then offload the traffic to the optical node together, the IPOC and OOC execute restoration path computation to select a restoration cross-layer link shared by all the disrupted services, and then trigger OpenFlow communication with the routers or switches. The BCLR scheme has a weighting mechanism based on the traffic engineering to calculate restoration path, which is called auxiliary graph and shown in [10] in detail. BCLR scheme considers the disrupted services as a bundle, and restores the aggregation services through the routing and resource assignment together. Due to the services bundle in the BCLR scheme, the bandwidth of the service traffic will increase. Upon receiving the collaborative recovery request (CORECOVERY_REQ) from OOC, including the information of cross-layer link failure and corresponding node, the IPOC chooses an available node attached to cross-layer link for all the disrupted services in common through the auxiliary graph. After restoration paths computation in IP layer is completed, the IPOC sends a collaborative recovery reply (CORECOVERY_REP) to OOC and FLOW_MOD message to each involved router. The router receives the FLOW_MOD and deletes the flow entries previously used by the disrupted path, and adds a new entry required for the restoration path. Fig. 4 depicts the interworking procedure of BCLR for aggregation services when cross-layer link failure occurs. Upon the CORECOVERY_REQ message from IP-N1 reaches, the IPOC chooses node IP-N8 to bypass the aggregation services (e.g., the S1 and S2) together with optical path. The reason is that the cross-layer link to IP-N8 meets the resource requirement for both S1 and S2. Analogously, when the CORECOVERY_REP message is arrival, the OOC obtains the optical bypass node (i.e., O-N4) and computes the restoration lightpath. In this case, the spectrum resources of the restoration cross-layer link should be sufficient enough for all the disrupted paths.

3.2.2. Separate cross-layer link restoration scheme

In the separate cross-layer link restoration scheme, the disrupted aggregation services can be separated and the separate restoration cross-layer link is computed for each restoration path. Also, the SCLR scheme has a weighting mechanism based on the traffic engineering to calculate restoration path using auxiliary graph [10]. SCLR scheme separates the disrupted services and finds each restoration path for them respectively. In SCLR scheme, the bandwidth of various disrupted services may be different, which may cause the results of two proposed schemes will be diverse. For instance, in Fig. 5(a), the various service requests S1 and S2 may be restored into different restoration paths by routing and resource allocation computation, and pass into the optical layer at different nodes (i.e., IP-N3 and IP-N5 in Fig. 5(a)). Therefore, an independent OpenFlow communication is triggered after each restoration path computation. After receiving a CORECOVERY_REQ from OOC, the IPOC computes a restoration path in IP layer for each involved service, and chooses the optimal cross-layer link

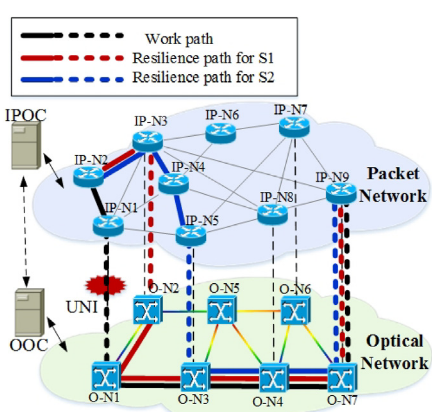


(a) The illustration of BCLR scheme.

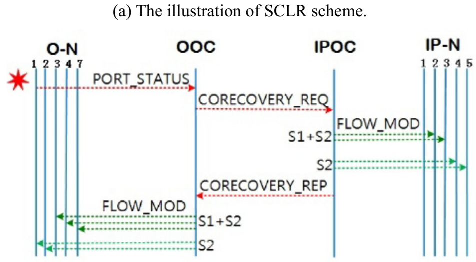


(b) The interworking procedure of BCLR scheme.

Fig. 4. The interworking procedure of BCLR scheme with software defined networking.



(a) The illustration of SCLR scheme.



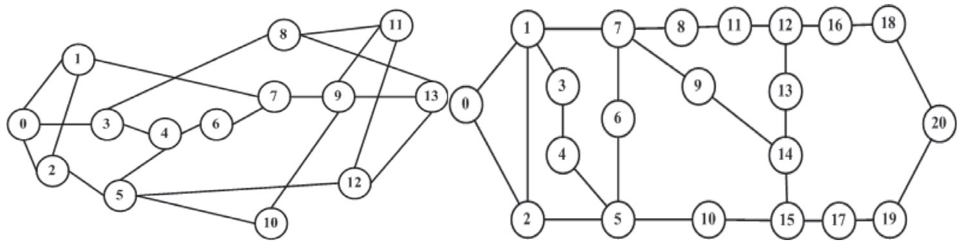
(b) The interworking procedure of SCLR scheme.

Fig. 5. The interworking procedure of SCLR scheme with software defined networking.

independently. After the IP layer restoration path computing, the IPOC sends a set of FLOW_MOD messages to each involved IP routers in order to modify the flow entries. In Fig. 5, the SCLR scheme is applied for the disrupted aggregation services (e.g., the S1 and S2) after a failure detected by IP-N1. In the SCLR scheme, when the CORECOVERY_REQ message arrives, the IPOC chooses an available node to bypass optical paths for S1 and S2, respectively. The S1 requires that the re-configuration of nodes are IP-N2, and IP-N3, and the bypass node is IP-N3. Similarly, the S2 requires the re-configuration of nodes are IP-N2, IP-N3, IP-N4, and IP-N5, and the bypass node is IP-N5. When the CORECOVERY_REP message reaches, the OOC obtains the optical bypass node (O-N2 for S1, O-N3 for S2) and computes the restoration lightpaths for S1 and S2. In this case, the IPOC and OOC need to re-configure a bypass node for each disrupted service.

4. Simulation results and discussions

The proposed cross-layer restoration schemes are evaluated under heavy traffic load scenario by means of C++ simulations using an event-driven simulator, compared with the conventional cross-layer link restoration (CCLR) [24]. We adopt the experiment topologies which are based on the NSFNet backbone (14 nodes, 21 links including 7 cross-layer links) and ARPA-2 network (21 nodes, 26 links including 10 cross-layer links) topology, as shown in Fig. 6. In the real environment, multiple IP routers are connected to one optical equipment (i.e., ROADM) usually, which can be easy to converge the traffic into the wavelength-level channel with the large bandwidth. In fact, the interconnection between each IP route is connected physically in our proposal. However, due to the nationwide NSFNet topology, the communication between IP routers is not always through one hop, which can be connected via one or multiple intermediate nodes. Since such intermediate nodes don't interwork with optical network, the topology of IP layer is abstracted as direct connection between adjacent routers by neglecting the intermediate nodes. In our simulation, we assume that both the routers and the optical switches are connected one-to-one with the identical topology of Fig. 6 for simplicity. The nodes shown in Fig. 6(a) and (b) are only the IP routers that are interconnected to optical transport network elements. Other intermediate IP routers are omitted in the network diagrams and calculations. We assume that the ROADM nodes are deployed into optical layer, where each node has the capability of the optical bypass. Also, each optical node supports 40 wavelengths with no wavelength conversion or 3R regeneration capability. We assume the maximum bandwidth of the IP layer is 1 Gbps and the bandwidth granularity is 100 Mbps, while the bandwidth granularity of the optical wavelength is 10 Gbps. In this paper, we don't consider the modulation format for simplicity. The path blocking probability means that a restoration path could not be found both in the optical layer and in the IP layer. We also assume the path blocking occurs at the IP layer which means the queue of router ports is full and packets are dropped. The maximum queue length is 8 in the simulation assumption. The CCLR scheme recovers the services interrupted by cross-layer link failure in IP layer. The CCLR scheme represents the conventional cross-layer restoration. When a cross-layer failure occurs, the controller will compute restoration path only in IP layer with the CCLR scheme. The connection requests are distributed among node pairs uniformly. They arrive at the network following a Poisson process and results have been extracted through the generation of 1×10^5 demands per execution. In the event-driven simulator, we consider the cross-layer link failures as events, while they arrive at the network following a Poisson process. The location of cross-layer link failure occurs is random in the topology. Three restoration schemes are evaluated using the same



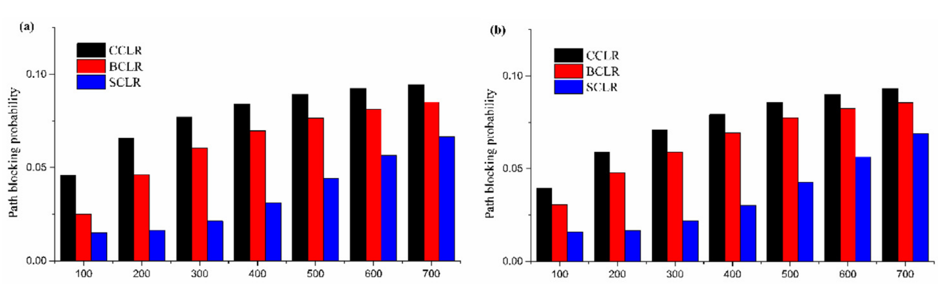
(a) NSFNet topology, node=14, link=21 (b) ARPA-2 topology, node=21, link=26

Fig. 6. Network topologies NSFNET (a) and ARPA-2 (b). The nodes shown in (a) and (b) are only the IP routers that are interconnected to optical transport network elements. Other intermediate IP routers are omitted in the network diagrams and calculations.

spectrum assignment and routing strategy. Here, the spectrum assignment is first-fit strategy, and the first k shortest path algorithm is used to calculate the end-to-end spectral lightpath. We use single modulation format for each flow to simplify the spectrum assignment. The total traffic is applied to the network across all nodes, while the ingress/egress traffic is distributed uniformly across all nodes. All simulations are executed in C++ based Linux GCC v4.4.7 tool on a computer with 2.4 GHz Intel E5620 and 12G RAM. The simulation results are shown in Figs. 7 and 8.

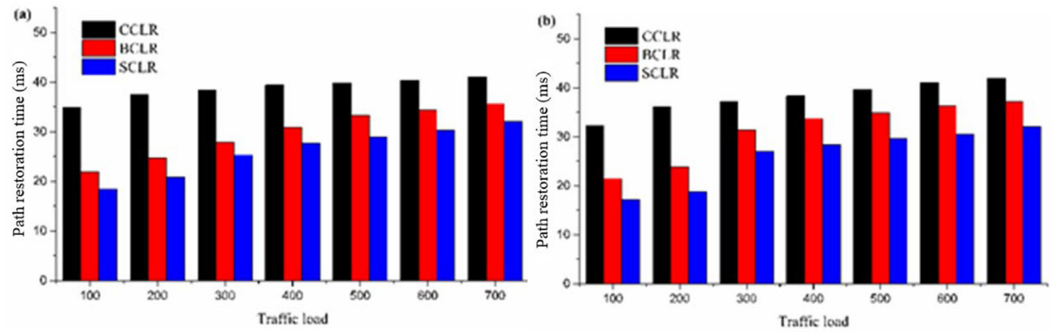
Fig. 7(a) and (b) compare the performances among CCLR, BCLR, and SCLR schemes in terms of path blocking probability in both network topologies NSFNet (a) and ARPA-2 (b). The units on the traffic load in the Fig. 7 is Erlang. It can be seen clearly, in both scenarios, that BCLR and SCLR schemes achieve much better performance of path blocking probability than the CCLR scheme. Specifically, with reducing the spectrum resource constraint condition of the restoration cross-layer link, the SCLR scheme achieves lower path blocking probability than that of the BCLR scheme. The reason is that both IP and optical network resources are considered in the cross-layer restoration scheme. It can help that many traffic flows are avoided to transfer into the heavy loaded router, in which lots of services may be blocked or lost due to the long queue. The recovery success rate of each strategy can be evaluated by the path blocking probability. The lower blocking probability is the higher recovery success rate will be. That is, the SCLR significantly improves recovery success rate. Another phenomenon can be found in Fig. 7(a) and (b) where the advantage of cross-layer restoration scheme is more obvious with the increase of offered loads. That is because the network under higher workload needs urgently to interwork and jointly optimize IP and optical resources with fine granularity. On the other hand, three various schemes may consume different network cost. In detail, the CCLR scheme recovers the services in IP layer in case of a cross-layer link failure. It causes that lots of IP routers are occupied for the restoration and thus increasing the energy consumption. With the BCLR scheme, the number of networking equipment and transponders used is lower than the one in SCLR scheme. It is because that BCLR scheme bundles the distributed services together and recovers them through one restoration path after the cross-layer link failure. That saves a number of the network costs. We can find that the network performance is the tradeoff between path blocking probability and network cost. The blocking probability of BCLR scheme is a little higher with lower network cost.

The performances among the CCLR, BCLR, and SCLR schemes in terms of path restoration latency in both the NSFNet and ARPA-2 network topology are compared in Fig. 8(a) and (b). The units on the traffic load in the Fig. 8 is Erlang. The latency reflects the average restoration delay until the services are recovered successful after a failure. In the real environment, the whole restoration latency is divided into three parts, which comprises the scheme processing time of controller, OpenFlow signal propagation latency, and software and hardware of device handle times. In our simulation, due to the lack of expensive hardware and experimental environment, it is hardly to emulate the whole latency accurately. Therefore, we simulate the signal propagation latency and software of device handle delay according to the survey data [31] for simplicity, which can find that the signal propagation time occupies a limited proportion in the overall latency compared to the software of device handle time. In the simulations, we obtain the restoration latency by estimating the computation time to call the timer event function. As shown in the figure, the SCLR scheme significantly reduces the path restoration latency compared to the CCLR and BCLR schemes. The reason is that in the BCLR scheme, the bundled service has a higher bandwidth and then leads to the path computation and resource assignment with much stricter resource constraints compared to SCLR. While the SCLR scheme can perform the path computation and resource allocation with the services separation. Therefore, BCLR scheme is more difficult to find available path to accommodate the services. The SCLR scheme can choose the optimal restoration cross-layer link for each single service without strict resource constraints. It allows saving a large amount of computation time. When a new cross-layer link failure



(a) NSFNet topology (b) ARPA-2 topology

Fig. 7. Path blocking probability of CCLR, BCLR, and SCLR schemes in (a) NSFNet. (b) ARPA-2.



(a) NSFNet topology (b) ARPA-2 topology

Fig. 8. Path restoration time of CCLR, BCLR, and SCLR schemes in (a) NSFNet. (b) ARPA-2.

comes, the SCLR can be triggered and the influenced services are recovered independently. This phenomenon is more obvious under heavy traffic because more requests need to be queued and the calculation times of CCLR, BCLR schemes increase, which will augment the delay time.

5. Conclusions

In this paper, we propose a novel cross-layer restoration scheme for data center services with software defined networking based on IP over optical network. Two proposed schemes, i.e., the bundle cross-layer link restoration (BCLR) scheme and separate cross-layer link restoration (SCLR) scheme, can provide the restoration using the multiple layer resources in case of a cross-layer link failure. The feasibility and performances of the proposed schemes are quantitatively evaluated by means of simulations in terms of path blocking probability and path restoration latency compared with conventional cross-layer restoration. Simulation results show that, compared with the CCLR scheme, the proposed BCLR and SCLR schemes can utilize cross-layer resources effectively, leading to a reduced blocking probability and enhanced end-to-end restoration responsiveness of data center services. Future interesting works will be focused on the influence on the scheme, which possibly make for further improving the resource utilization. Also, the scheme under mixed failures and multiple failures scenarios, and experimental demonstration on our OpenFlow-based SDN testbed will be researched in our future works.

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