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Towards programmable on-demand lightpath services: current state-of-the-art and open research areas

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Abstract: With emerging programmable network architectures gaining momentum in the networking industry, it is necessary to look at how the services currently offered on traditional network architectures can be fully migrated to the programmable networks. In traditional networks, lightpaths are used for providing high-bandwidth consuming services that are usually sensitive to delay. Lightpath scheduling requires admission control mechanisms, routing and wavelength assignment algorithms, and protection and restoration mechanisms that ensure reliable and efficient lightpath routing. Software defined networking (SDN) is the emerging programmable network architecture that paves the way for easier network management and configuration by using application programming interfaces. The state-of-the-art in lightpath routing for wavelength division multiplexing networks focusing on lightpath scheduling, routing, protection and restoration in optical software defined networks is surveyed. Moreover, open research issues for SDN lightpath routing solution are discussed.

1 Introduction

The rapid influx of new internet applications such as video-on-demand, video conference and distance education requires a bandwidth-guaranteed data transport model. These applications have forced network designers/operators to consider and employ technologies such as wavelength division multiplexing (WDM) in their optical transport networks. WDM is a multiplexing technology wherein the bandwidth available on a fibre is partitioned into multiple wavelength channels, each of which is capable of carrying data [1]. Lightpath is an all optical data transmission technology between each source–destination pair, which is implemented by assigning the same wavelength throughout a path. The data transmitted through a lightpath is switched entirely in the optical domain without requiring optical-to-electrical conversion [2]. The requirement of keeping the same wavelength is known as the wavelength-continuity constraint (WCC) [3]. Lightpath connections are often used to carry critical and large customer data and as such, reliability and availability of the optical network are the most critical elements required by network operators to serve user demands and meet service-level agreements. Networks have to be designed in such a way that in the event of a network failure, services are not interrupted or abandoned. The ability of a network to continue routing lightpath services during and after a network failure is referred to as survivable lightpath routing.

Survivable lightpath routing employs different methods, such as protection and restoration mechanisms, to ensure that a network can survive failures and continue with lightpath routing. Protection mechanisms include redundant routing resource strategies in the case of failures. Restoration mechanisms include strategies that deal with how to restore traffic affected by network failures. Different protection and restoration mechanisms can be employed to suit different types of lightpath connections in a network. These mechanisms include lightpath connections that are planned well in advance and those that are ad hoc. Lightpath routing is categorised based on two traffic models: the *static traffic model* and the *dynamic traffic model*. Lightpath connection requests under a dynamic model arrive at random and have to be provisioned as needed. Lightpath connections that are of the static model are usually a set of connections that are known upfront. Survivable lightpath routing in WDM networks has been studied extensively, for example, in [4–6] and deploying such a network often comes with extra cost as it sometimes requires redundancy in the network infrastructure to cater to network failures.

In current commercial core networks, lightpath provisioning is managed and controlled through an operator-driven centralised entity called an element management system (EMS) and/or a network management system (NMS) [7], which monitors and manages different network components. This control mechanism is reliable for static traffic. However, the rapid increase in dynamic traffic requires adaptive and intelligent control architectures to guarantee lightpath provisioning within a dynamic environment. With technology growing at a fast pace, networks have been facing different technical difficulties such as the rigidity of using different NMSs and management of different vendor equipment that form part of the network design. Various research initiatives such as the Clean Slate Internet Program (CSIP) have been initiated to address rigidity and other challenges [8]. A major achievement of the CSIP initiative is Software defined networking (SDN), which introduced the idea of programmable networks.

SDN provides a framework for decoupling the data plane from the control plane. The framework enables direct programmability of flows on packet-forwarding hardware systems. The control plane consists of software-defined controllers, which are usually based on the OpenFlow protocol [9]. SDN provides ways to increase the ability to switch and groom transport bandwidth over optical resources, as well as switch optical capacity by using transport SDN. Southbound interfaces are application p interfaces (APIs) used dynamically to enforce communication between the control plane and the data plane. OpenFlow is a southbound interface protocol which allows the control and management of different network-forwarding devices.

Network operators are conducting proof of concepts testing the full migration of services from legacy networks to the new SDN network. Therefore, it is vital to study and understand the impacts and benefits of adopting SDN networks as far as different network services are concerned. Thus far, various research papers on SDN investigating different aspects, such as, to mention a few, security and traffic engineering, have emerged [10, 11]. Akyildiz *et al.* [10] presented a detailed review on traffic engineering for SDN, focusing on flow management, fault tolerance, topology update and traffic characterisation. Wang and co-authors [11] reviewed problems caused by network updates and solutions for SDN networks. Scott-Hayward *et al.* [12] reviewed network security for

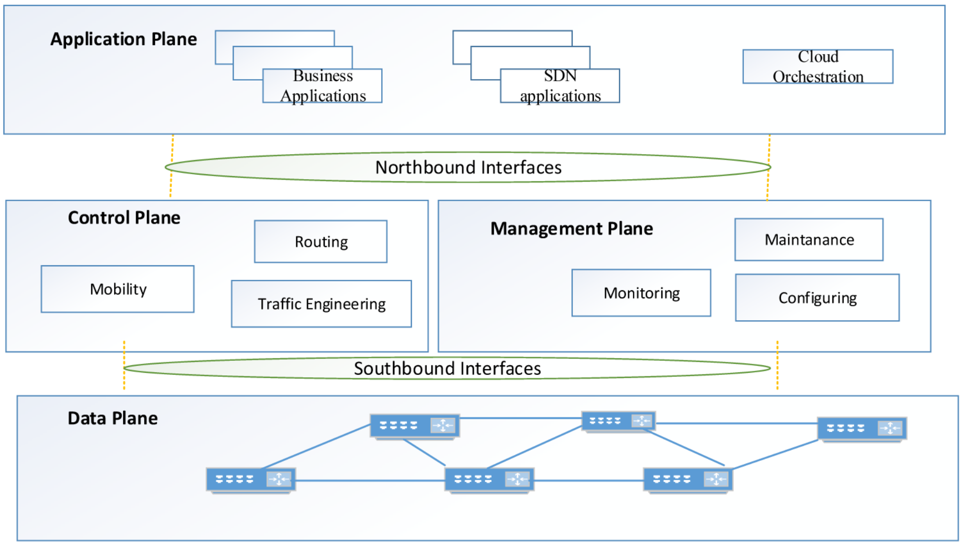

Fig. 1 *SDN logical architecture*

SDN. To the best of our knowledge, this paper is the first to review lightpath provisioning and routing on SDN-based networks. Classical lightpath provisioning and routing for IP and generalised multiprotocol label switching (GMPLS) networks are briefly discussed, followed by a survey of the state-of-the-art in lightpath for SDN. This paper also highlights some of the open research areas for SDN networks for lightpath routing with a focus on admission control architecture, routing and wavelength assignment, and protection and restoration.

The rest of this paper is organised as follows: Section 2 provides an overview of SDN networks. Section 3 provides a review of lightpath. Section 4 outlines open research areas for lightpath establishment on programmable network architecture and Section 5 concludes the paper.

2 SDN overview

SDN is a new networking paradigm that paves the way for virtualising network resources in an on-demand manner. Most network service operators are adopting the SDN paradigm and at the same time dealing with the migration of different network services to new SDN network architectures.

SDN decouples the control plane from the data plane and offers control of the network through programming by using APIs. The use of APIs offer benefits such as enhanced configuration, improved performance and real-time centralised control of a network based on both instantaneous network status and user-defined policies. As illustrated in Fig. 1, the SDN concept can be defined as network architecture with four planes:

- *Control plane:* The controller acts as a broker between the application plane and the data plane and is responsible for topology discovery, path selection and assignment, policy declaration and network security checks.
- *Management plane:* A management plane is a set of applications (e.g. load balancers, firewalls and routing algorithms) that utilise the northbound interface to implement control and operation logic. Primarily, a management application defines policies, which are pushed down to the data plane for execution. Due to the lack of backward compatibility of this approach, Haleplidis and co-authors [13] proposed a management plane which is at the same level as the control plane. The role of the management plane is to monitor and maintain forwarding devices, for instance, making decisions regarding the operational status of network devices. Additionally, the management plane may be used to configure the forwarding devices, but it does so occasionally as compared to the control plane. Like the control plane, the communication between the management plane and the data plane is through a southbound interface as shown in Fig. 1. This ensures compatibility of the management plane with conventional network protocols such as the simple network management protocol (SNMP) [14], the border gateway protocol (BGP), the path computation element protocol (PCEP) and the network configuration protocol (NETCONF) [14].
- *Data plane:* The data plane consists of interconnected virtual and/or physical network devices. There are two planes that reside in the data plane, namely: (i) the forwarding plane and (ii) the operational plane [13]. The forwarding plane is responsible for handling and forwarding packets. Packet-handling includes dropping, rewriting some headers and forwarding packets to the controller. The operational plane is responsible for the status of the network devices; this includes network ports and interface status [13].
- *Application plane:* Various applications and services are developed to program the control plane to achieve network functions specified by network operators. Examples of such applications include cloud orchestrators and business applications. The SDN application layer creates new policies, which are directed via the control plane and enforced at the data plane.
- *Application programming interfaces:* Two APIs are used in SDN, namely, the northbound interfaces (NBIs) and the southbound interfaces (SBIs). SBIs are used for communication between the controller and the data plane. Although there are many other SBIs such as Forces [15] and Border Gateway Protocol Link State (BGP-LS) [16] among others, OpenFlow is the mostly used and adopted SBI. NBIs are used for communication between the controller and the application plane. RESTCONF is the most widely adopted NBI in the SDN community [17].

SDN ensures optimal network resource utilisation to support virtual machines. The ability to virtualise the physical network environment into its logical representation can help reduce the overall CAPEX and OPEX. SDN makes it possible to build switches from commercial-off-the-shelf hardware components [18]. Additionally, managing a virtual environment takes considerably less time than managing a physical environment, which requires manual collaboration between different operators.

3 Lightpath overview

This section provides an overview of end-to-end lightpath routing in traditional WDM optical networks. Emerged developments in lightpath routing using SDN are also highlighted. The first subsection starts by describing the admission control method for scheduling lightpath connections. Lightpath establishment, provisioning, survivable lightpath routing and control architecture are also discussed.

3.1 Lightpath admission control

In real world networks, there are different types of lightpath service requests which have to be provided, for example, immediate and advance lightpath requests. The first step in providing lightpath services is to have an efficient admission control system. The admission control system determines whether the network has sufficient resources to fulfil a lightpath connection request, and has information on all available network resources, scheduled lightpath connection requests and their durations, and network capacity at a particular time. When a lightpath connection request arrives, the system performs a routing and wavelength assignment (RWA) to decide whether to accept or reject the request based on available network resources, quality of services and network load. If resources are available, the lightpath connection is scheduled or provisioned. Otherwise, the lightpath connection request is rejected. In essence, the admission control system monitors and keeps track of all network resources required for lightpath provisioning and scheduling and also classifies the incoming request based on a particular priority. In most cases, the admission control system includes payment models which are revenue-driven [19, 20]. In large networks the management of the required network resources may be tedious as different NMSs may need to be monitored to keep track of available resources.

SDN helps to cut down the use of multiple network EMSs which are usually due to the use of different network equipment from different vendors to a single centralised controller [21]. However, it has been shown that the SDN centralised controller approach suffers from the *single point of failure* problem [22]. To overcome the single point of failure problem, there have been developments in deploying distributed controllers [23]. Therefore, it may be interesting to investigate how efficient and timeous the distributed controller approaches are in managing network resources required for lightpath scheduling and provisioning. An investigation of methods of queuing lightpath requests based on different priorities is required for the distributed controller approach.

The control admission system is connected to the lightpath control management system, which is responsible for lightpath connection and tearing down.

3.2 Control architecture

To establish and tear-down lightpath connections, a control mechanism is required. Generally, lightpath control can either be classified as centralised or distributed. In centralised control, a single entity is responsible for the management and control of the optical network and as such, it has a global view of all network resources. Although centralised control is relatively simple, interoperability and scalability concerns, as well as significant technical bottlenecks such as real-time lightpath provisioning, automatic network topology reconfiguration and fast connection recovery, can arise when dealing with time-sensitive traffic [24]. These bottlenecks automatically disqualify the centralised control mechanism in large dynamic networks. A widely deployed control mechanism is thus the distributed control, because of its excellent scalability and fast reaction to network events such as link failure and addition of optical components [25, 26]. Nevertheless, distributed control presents its own problems. The most prominent problem of this mechanism is the propagation delay of link state advertisements. This is due to factors such as non-negligible propagation delays, infrequent network state updates and topology aggregation [27]. This is still an open challenge in traditional optical networks. It has been shown that programmable network architecture can alleviate this challenge, especially if the programmable network is deployed using the centralised controller approach [28]. However, for a distributed controller approach, this problem requires further investigation.

3.3 Lightpath establishment

This section describes the lightpath establishment process which is performed during lightpath admission and scheduling in traditional optical networks. Lightpath establishment components such as routing and wavelength assignment together with the necessary protocols required to realise lightpath are discussed. Lightpath establishment in SDN-based optical networks is also described.

3.3.1 Routing and wavelength assignment: A lightpath generally spans more than one fibre link. Lightpath establishment involves performing RWA. That is to say, a particular route and wavelength has to be assigned along that route. This is known as the RWA problem [27]. The RWA problem is typically decoupled into two sub-problems: (i) the routing sub-problem and (ii) the wavelength assignment sub-problem. The decoupling of the problem is done to make the problem more manageable [28]. The routing sub-problem addresses route/path allocation for a lightpath connection. The wavelength assignment sub-problem allocates a wavelength resource to a defined path/route. The RWA problem is NP-complete; as a result, heuristics or meta-heuristics are usually employed [27]. In general, a RWA can be performed under a WCC. In a WCC compliant network, routing nodes do not have the capability (i.e. wavelength converters) of changing or converting wavelength during lightpath transmission. As such, a lightpath has to use the same wavelength through all the fibre links it traverses. Fig. 2 illustrates this by highlighting two routes using two different wavelengths, with one lightpath connection using λ_1 and another lightpath connection using λ_2 from source to destination. However, the WCC can lead to ineffective usage of wavelength channels [29, 30]. Alternatively, some or all of the routing nodes may have wavelength conversion capability, which makes it possible to change a wavelength to another available wavelength along a lightpath route.

Lightpath routing is classified based on two traffic models, namely, the *static traffic* model and the *dynamic traffic* model. As such, the RWA is different within each of these models.

Static traffic model: In a static traffic environment, a set of connection requests are known in advance. The goal is to allocate lightpaths to meet all traffic demands, such that various cost functions are minimised (e.g. minimising the total number of wavelengths and/or fibres in the network). The RWA problem for static traffic demands is known as the S*tatic Lightpath Establishment (SLE) problem.* The *SLE* is performed offline. That is, routing and wavelength assignments are performed without any other active lightpath in a network [29]. The SLE is well-studied in the literature [3, 30]. The routing sub-problem is addressed using methods such as fixed routing, least-congested routing or fixed-alternate routing [3]. The fixed routing mechanism, which is the simplest and straightforward, uses the shortest path algorithms such as Dijkstra [31] or Bellman-Ford [32]. However, fixed-routing has risks of high blocking probabilities when shortest routes do not have available wavelengths. The fixed-alternate mechanism solves the routing problem by considering multiple routes for a lightpath. The fixed-alternate method provides some level of fault tolerance as alternate routes can be used not only in the case of faults, but it also has a higher blocking probability. For the least congested method, a set of routes is first determined. The best route is selected from the predetermined set based on the *least congested* link. A least congested link is defined as a link with a larger number of available wavelengths. The least congested method is computationally complex and has higher blocking probabilities as compared to the fixed-alternate method. The routing sub-problem can also be formulated as an integer linear programming (ILP) problem, with the main objective of minimising the maximum number of lightpaths and the number of wavelengths on any link. ILP is more feasible for smaller networks because it is computationally complex and requires significant running time [33]. For moderate-sized and large networks, heuristic-based approaches such as tabu search, local search, stochastic diffusion search, swarm intelligence algorithms and others have been successfully employed to solve the SLE problem [33, 34].

The wavelength assignment sub-problem can either be solved in parallel with the routing problem or after routing has been determined. Usually, in SLE, the two problems are solved in parallel. However, when multiple required wavelengths are available on a route, wavelength assignment has to be performed separately after routing. In SLE, the wavelength assignment is

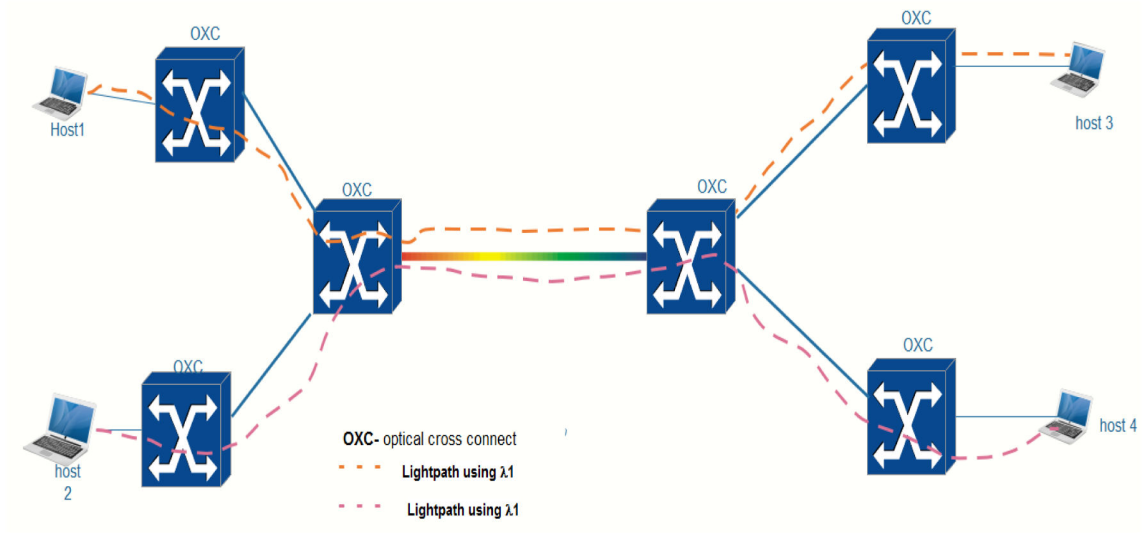

Fig. 2 *Wavelength-routed WDM network with lightpath connections following the WCC by using the same wavelength throughout an entire path (with connection 1 using λ_1 from source (host 1) to destination (host 3) and connection 2 using $\lambda 2$ from source (host 2) to destination (host 4)SDN logical architecture*

usually formulated as a graph-colouring problem [3]. The graph colouring problem takes a set of lightpaths and their associated routes as input and assigns a wavelength to each lightpath such that any two or more lightpaths sharing the same link use the same wavelength. As with the routing sub-problem, a wavelength assignment can also be formulated as an ILP problem. The differences lie in that WCC is imposed in the wavelength assignment problem. The wavelength assignment problem can also be formulated using different heuristics based on different factors and requirements. More wavelength assignment heuristics are discussed in the next section. In general, the SLE problem has been studied using different methods such as tabu search [35], genetic algorithms [30], simulated annealing [33], particle swarm optimisation [36] and others [37]. The choice of the heuristic approach to be employed is guided by several factors such as running time, resiliency, computational complexity and also the optimality of solutions offered by a heuristic. For example, some heuristics solve the RWA jointly rather than following the two-step approach [35].

Static traffic model network environments make it easier to manage and control all lightpath requests since all traffic demands are well known in advance. However, static traffic network environments make it impossible to accommodate the rising needs for flexible dynamic lightpath scheduling.

Dynamic traffic model: Connection requests in a dynamic traffic model are received in a stochastic fashion. The main objective addressed in a dynamic traffic model is to decrease the blocking probability for demands, utilising a fixed number of transceivers [25]. A demand is said to be blocked when there are insufficient resources to route it. Once a demand is honoured, it is terminated after a finite amount of time. The RWA problem for dynamic traffic demands is referred to as the *dynamic lightpath establishment* (DLE) problem. The RWA problem for DLE is also NP-complete. As a result, heuristic algorithms are employed. DLE is performed online, i.e. RWA is performed taking into consideration all other scheduled and active lightpath demands in the network. The routing sub-problem for DLE is usually addressed using adaptive routing scheme [38]. Adaptive routing keeps track of the state of the network by assigning a negative link cost to links that are unavailable. All unused links have a link cost of one. Adaptive routing selects the best possible route by determining the shortest path from the list of unused links. An advantage of adaptive routing is that it offers less blocking as compared to fixed routing, alternate fixed routing and the least-congested methods. However, it has a longer average set-up time [33]. The wavelength assignment sub-problem for DLE is performed in parallel with the routing sub-problem. The wavelength assignment schemes are [3]:

- *Random wavelength assignment*: In this simple approach, a set of all available wavelengths along the required path is determined, and then a wavelength is randomly selected within the determined set. However, this method requires global knowledge of the network.
- *MAX-SUM (MS):* This scheme is usually applied on multi-fibre link networks. For each link, link capacity is determined for each wavelength as the number of fibres on which the wavelength is unused. Path capacity for each wavelength on a link is determined as the number of fibres on which wavelength is available on the most-congested link along a particular path. Given a list of lightpaths with their precomputed routes, MS assigns wavelengths so as to maximise the available path capacities after lightpath establishments. The MS scheme is preferred for high network loads [39].
- *Relative capacity loss (RCL):* RCL is the opposite of MS. RCL assigns wavelengths so as to minimise capacity loss. RCL performs better than MS in terms of blocking probability.
- *First-fit (FF):* Wavelengths are numbered and packed in an ascending order. Wavelengths are associated with an ordinal number with lower ordinal numbers associated with unused wavelengths and higher ordinal numbers associated with used wavelengths. When assigning wavelengths, FF considers the lower numbered wavelengths first and the first available wavelength is assigned. FF offers less computational cost, because the wavelength search space does not have to be searched entirely during wavelength assignments.
- *Min-product (MP):* MP is the multi-fibre version of FF. MP tries to reduce the number of fibres used in a network by packing wavelengths into fibres. Although it offers better resource utilisation, it introduces more computational costs as compared to FF.
- *Least-used (LU):* LU tries to distribute load evenly among all wavelengths by assigning used wavelengths first. As compared to FF, LU also requires global information about all wavelengths in the network to make informed decisions when assigning wavelengths.
- *Most-used (MU):* MU assigns wavelengths by selecting the most used available wavelengths. As the opposite of LU, MU also has a high dependency on the accuracy of the state of the network.
- *Least-loaded (LL)*: LL assigns wavelengths by choosing a wavelength that has the largest residual capacity on the most-loaded link along a particular route. LL is usually applied to multi-fibre networks. LL has lower blocking probabilities as compared to MU, but offers high communication overheads.
- *Wavelength reservation (WRsv)*: This method is used to reserve wavelengths for lightpaths with multiple hops. Thus, it offers an

increased acceptance ratio for lightpaths with multiple hops and a low blocking ratio for single hop lightpaths.

- *Protecting threshold (PThr): PThr* is a variant of WRsv. In PThr, a single hop lightpath is assigned a wavelength when the number of idle wavelengths on a link is higher than a defined threshold. This method offers a low rejection ratio of single hop lightpaths. WRsv and PThr are usually used when special reservation of resources is required.

The choice of wavelength assignment method to be used is dependent on various factors, for instance simplicity [40], multi-fibre network [41], single-fibre network [42], load-balancing or blocking probability [43]. These wavelength assignment methods can be applied either online or offline. Therefore, they are applicable to both static and dynamic traffic models.

DLE can further be classified as *immediate reservation* (IR) or *advance reservation* (AR) requests [44]. IR requests are made only when a lightpath service is needed, and are thus executed immediately after receiving a connection request [45]. The transmission duration for dynamic traffic is unknown and assumed to be infinite for static traffic demands. A disadvantage of IR connection requests is increased blocking probability, due to the unavailability of network resources during the time that the connections may be required. The blocking probability may be intolerable for customers that require guaranteed bandwidth at the specified time. An attractive solution to the blocking probability problem is the AR model, which allows customers to make reservations ahead of time [45]. Not only does the AR model guarantee bandwidth services, but it also allows networks to optimally plan the required wavelength allocations.

3.3.2 Lightpath establishment protocols: RWA is the most vital component of lightpath establishment and routing. However, lightpath establishment does not only require heuristics to determine routes and assign wavelength, but also requires certain protocols to realise reliable RWA. Lightpath establishment requires routing, resource reservation and signalling protocols. During lightpath establishment, routing protocols employ different routing schemes for defining efficient lightpath routes. A resource reservation protocol uses wavelength assignment schemes to acquire the necessary wavelengths for lightpath routing.

Signalling protocols are used to exchange control information between network nodes to ensure that each node is up-to-date with the state of the network and to avoid resource reservation conflicts. The signalling protocol usually works hand-in-hand with the resource reservation protocol. IP-based and GMPLS networks support different routing, reservation and signalling protocols. IP-based networks employ open short path first (OSPF) or the intermediate system–intermediate system (IS-IS) as the routing protocol and also as the signalling protocol. The OSPF and IS–IS protocols use static link weights to perform RWA and do not manage how network nodes handle multiple routes when routing lightpaths. Also, the OSPF/IS–IS does not have the capability to share lightpath load among available routes to avoid nodes overloading. Thus, the OSPF/IS–IS is not flexible in solving RWA, more particularly for the dynamic traffic model.

GMPLS networks were introduced to overcome the limitations of IP-based networks. The GMPLS uses the resource reservation protocol (RSVP) as the signalling protocol and resource reservation protocol, and OSPF-traffic engineering (OSPF-TE) as the routing protocol. In distributed networks and elastic optical networks (EON), GMPLS may experience limited efficiency and manageability of distributed path computation. To alleviate this limitation, the GMPLS is usually assisted by an active path computation element (PCE), which is purely dedicated to routes computation.

Compared to IP-based networks, GMPLS can share and optimise lightpath load among available routes. The RSVP uses label switching path (LSP) tunnels when reserving resources. For example, each source and destination pair may be assigned resources by multiple LSP tunnels. Lightpath traffic for the pair is shared among the dedicated LSP tunnels. Since dedicated tunnels are used for each pair, the number of tunnels required in larger networks would be cumbersome. Thus, the GMPLS introduces scalability and robustness problems [46]. These problems are believed to be relieved by SDN networks.

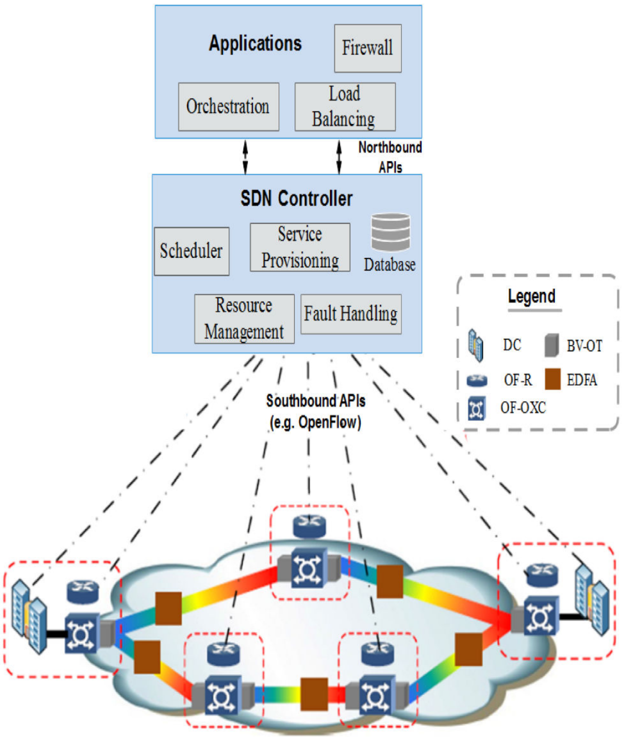

Fig. 3 *Typical SDN-enabled WDM network architecture*

3.3.3 Lightpath establishment in SDN: The SDN framework is an emerging networking architecture paving the way for more advanced softwarised networks, which offers alternative control planes as compared to some of the latest traditional networks, which use GMPLS. Most SDN frameworks are based on the OpenFlow protocol [47], which is used for communication between a centralised controller and SDN nodes. OpenFlow supports optical transport networks with certain extensions [48], and thus, a controller should be extended to support lightpath establishment and routing. As shown in Fig. 3, a typical SDN-enabled WDM network consists of two domains on the infrastructure layer, namely, the packet switched and optical circuit domains. This is commonly referred to as IP over WDM [49] overlay networking. The infrastructure layer components include data centres (DCs), OpenFlow-enabled routers (OF-R), OpenFlow optical cross-connect (OF-OXC) devices, Erbium-doped fibre amplifier (EDFA) and bandwidth variable optical transponders (BV-OT). The SDN controller interacts with both the optical and packet domains using the OpenFlow protocol. The SDN controller constitutes control functions for service provisioning, scheduling, fault-handling and resource management [50, 51]. The resource management module periodically discovers the data plane functions (such as nodes and links) and collects network state information (including state of lightpaths and virtual links). This information is stored as in the database. The resource management module has two additional critical roles. First, it enforces lightpath set-up requests from the service provisioning application on the data plane. Second, it gathers alarms concerning possible network failures and notifies the fault-handling module for appropriate counter actions. Failures that result in network service disruptions are forwarded to the service-provisioning module which activates a protection and/or restoration mechanism to correct the failure. The service-provisioning module handles path computation utilising the network state information stored in the database. It also listens to service requests from other applications (such as orchestrators and user interfaces) that program new traffic engineering policies via the northbound API. The scheduler receives information regarding future lightpath demands and stores the information in the database. When lightpath provisioning deadlines arrive, the scheduler sends a request to the service-provisioning control module which either honours (configures a lightpath) or blocks the requests depending on resource availability.

More recently, a number of studies on lightpath provisioning using SDN have been conducted [52–54]. Garrich *et al.* [52] proposed an SDN-based optical network that focused on time-synchronisation operations with an objective to reduce lightpath disruption time. Matrakidis and co-authors [53] proposed a framework for dynamic multi-layer resource allocation for SDN-based optical networks using lightpath as an application. In some studies [52], it has been shown that lightpath routing cannot be initiated until RWA is completed and relevant resources required for establishing connections are reserved and configured. In SDN, configuration and reservation are done by configuring all nodes that form part of the lightpath route, thereby adding flows onto each node. To initiate lightpath, the controller should have a confirmation that all the required connections are configured and reserved. Thus, OpenFlow has to be extended to include notification messages from the nodes after each flow addition. Alternatively, the controller employs a flow timer, which defines a certain time delay before a lightpath can be established by assuming that after the predefined time, all necessary resources are configured and reserved [55]. Mayoral *et al.* proposed a novel SDN-based control plane which incorporated stateful and active PCE into an OpenFlow controller. Their controller establishes and provisions lightpaths through the use of OpenFlow and PCE protocols. Another method of using SDN for lightpath establishment and routing is through the extension of the OpenFlow network to include GMPLS protocols [55, 56]. In such a network, the data plane is a GMPS-based network, which is managed by the SDN controller. The controller manages the network topology information and computes routes for lightpath routing. The GMPLS control plane performs lightpath establishment by configuring the routes by using the RSVP-TE protocol. The OpenFlow controller and the GMPLS control plane communicate through a user network interface. SDN-based control planes have shown to provide shorter lightpath set-up times as compared to the normal GMPLS/PCE control plane [56]. However, thus far, it is not clear what other benefits SDN will offer as far as GMPLS/PCE is concerned. It is important to quantify the benefits that SDN offers to GMPLS/PCE for lightpath establishment and routing.

RWA is a crucial component of lightpath establishment. Most of the studies on lightpath establishment and routing focus more on the feasibility of lightpath establishment and routing in SDN and not much on the efficiency of RWA heuristics in SDN. Lee *et al.* proposed a RWA algorithm called Hottest Request First (HTRF), which was compared to Heaviest Request First (HRF) using an SDN-based optical network [45]. The HTRF algorithm tries to solve the RWA problem while trying to reduce the cost of computational complexity and to increase network throughput. Yao *et al.* applied the ILP RWA algorithm onto the SDN-based optical network with the objective of reducing the number of shared physical links of each lightpath's multiple routes [57]. The two RWA methods performed well with HTRF gaining 15% of the total network throughput and ILP achieving the least common link usage. The two studies were limited to SLE. Studies considering different factors for RWA, for both DLE and SLE, are required to quantify the efficiency of lightpath establishment in the programmable networks. Moreover, the performance of RWA methods in distributed SDN networks need to be investigated as RWA methods in large scale networks have proved to be usually time-consuming [58]. The time-consuming factor may ultimately lead to performance limitations, limiting scalability.

With the forever evolving high-speed data transmission, the RWA in the SDN-based optical network would have to cope with emerging requirements [59]. Therefore, it would be worthwhile to consider machine-learning methods for RWA for both the SLE and DLE.

3.3.4 Survivable lightpath routing: Reliable lightpath routing is an important feature in lightpath routing as it guarantees service delivery even during network failures. This section describes survivable lightpath routing as a component of the lightpath system.

Survivable lightpath routing deals with the ability of a network to continue routing lightpaths during and after network failures. This section describes restoration and protection methods as employed in traditional optical networks and also as applied to SDN-based optical networks. WDM networks are susceptible to component failure such as a link or node failure, which can potentially lead to a severe traffic disruption. Protection and restoration mechanisms are employed to guarantee survivable networks and to ensure that service level agreements are met [60, 61]. Protection mechanisms proactively compute and reserve back-up resources prior to a network component failure [62].

Restoration mechanisms dynamically discover back-up resources upon an occurrence of network component failure [19]. As defined by the Metro Ethernet forum, protection and restoration mechanisms must recover and restore network traffic within the time of 50 ms of a failure [63].

Protection and restoration schemes differ in their assumption based on application, for example, static or dynamic traffic model, network control (centralised/distributed), or WCC [25]. As highlighted in Fig. 3, protection and restoration methods for lightpath routing can be classified into *path-based* and *link-based methods*. *Linked-based* methods reroute lightpath traffic around the failed component (e.g. a node or a link). *Path-based* protection/restoration methods determine an entirely new back-up path between source and destination nodes pairs for each disrupted lightpath connection. Thus, *path-based* methods require more time as compared to link-based methods. Protection mechanisms require additional dedicated network resources to protect and restore traffic from failure.

In lightpath routing, the primary path refers to the working path and the back-up/secondary path refers to an alternate path in which traffic is switched to after a failure. For lightpath protection methods, link- and path-based schemes are further classified into:

- *Dedicated back-up methods:* Each primary path/link should have an exclusive dedicated back-up path/link. During routing, the same copies of traffic may be transmitted on both routes/links and the receiver can choose either of the copies from the two paths/links. During failure, this method is fast and safe because the back-up route already has the transmitted data. However, the dedicated back-up method is costly as it requires redundancy in the form of additional network resources.
- *Back-up multiplexing methods:* This method allows sharing of back-up resources by allowing two or more primary lightpaths to share the same back-up path. However, this method assumes a single link failure and that the primary lightpaths are disjoint (i.e. they do not fail at the same time).
- *Primary back-up multiplexing methods:* This method is the opposite of back-up multiplexing in that it allows resources to be shared among a primary lightpath and one or more back-up paths. This method is usually applied in dynamic traffic model environments.

As compared to restoration mechanisms, protection mechanisms are expensive but are faster in restoring but do not guarantee survivability during network failures. Restoration and protection schemes for traditional WDM optical networks is a well-studied topic supported by literature, simulations and real network experiments looking at different factors such as risk-disjoint [64], disjoint path selection [65], distributed networks [66, 67], shared protection [68], restoration [69] and others [70].

With SDN being the widely adopted network architecture, it is imperative to look at options that are available for lightpath survivability in programmable networks. For lightpath provisioning, the controller maintains a lightpath database which contains a list of all active lightpaths in a network.

A typical lightpath restoration process in SDN includes: (i) compiling a list of disrupted lightpaths by using the lightpath database, (ii) releasing the resources that were occupied by the disrupted lightpaths in the traffic engineering database (TED), which contains information on traffic routing and resources in the

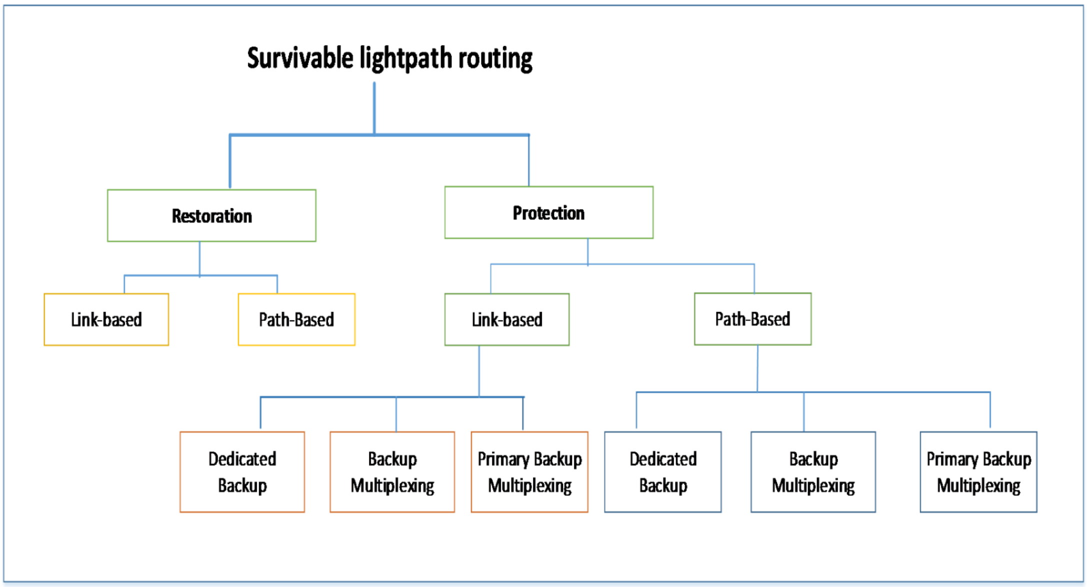

Fig. 4 *Taxonomy of protection and restoration methods*

network and (iii) calculating the back-up paths for the disrupted lightpaths and updating the TED with the associated resources for the back-up paths.

SDN by nature follows a reactive mechanism to restore network traffic during failures. The controller is responsible for computing paths and modifying flows in the network nodes. A new flow is added into a switch only when a switch sends a *Packet_in* message to the controller. Each flow is configured with two timers, the *idle timeout* and *hard timeout*. The *idle timeout* defines the time at which a flow has to be deleted after being inactive for a particular period. The *hard timeout* defines the lifespan of a flow. After the predefined time, a flow is automatically deleted from the switch. Recovery from a node/link failure depends on the time when a particular switch requests a new flow configuration from the controller. The old flows are not deleted until one of the timers has expired. The existence of old and new flows might lead to conflicts during routing because traffic might be routed using the failed route. This restoration mechanism is referred to as the *fast failover recovery* method.

As per the defined 50 ms recovery time requirement [63], the fast failover recovery method takes longer to restore traffic as it relies on a switch to request a new flow from the controller [71–73]. To alleviate the problems of the reactive nature of the OpenFlow failover recovery method, a protection method was introduced. The OpenFlow protection method installs back-up paths together with primary paths into the switch's ternary content-addressable memory before any failures [74, 75]. During failures, the switch can reroute traffic onto the backup path without troubling the controller [76]. The standard OpenFlow protection and restoration methods require modifications when applied to different network services and different network environments. For example, the fast failover method requires some modifications for dynamic multicast group session services [77].

Protection and restoration for lightpath routing was introduced by Lie *et al.* [78], who followed the reactive OpenFlow failover recovery method. However, their method included alarms, which were added by extending the OpenFlow to trigger the controller when there is a link failure. Their method considered one lightpath connection failure. Cugini *et al.* also investigated lightpath restoration in SDN optical networks by considering hardware parallel nodes configuration delay [79]. In their method, when the list of disrupted lightpaths and associated back-up paths are determined, the controller configures all the nodes that form part of a back-up route in parallel for each back-up path by using OpenFlow flow modification messages. The parallel node configuration method leads to node-configuration contention which might cause longer recovery delays. To improve this work, Cugini *et al.* further introduced bundle restoration method which uses OpenFlow BUNDLE messages. In another study, Lui *et al.* studied dynamic lightpath restoration by considering physical layer impairments [80].

In SDN environments, the communication of a controller and the data plane can be in-band or out-of-band. In an in-band environment, one communication channel is used for both control messages and data forwarding. In an out-of-band environment, a dedicated port is used to send control messages. The in-band environment poses challenges for network protection and restoration purposes when there is a network experience link failure because, the main communication with the controller would be broken. Zhang *et al.* studied the dynamic path restoration mechanism for an out-of-band environment following the SDN-centralised controller approach [81]. However, their method cannot restore the network in the case of controller failure.

Protection and restoration in SDN optical networks using back-up multiplexing was introduced by Gao *et al.* [82]. In their study, a path link disjoint method was used to improve lightpath survivability for a static traffic model.

As compared to protection and restoration methods in traditional WDM networks, depicted in Fig. 4, SDN protection and restoration methods follow the link-based and path-based methods. Moreover, few of the link-based and path-based SDN protection methods employ back-up multiplexing techniques (e.g. in [82]), and most use dedicated back-up methods. Although, dedicated back-up methods guarantee quicker network restoration, they require extra resources to be employed. Therefore, it is worthwhile investigating back-up multiplexing techniques for SDN networks.

The studies highlighted in this section have all considered restoration and protection methods assuming static traffic models in a single centralised controller networks and indicate that OpenFlow SDN optical networks for lightpath routing perform better compared to traditional GMPLS optical networks in relation to configuration and recovery times. Investigations that address lightpath restoration for dynamic traffic models and distributed controller network are required to ensure resilience of such network environments.

4 Research directions

Although SDN is an emerging candidate for faster and cheaper networks, there are still many aspects that have to be properly addressed to ensure reliable and efficient network services provisioning, control, resiliency, security and management. Even though a significant amount of research has been carried out with a focus on lightpath routing in SDN [73–82], there still remain a number of research issues that require further research. This section describes open research areas for lightpath provisioning and management in SDN environments.

4.1 Lightpath establishment

Lightpath establishment in SDN requires extensions to OpenFlow to enable efficient lightpath routing. Extensions include adding messages that will either assume a certain time delay or enable each node to send notifications to the controller after each flow addition for lightpath routing. The notification messages to the controller for each flow addition may give rise to propagation delay issues; more specifically, for lightpath establishments in large and distributed SDN networks.

GMPLS based optical networks are mostly preferred in traditional optical networks for lightpath establishment because they have the capability to optimise and share lightpath load among available routes. However, the GMPLS networks suffer from scalability and robustness issues. The emergence of SDN brought up the incorporation of GMPLS into OpenFlow networks for the realisation of faster and shorter lightpath set-up times. However, it is not apparent how SDN networks are to alleviate GMPLS scalability and robustness issues. Research focusing on the benefits of SDN over GMPLS and use GMPLS within SDN is required to clearly understand and define efficient technologies for lightpath establishment.

4.2 Lightpath admission control

Admission control is essential for efficient lightpath scheduling, provisioning and providing quality of service for different service providers. Thus far, not much research has been done on lightpath queuing and scheduling based on different quality of services in SDN. Admission control mechanisms capable of managing lightpath scheduling for different traffic models on distributed and centralised SDN networks are highly desirable. More work looking at SDN-based admission control systems that clearly manage and schedule customer requests to easily improve and drive revenues for network operators is required.

4.3 Routing and wavelength assignment

RWA is the core component of lightpath establishment which employs different heuristics for resource assignment and reservations. In traditional optical networks, RWA is a well-matured topic which addresses RWA in different scenarios such as, different traffic models, distributed networks and others. Most of the SDN based studies focus more on the feasibility of lightpath routing and establishment, and not much on the efficiency of the RWA methods. Research focusing on the performance and reliability of RWA methods could improve the overall network performance and provide useful insights. Moreover, research that quantifies the efficiency of RWA methods in SDN distributed networks is important because it was identified in traditional distributed networks that some of the RWA methods can degrade the overall network performance in large networks. Furthermore, with SDN paving the way for more advanced softwarised networks, lightpath routing would have to evolve with the emerging data transmission requirements. Thus, it would be worthwhile to consider machine learning methods for RWA for both the SLE and DLE.

4.4 Fault management

Protection and restoration methods ensure that networks can easily and efficiently handle different network failures with minimal data losses and transmission delays. For protection, SDN networks employ dedicated link based and path based mechanisms which require extra network resources. In most cases, dedicated resources are expensive. As such, it is ideal to explore alternative, cheaper methods such as, backup multiplexing for SDN-based networks.

Failure in WDM optical networks may cause, more particularly, multiple link failures and optical cross-connect failures. This is because multiple fibres are usually coupled together in a single-fibre conduit. A cut to the conduit, may affect more than one fibre, thereby causing multiple link failure. Research examining recovery methods for multiple failures in SDN-based optical networks are crucial to ensure the resiliency of SDN networks.

Existing studies on protection and restoration focus on a single centralised controller and assume static traffic environments. Thus, research into lightpath protection and restoration methods on distributed and dynamic traffic models are important topics in SDN-based optical networks.

5 Conclusion

As adoption of SDN networks continues to emerge, network services will need to be fully migrated from legacy networks to new SDN networks. Understanding the implications of the migration of different network services is vital to ease and speed up the migration process. Various research studies focusing on different SDN aspects such as traffic engineering and security were conducted. This paper, to the best of our knowledge, has provided a first review on the state-of-the-art for lightpath services on SDN-based optical networks. A classical review on lightpath establishment in traditional WDM networks is given with an overview on lightpath establishment in SDN focusing on RWA, control admission, lightpath establishment protocols, protection and restoration. Research directions for efficient lightpath establishment in SDN are also described.

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