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Survey Paper

A survey of WDM network reconfiguration: Strategies and triggering methods

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ABSTRACT

We survey the state-of-the-art technologies in Wavelength Division Multiplexing (WDM) network reconfiguration. Our focus is the strategies and triggering methods. We compare the proposed technologies in the literature from different perspectives: traffic-changes triggered vs. other events triggered, centrally-managed strategies vs. distributed strategies, new lightpath demands known vs. future user traffic unknown, adaptive/reactive approaches vs. proactive approaches, traffic prediction based vs. traffic uncertainty proof approaches. We outline the entire landscape of the strategies and triggering methods of WDM network reconfiguration from WDM network operators' point of view. There are gaps in research and in field trials, which must be addressed, so that the great potentials of WDM network reconfiguration may be realized to add significant flexibility in network operations.

1. Introduction

Network reconfiguration is an important mechanism for network operators to optimize network performance and traffic delivery. It adds great flexibility in network operations. Reconfigurations are conducted in response to changes of user traffic, network failures, or new deployment of network resources. Network reconfiguration and traffic engineering have a common purpose, i.e., to facilitate efficient and reliable network operations while simultaneously optimizing network resource utilization and traffic performance. However, these goals are achieved by different means, i.e., in network reconfiguration by changing bandwidth capacity between node pairs, vs. in traffic engineering by changing the way that traffic uses bandwidth. Essentially, network reconfiguration can be considered as a mechanism of putting the network bandwidth where the traffic requires it. Informally, network reconfiguration is also called "topology engineering" [1]. In contrast, traffic engineering is to put the traffic where the network bandwidth is available [1].

1.1. How are WDM network reconfigurations accomplished?

Wavelength Division Multiplexing (WDM) network reconfigurations are accomplished by establishing new optical connections (i.e., lightpaths), removing or changing existing lightpaths. A reconfiguration of a lightpath means changing its originating or terminating node (or both), its route over a fibre network, and its usage of optical domain resources, e.g., wavelength switching fabric, switch input and output ports, wavelength channels in fibres, and wavelength converters.

WDM technologies provide a capability of dynamic establishment, removal or alteration of lightpaths. An optical cross-connect (OXC) switches incoming lightpaths to outgoing ports, whose switching configuration may be dynamically re-arranged. In a more integrated form than an OXC, a Reconfigurable Optical Add-Drop Multiplexer (ROADM) provides lightpath-level add or drop, as well as pass-through, with remote-controlled reconfiguration. Instead of permanent adding or dropping the same lightpaths, a ROADM can be remotely configured to add or drop different lightpaths at different time. An OXC or a ROADM may be equipped with wavelength converters that

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transform the wavelengths of lightpaths, resulting in more freedom in using wavelength channels. Tunable transmitters and receivers, as well as tunable transceivers and transponders, provide flexible access to wavelength channels. Tunable regenerators provide a flexible extension of the reach of lightpaths. Electronic variable optical attenuators provide automated wavelength power balancing among the wavelength channels carried by one fibre. In the control plane, the Generalized Multi-Protocol Label Switching (GMPLS) control protocols enable dynamic lightpath setup and removal, fast shared optical-layer mesh protection, and restoration.

1.2. Goals and benefits of network reconfiguration

The goal of network reconfiguration is to accommodate more traffic demands, as well as to optimize network operations such as cost minimization or utilization maximization. The benefits of WDM network reconfiguration are illustrated by the following two examples, in which the traffic may be at the lightpath level (Fig. 1), or at a sub-lightpath level (Fig. 2).

1.3. Scope of this survey

A new comprehensive survey is warranted by tremendous progress that has been made in WDM network design, planning, operations and management. The research and development of optical networking over the past two decades showed that some technologies are more successful to be adopted by industry and have more impacts on network evolution than others [2]. We are motivated to review the existing WDM network reconfiguration technologies based on an updated vision on optical networking technologies and trends.

Our focus is the network reconfiguration that considers the penalty of reconfiguring existing lightpaths. This survey does not cover standard WDM Routing and Wavelength Assignment (RWA) schemes, although standard RWA schemes could be considered as a special case of

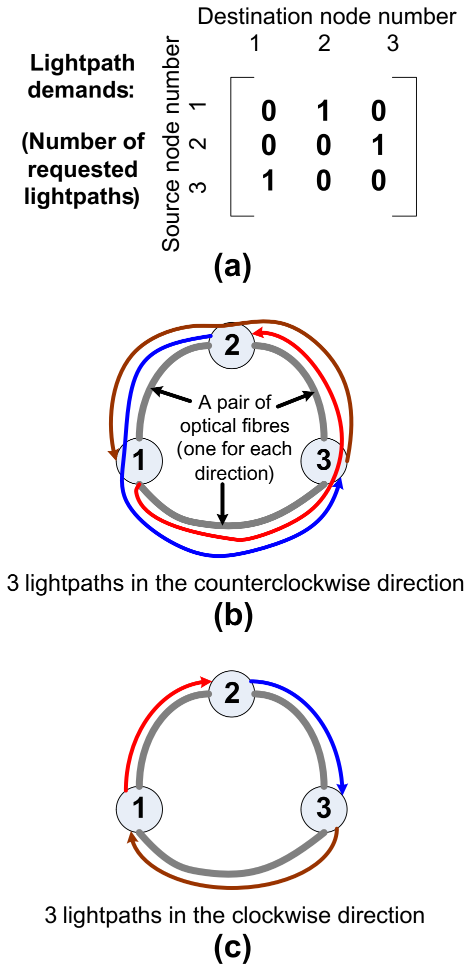


Fig. 1. WDM network reconfiguration when the traffic is at the lightpath level, (a) Lightpath demands; (b) When three lightpaths are set up in the counterclockwise direction, two wavelength channels on each link are occupied; (c) When three lightpaths are set up in the clockwise direction, only one wavelength channel on each link is occupied.

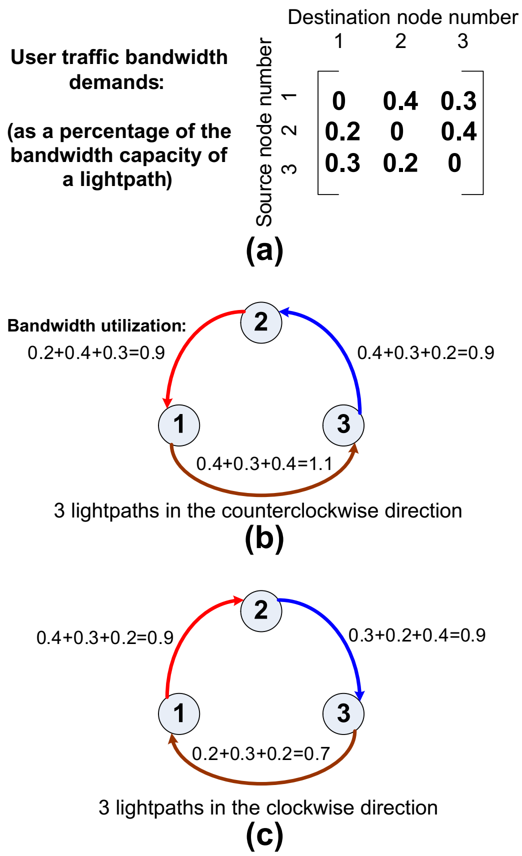


Fig. 2. WDM network reconfiguration when the traffic is at a sub-lightpath level, (a) User traffic bandwidth demands (user traffic uses least-hop-number routing over lightpaths); (b) When three lightpaths are set up in the counterclockwise direction, the maximum carried traffic of the three lightpaths is 1.1 (i.e., an over-reservation); (c) When three lightpaths are set up in the clockwise direction, the maximum carried traffic of the three lightpaths is 0.9.

WDM network reconfiguration, in which there is no existing lightpath and thus reconfigurations are freely conducted. However, our survey covers a few exceptions where RWA schemes are designed in such a way that minimal (or none) future reconfiguration is required.

A virtual topology is viewed from different angles in WDM network reconfiguration and virtual topology design/reconfiguration. In WDM network reconfiguration, a virtual topology is considered from a WDM network operator's perspective; while in virtual topology design/reconfiguration, a virtual topology is considered from the user traffic's perspective. A WDM network operator constructs a virtual topology by using optical layer resources, and then hands over the usage of the virtual topology to users (illustrated in Fig. 3). For user traffic, a lightpath is treated as a point-to-point link, i.e., a virtual link, although a lightpath may be established over a fibre network by travelling through one or more fibres. The collection of virtual links forms a virtual topology for user traffic [3] (Fig. 4). In some

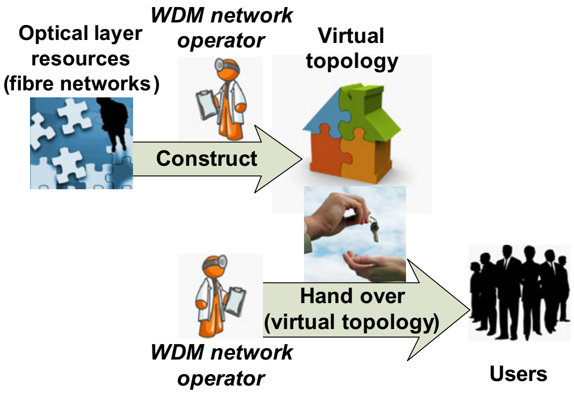


Fig. 3. A WDM network operator constructs a virtual topology by using optical layer resources, and then hands over the usage of the virtual topology to users.

literatures, the term "logical topology" was used for the same meaning of virtual topology. Our survey is from a WDM network operator's perspective as opposed to from user traffic's perspective. When a virtual topology design only considers a single given pattern of user traffic without considering the constraints of lightpath reconfigurations (e.g., [4,5]), it is out of the scope of our survey.

Primarily, we focus on reconfigurations of working lightpaths that carry user traffic. The working lightpaths may or may not be protected by backup lightpaths. If reconfigurations are conducted solely on the backup lightpaths that do not carry user traffic at the time of reconfigurations, such reconfigurations are not considered in our survey. Reconfigurations only on backup lightpaths may be conducted without disruptions to working lightpaths, e.g., [6–10]. However, our survey covers over-provisioning of working lightpaths using spare capacity for the purpose of reducing future reconfigurations [11], although the over-provisioned capacity may not be used to carry user traffic immediately and all the time.

WDM network reconfiguration resembles the reconfiguration of Virtual Paths (VPs) in Asynchronous Transfer Mode (ATM) networks [12–17]. However, WDM network reconfiguration is more influential due to wide-deployment of WDM networks, in-depth research and advanced development of WDM reconfiguration technologies. WDM network reconfiguration has a special difficulty compared with VP reconfiguration in ATM networks, due to the large and fixed bandwidth granularity of lightpaths [18]. Lightpath reconfigurations take longer time than VP reconfigurations.

A few survey papers discussed WDM network reconfiguration in a broad context. In survey paper [1], reconfiguration was discussed as part of network traffic engineering including network survivability, traffic grooming, impairment-aware routing, virtual-topology engineering, and coordination among multiple layers of network architecture. In survey paper [18], the management and control issues and corresponding approaches were discussed for the

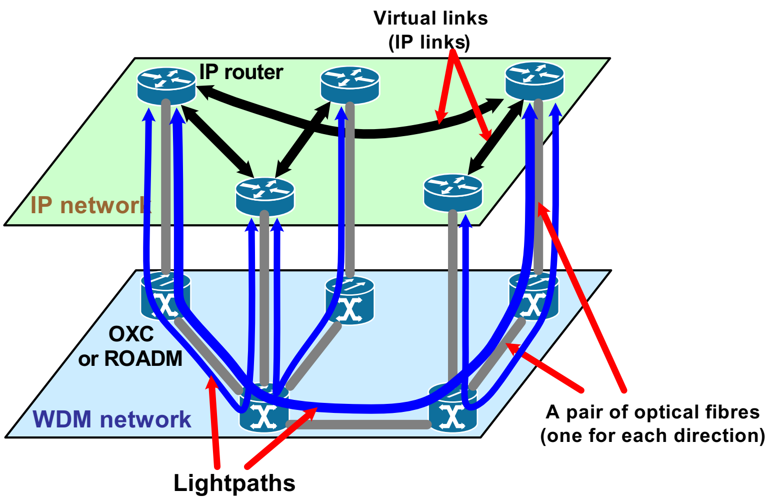


Fig. 4. The collection of virtual links forms a virtual topology for user traffic.

configuration, fault, and performance management of IP over dynamic WDM networks.

1.4. Three phases of WDM network reconfiguration

Given a network operating in topology T_1 which is optimized for network state S_1 (defined by network resource availability and input traffic pattern) and a changed network state S_2 for which topology T_2 is optimal, the reconfiguration problem is to find out when and how to change the network topology with minimal disruptions and efforts. The knowledge about network state S_2 may be limited or unavailable, at the time of designing topology T_2.

WDM network reconfiguration consists of three phases [19]: (1) making a reconfiguration policy decision whether a reconfiguration should be conducted; (2) selecting a new virtual topology based on a certain optimization objective; and (3) migrating from the current topology to the new topology. In Table 1, we list the problems that need to be solved during the three phases of WDM network reconfiguration.

In a simple manner, the three phases are conducted sequentially and iteratively. The outcome of one phase is to be used as an input to the next phase. If the decision in the first phase is to reconfigure the topology, then the second phase is conducted. After a new topology is designed in the second phase, a topology migration is conducted in the third phase.

In some variations, more complicated relations among the three phases exist. For example, in the first phase, the decision on reconfiguring a topology or not may depend on whether a migration that satisfies certain criteria exists. Another example is the design of a new topology in the second phase that considers migration constraints.

1.5. Organization of this survey

The rest of this paper is organized as the following: in Section 2, we will provide an overview the reconfiguration strategies and triggering methods. In Sections 3–7, we survey different reconfiguration strategies and triggering methods based on a roadmap shown in Fig. 5. Specifically, in Section 3, we will review one of traffic-change triggered and centrally managed strategies, assuming that new lightpath demands are known. The other branch of traffic-change triggered and centrally managed strategies will be reviewed in Sections 4 and 5, where future user traffic is unknown. We discuss adaptive approaches (in Section 4), and proactive approaches (in Section 5). In Section 6, we survey the traffic-change triggered, distributed managed strategies. In Section 7, we review other events triggered reconfigurations. In Section 8, we provide our opinions on the open issues for future research. Finally, in Section 9, we will summarize the WDM network reconfiguration strategies and triggering methods.

2. Triggering methods and strategies of reconfiguration

From a WDM network operator's point of view, a reconfiguration can be triggered by any of the following events [20,21]:

1. Traffic pattern change;
2. Addition of network resources;
3. Deletion of network resources due to a network failure;
4. Deletion of network resources due to a planned network maintenance.

The four types of triggering events have different characteristics and therefore different impacts on reconfiguration. First, traffic pattern change is a continuous process. Most WDM network reconfiguration methods assume such change is monitored at fixed time intervals, which is easy to implement in practice. Current centralized management systems typically allow the traffic statistics to be collected at fixed time intervals. For example, in the Simple Network Management Protocol (SNMP), the typical monitoring time interval is every 5 min. Second, the occurrence time of addition or deletion of network resources due to a planned network maintenance is known to the network operator.

Table 1
Example problems that need to be solved during the three phases of WDM network reconfiguration.

Should the current topology be reconfigured?
• Should it be reconfigured when the traffic changes?
• How is a traffic change monitored and detected?
• Should it be reconfigured when there is a failure in the network?
• Should it be reconfigured when new network elements and capacity are added?
When should the topology be reconfigured?
• How much traffic change will trigger a topology reconfiguration?
• How much degradation of which network performance will trigger a topology reconfiguration?
What is the new topology?
• What is the design objective of the new topology?
• How many lightpaths are allowed to be reconfigured?
• What are the tradeoffs between increasing throughput and reducing disruptions?
• Does the new topology consider the optical layer constraints in setting up lightpaths?
How does the current topology be reconfigured to the new topology?
• Is the reconfiguration accomplished in a centralized or distributed manner?
• What is the sequence of lightpath establishments and removals?
How should the user traffic adapt to the new topology?
• What is the sequence of user traffic flow rerouting?
• How is the user traffic handled during the virtual topology transition?
• How is the lost user traffic recovered?
• How is a routing loop possibly formed during virtual topology transition removed?

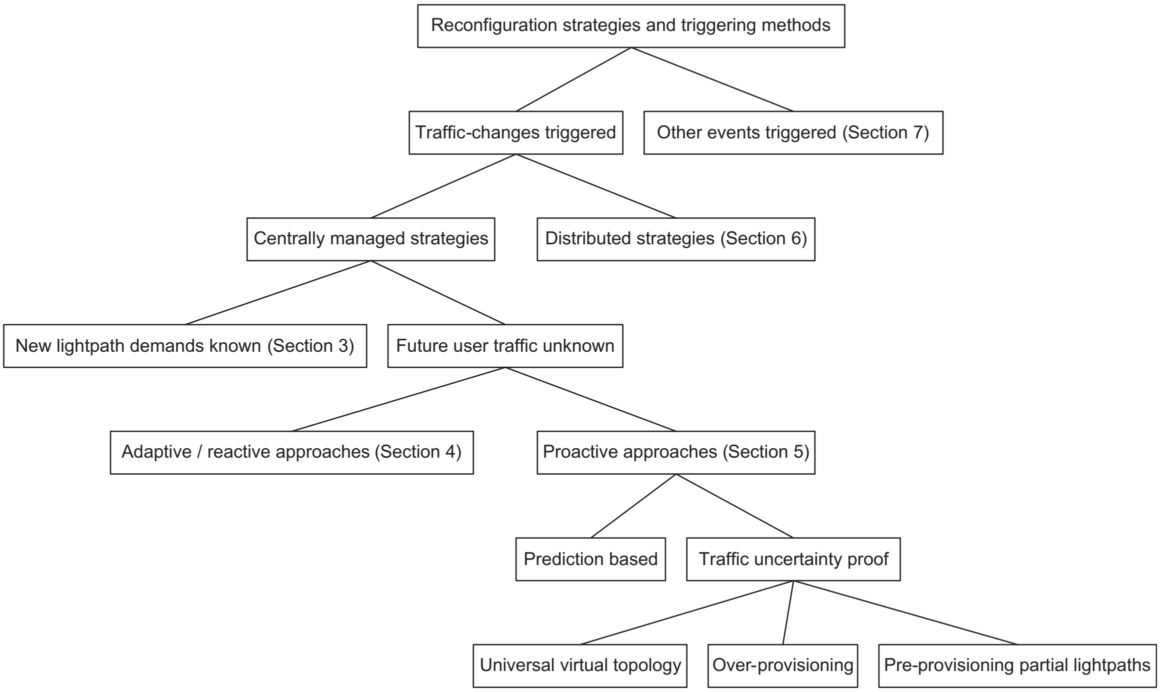


Fig. 5. A roadmap of reconfiguration strategies and triggering methods.

The corresponding reconfiguration may be scheduled in advance. Third, in theory, a network failure could trigger a reconfiguration immediately, i.e., failure restoration could be integrated into a reconfiguration, which is used in a few reconfiguration methods [22–27]. Most reconfiguration methods are triggered after the completion of protection and restoration due to protection's strict time requirement, which can hardly be met by reconfigurations. Reconfigurations are more valuable in providing protection against subsequent failures [9,28], and in bringing the network operation back to a more optimized topology.

Note that in this paper, when a reconfiguration is triggered, we mean a decision making process is triggered. The results of the decision could be keeping the current topology unchanged. In some literatures, when a reconfiguration is triggered, they mean a topology that is different from the current one has been chosen.

Although fundamentally all the reconfiguration triggering events cause a mismatch of the optimal resource allocation and a traffic pattern, the extent of such a mismatch is very much different. Addition or deletion of network resources causes a greater mismatch than traffic changes. Thus, reconfigurations use different strategies when it is triggered by different types of events.

In [29], simulation results showed that reconfiguration triggering methods were highly important, and even the best reconfiguration algorithm did not perform well if it is not triggered properly.

For traffic pattern changes, in [29], three triggering methods were compared: periodic time-triggered, and event-triggered either by a blocking of a new user traffic request or a departure of existing user traffic. It concluded that periodic triggering is more effective among the three methods. A detailed comparison between the three methods provided more insights. The departure events triggered reconfigurations too frequently that most of the time reconfigurations were not feasible. The blocking events triggered reconfigurations too seldom that reconfigurations were always feasible. Time-triggered reconfigurations had a moderate success ratio. Deferring reconfigurations until a user traffic is blocked increased blocking and decreased lightpath capacity utilization. Departure event-triggered method achieved good lightpath capacity utilization at a cost of a lower average optimal routing ratio, higher disruption (measured by the number and total volume of rerouted user traffic) per reconfiguration action.

Vast majority of existing reconfiguration methods use centrally managed triggering methods, in which reconfiguration decisions and optimization are made by a central entity (such as a network operator) based on the state of the entire network. This implies a centralized management system is used to collect such information in a realtime manner, i.e., the current traffic statistics and resource status of the entire network are known to the centralized management system with a negligible time delay. The reconfiguration function may be implemented in a Path Computation Element (PCE) as part of the centralized management system (e.g., proposed in [30]).

The traffic pattern of the entire network is usually given in the form of traffic volume between each node pair, which could be represented by a traffic matrix. For any given node pair, if its traffic volumes for both directions are identical, the traffic matrix is symmetric. Reconfiguration generally handles asymmetric traffic.

3. First strategy: new traffic is assumed known

In the first strategy, new lightpath demands are presumably known. For short, we call it the ‘‘known-demand strategy’’. This strategy is used in two scenarios. In the first scenario, a WDM network operator receives lightpath demands from service providers that carry user traffic such as IP traffic. The service providers perform IP-layer routing of user traffic over the virtual topology. The service providers and the WDM network operator may belong to different business units of the same multi-service provider. Alternatively, the service providers may be customers of the WDM network; while the WDM network offers an optical virtual private network service or a leased lightpath service. The WDM network operator collects lightpath demands and performs reconfigurations at regular time intervals [31–40], or when a certain number of new lightpath demands are accumulated. Lightpath demands may be allowed to slide within their time windows, but reconfiguration for scheduled lightpaths is not studied so far in the literature. In [41], it argued that changing the starting time of lightpaths during the reconfiguration is not desirable, as it may need re-negotiating with lightpath users. However, with no or little re-negotiation (i.e., a simple notification) with lightpath users, performance may be improved by taking advantage of starting time flexibility of forthcoming lightpaths. In [21], traffic models for reconfiguration were classified into three categories: spatial, temporal, and spatial–temporal distributions.

In the second scenario of the known-demand strategy, a WDM network operator provides on-demand lightpath service in realtime, and occasionally reconfigures the WDM network. Lightpaths are dynamically provisioned. The provisioning must be completed within a short time. It is conducted only based on the network status at the time of arrival of individual lightpath demands. No reconfiguration of existing lightpaths is allowed. So after a certain number of such dynamic provisioning, the usage of network resources deviates from the optimal. As a result, the performance of dynamic provisioning degrades, i.e., new lightpath demands are blocked due to a poor usage of network resources by existing lightpaths. Then reconfiguration is conducted to bring the network status close to the optimal. In [42,43], reconfiguration was conducted periodically for only backup lightpaths or both working and backup lightpaths. In [44], reconfiguration was performed based on projected future lightpath demands. Although it did not assume future lightpath demands are exactly known, it provided a better prepared network resource availability if future lightpath demands follow a similar pattern, so that average blocking was reduced. In [45], reconfiguration was conducted after a certain number of users joining or leaving a multicast session.

It is impractical to know the exact volumes of individual user traffic flows in advance, due to the potential huge number of user traffic flows, their individual dynamics, interactions and aggregated behaviours. So in the known-demand strategy, only aggregated user traffic is assumed known, in the form of either new lightpath demands or average bandwidth demands. The aggregated traffic is significantly impacted by the user traffic routing over virtual topology, which is simplified or neglected by the known-demand strategy. In [46,31,32], average bandwidth requirements of user traffic were given for each node pair. In the IP-layer, shortest path routing was used and there was no load balancing. In [47], user traffic (i.e., ATM flows) was known in advance. In [48], user IP traffic between all node pairs was known in advance. In [33,34], lightpath demands were given between each node pair. In [49], user traffic between all node pairs was known, and a limited number of candidate shortest paths between each node pair were used to route traffic over a virtual topology. It pointed out that such simplified traffic routing tended not to significantly reduce throughput. In single-hop WDM networks, the user traffic between a node pair may be directly mapped to the lightpath demands between the same node pair, e.g., in [50].

It is natural to separate the operations of the optical layer and the user traffic layer (predominantly the IP-layer) and at the same time to allow their interactions. Service providers that carry user traffic conduct frequent user traffic balancing, and occasionally request new lightpaths or change existing lightpaths for long-term optimization. In [51], simulation results showed that WDM network reconfigurations improved network resource utilization only when traffic fluctuations exceeded a certain threshold. Below such a threshold, it was efficient to deal with traffic changes only using traffic balancing at the IP/MPLS layer without WDM network reconfiguration. However, such a threshold value was obtained by simulations for a small 10-node network. Unfortunately, the thresholds for other practical networks are unknown. No guideline was provided.

Essentially, a service provider proposes a virtual topology to a WDM network operator, when it requests lightpaths. The WDM network operator uses the lightpath demands as an input, and decides which lightpaths should be accepted based on its objective and resources. Then, a virtual topology will be implemented for the service provider, which generally is a subset of the originally proposed virtual topology. Since the WDM network operator normally keeps the lightpath rejection rate relatively low (e.g., below 10%), the implemented virtual topology matches the proposed one very well, although not perfectly. The service provider may propose a modified virtual topology in the next round. This process iterates to meet the service provider’s changing requirements. The interactions between service providers and WDM network reconfiguration are shown in Fig. 6.

The known-demand strategy fits the operation of a WDM network for multiple service providers and different services. A WDM network may (and preferably) be operated independently of the data format and protocols of user traffic. With the known-demand strategy, some lightpaths may be used for IP-based user traffic, some for non-IP based user traffic (i.e., cable TV signals, connections of time division multiplexing, certain non-IP based storage area networks, and leased lightpaths). The service providers could be competitors. Reconfiguration may consider

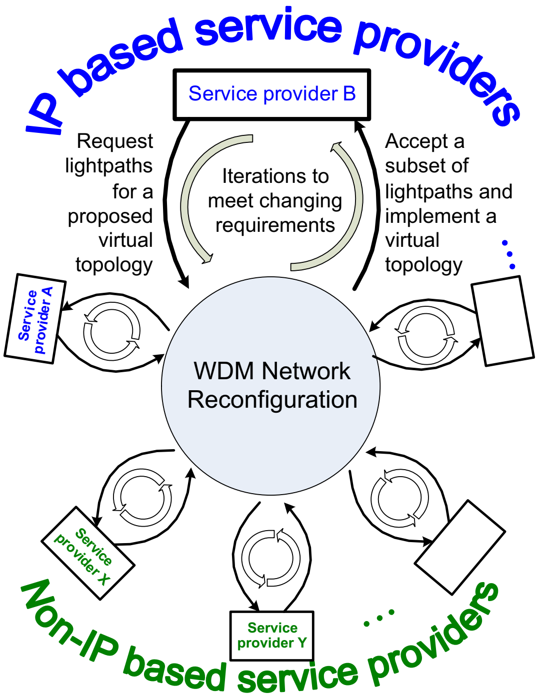


Fig. 6. Interactions between service providers and WDM network reconfiguration.

the lightpath demands from different providers together to achieve better usage of overall resources.

In the known-demand strategy, the reconfiguration time interval is in the order of at least hours, and in most cases days or weeks. The rationale is that in dynamic WDM network operation, although some lightpaths are not provisioned optimally, no performance degradation is observed, because the poorly provisioned lightpaths may depart before the resources that they used are absolutely required for new lightpath demands.

4. Second strategy: an adaptive strategy for unknown new traffic

In the second strategy, adaptive approaches are used to react to traffic changes. For short, we call it the "adaptive strategy". Network operator measures certain performance metrics of network operation, e.g., a lightpath's average bandwidth usage. The adaptive strategy primarily aims at optimizing the operation of IP-over-WDM networks. The adaptive strategy can be modeled by a feedback control loop, shown in Fig. 7. WDM network reconfiguration works as a controller unit in a feedback control. Reconfiguration adjusts a virtual topology based on performance degradations, assuming no a priori knowledge about traffic changes.

4.1. Performance metrics, triggering mechanism, reconfiguration actions, and frequency of performance comparison

Different performance metrics, triggering mechanism, reconfiguration actions, and frequency of performance comparison were proposed for the adaptive strategy. We summarize the applications of the adaptive strategy in reconfigurations of WDM wide area networks in Table 2. Most of the proposed performance metrics are from the user traffic perspective, e.g., carried user traffic on each lightpath in [52], average lightpath hop number of user traffic in [53], success or failure of accommodating an arrival user traffic flow in [54]. An exception is using a lightpath blocking to trigger a reconfiguration proposed in [55]. Performance comparisons were proposed to be conducted at regular time intervals, or at the occurrence of certain events such as blocking.

In [76–78], adaptive reconfiguration methods were compared for two types of triggering mechanisms: a potential blocking of a new lightpath request if no reconfiguration is conducted, or a fixed time interval for preventive reconfiguration. With full wavelength conversion, the first mechanism greatly outperformed the second one. Without wavelength conversion, the first mechanism was still efficient. Path adjusting only improved the performance of wavelength retuning slightly. The second mechanism improved the blocking performance, but was not as notable as wavelength retuning. A combined use of both mechanisms was very promising in the case of no wavelength conversion, but did not improve performance in the case of full wavelength conversion.

Reconfigurations in WDM local area or access networks are triggered at a time scale comparable to the queuing time of IP packets in a router (e.g. in a time scale of milliseconds), several orders of magnitude more frequently than in WDM wide area networks. Applications of the adaptive strategy in reconfigurations of WDM local area and access networks are summarized in Table 3.

4.2. Scalability, stability, and interactions with upper layers

4.2.1. Scalability

The adaptive strategy is generally scalable to the size of network and the number of traffic demands. Although the adaptive strategy that is discussed in this section still uses

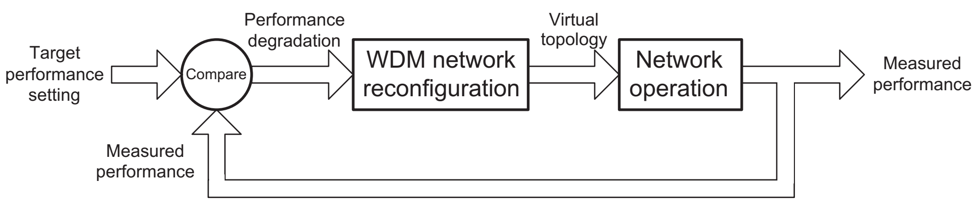


Fig. 7. A feedback control loop model for the adaptive strategy.

Table 2
Applications of the adaptive strategy in reconfigurations of WDM wide area networks.

Performance metrics	Triggering mechanism	Reconfiguration actions	Frequency of performance comparison	References
Carried user traffic on each lightpath, either averaged over an observation period, or sampled at the end of an observation period. Moving windows were used to smooth measured traffic in [52]. Moving average was applied to the measured traffic value in [56]	Low and high thresholds on the carried user traffic are set for each lightpath. A reconfiguration is triggered when measured user traffic load is above the high threshold, or is below the low threshold. In [57], the normal bandwidth level of a given lightpath was defined as its daily maximum measured traffic load averaged over one week period. If the lightpath bandwidth utilization exceeds 140% of its normal bandwidth level for three consecutive measurements, it was assumed an IP-layer traffic surge occurred. If the lightpath bandwidth utilization falls below its normal bandwidth level, or if it stays between its normal bandwidth level and the 40% threshold level for six consecutive measurements, it was assumed an IP-layer traffic surge finishes	Add one lightpath if measured user traffic is above the high threshold; delete one lightpath if measured user traffic is below the low threshold, unless the deletion may result in a disconnected network. In [57], to handle the extra traffic during an IP-layer traffic surge, an additional lightpath between the router pair is dynamically established, which is removed after the IP-layer traffic surge finishes	Periodically, an observation period is set to hundreds of seconds	[52]
			Periodically, every 5 min	[57]
			Periodically, every 2 s, traffic loads are measured at the ingress nodes of packets and lightpaths, and the utilized bandwidth information is advertised by OSPF	[56]
		Lightpaths to be added or deleted are the output of an optimization algorithm. Existing lightpaths are allowed to be rerouted	Periodically, an observation period is set to 15 min	[58]
		Lightpaths are assigned priorities based on the IP flows that are carried over them. Then, the priorities are compared for the lightpaths to be deleted and to be set up. Deletion of a lightpath is carried out only if the lightpath has a low priority	Unspecified	[59,60]
		Four types of actions are used to react to traffic changes: lightpath addition, lightpath deletion, splitting a lightpath into multiple segments, and swapping of wavelengths of existing lightpaths		[61]
	Unconditional	Iteratively remove the least utilized lightpath to preserve resources for future lightpaths, while lightpaths are dynamically established	Unspecified	[62,63]
	A regression-based technique is used to select appropriate values for the reconfiguration triggering parameters, e.g., the low and high thresholds used in [52]	Unspecified	Unspecified	[64]

(*continued on next page*)

Table 2 (*continued*)

Performance metrics	Triggering mechanism	Reconfiguration actions	Frequency of performance comparison	References
Average lightpath hop number of user traffic	When the average weighted lightpath hop count is deviated from the near optimal point by a specified margin (e.g., 10%)	The proposed heuristic algorithms generate action plans	When a new user traffic flow arrives, or an existing user traffic flow departs	[53]
	When the average lightpath hop number of user traffic exceeds 1.5, which indicates that most user traffic does not use direct lightpaths			[65]
Capacity on any alternative route between a given pair of routers	Only when there is no capacity on any alternative route between a given pair of routers. In a graph representing spare network capacity, this is formulated as a disconnection of source and destination nodes		Unspecified	[18]
The gain of "network efficiency" (measured by the additional fraction or multiple of the traffic demand matrix that can be accommodated by the network, assuming the user traffic scales up proportionally to the current load)	Network efficiency exceeds a threshold	Four-phase re-routing scheme	Unspecified	[66]
Success or failure of accommodating an arrival user traffic flow	When the normal routing fails to accommodate the user traffic flow over existing lightpaths	Reroute one existing lightpath	Each time a user traffic flow arrives	[54]
		Reroute one existing lightpath based on a local search from a given topology		[41]
Success or failure of accommodating an arrival lightpath	When the normal routing of the arrival lightpath fails	Only change wavelength but keep the same route. Edge disjoint lightpaths are reconfigured in parallel	Each time a lightpath request arrives	[55,67,68]
		Change the route and wavelength of existing lightpaths		[69]
Maximum carried user traffic on each lightpath	The target performance setting is dynamic, and is set to the best achievable one by applying the specific actions to the current topology, i.e., the triggering condition is whether a 2 or 3-branch exchange reduces the maximum carried user traffic on each lightpath	Only one small local change (i.e., 2 or 3-branch exchange) is allowed in each action. The destination nodes of the selected 2 or 3 links are exchanged	Regular intervals. Simulation results were obtained where traffic matrix evolved from one independent traffic matrix to another in 10 or 20 s, and reconfigurations were conducted every 1–10 s	[70–72]
The gain of the reduction in a lightpath load due to the establishment of a direct lightpath between a node pair compared to the increase in the load on lightpaths as a result of traffic rerouting	Only when a reconfiguration improves the result of cost-benefit analysis	New lightpaths in ring networks are established by using two operations: splitting and merging of existing lightpaths	Periodically	[73,74]
Average IP packet loss rate at each link	The average packet loss rate of the entire network exceeds a threshold	A lightpath is added	Unspecified. The computation time for a 40-node network is 95 s. Thus, reconfigurations should be less frequent than one in a few minutes	[75]

centralized management system, the information that the centralized management system handles is linear to the size of a network and the number of traffic demands. For example, when the carried user traffic on each lightpath is used as a performance metrics in [52], the control information grows linearly with the number of lightpaths. The reason of requiring the centralized management system is that the decision of adding or removing which lightpath

Table 3
Applications of the adaptive strategy in reconfigurations of WDM local area or access networks.

Performance metrics	Triggering mechanism	Reconfiguration actions	Frequency of performance comparison	References
Average expected aggregate queue length of IP packets	The triggering condition is whether there exists a better topology that reduces average expected aggregate queue length of IP packets in the whole network	Reconfiguration plans are the output of the proposed algorithms	Periodically at the end of each transmission frame	[79,80]
Queue length in access routers in an IP-over-WDM access network	A lightpath connects the gateway router to an access router, until the queue in the access router is empty	Reconfigure the lightpath to connect the gateway router to another access router	Reconfiguration on short time scales that are comparable to the queuing time of IP packets in a router	[81]
A derived performance metrics for quantifying resource usage for QoS constraint applications	The expected reward-cost function for a reconfiguration is maximized, and the QoS requirements are guaranteed	Reconfiguration plans are the output of the proposed algorithms	Every 1 ms	[82]

needs global information and the actions need global coordination. The distributed strategy will be discussed shortly in Section 6 of this survey. The centralized management system is stressed by taking performance measurements and receiving this information in every a few seconds as proposed in [56] or tens of seconds as used in [70]. Considering individual IP flows carried over a lightpath (e.g., proposed in [59,60]) does not scale due to the large number of potential IP flows. Compared to reconfigurations of label switched paths of MPLS [83], reconfigurations of lightpaths have advantage of scalability, thank to the reduced number of connections that need to be coordinated, however at a cost of bigger disruptions.

4.2.2. Stability

When reconfigurations are triggered by a certain performance metrics, it is important to avoid unnecessary reconfigurations caused by temporary network state fluctuations. A common method is taking the performance metrics as an average during a period of time, so that temporary fluctuations within the measuring period do not easily trigger reconfigurations. Other techniques to smooth the performance metrics include using moving windows as in [52], or moving average as in [56]. In [84], a technique was used over a time window long enough to estimate steady state traffic conditions. An exponentially weighted mean was used to alleviate transient effects of the measured performance metrics. A trade-off exists between avoiding unnecessary reconfigurations and being sensitive to network state changes. Note that WDM network reconfigurations interact with other network adjustment mechanisms such as TCP congestion and flow control. If the adaptive strategy does not react to network state changes with a reasonable sensitivity, other network adjustment mechanisms may dominate the overall network reactions, or user behaviours may be tuned to a different usage pattern.

In the adaptive strategy, reconfigurations are performed at regular time intervals in the order of minutes. The rationale is that frequent but smooth small reconfigurations may react quickly to traffic fluctuations and release congestions faster than major reconfigurations in every several hours. In [85], an evaluation was conducted in every 5 min to determine a single lightpath that needs to be added or deleted. In [43], frequent and infrequent reconfigurations were compared. Shared path protection was used in its online lightpath provisioning. Optimal resource usage was obtained by an offline optimization. As expected, frequent reconfigurations brought the network operation state close to optimal, which resulted in less blocking. However, this benefit was achieved at the cost of more number of reconfigurations in total than using infrequent reconfigurations, because a lightpath that used its resources in a sub-optimal way may finish before its occupied resources were needed for other lightpaths.

An implicit assumption in the adaptive strategy is that the time for reconfiguration is much shorter than the observation period. In [52], the length of observation period was about 100–800 s. In [58], the time interval to monitor user traffic load on lightpaths was suggested to be 15 min. Therefore, the total time for computing a new virtual topology and migrating to a new virtual topology should be within no more than a fraction of the observation period (e.g., 20%). This explains the reason that most adaptive reconfiguration methods (e.g., [52,58,56]) only take simple actions such as adding or deleting one lightpath at a time.

Adaptive reconfiguration methods face a challenge of promptly reacting to user traffic fluctuations. In addition to the time of computing a new virtual topology, reconfiguration actions need time to complete, which normally need coordination by signalling mechanisms or a centralized management system. The reconfiguration time becomes a major barrier when slow tuning photonic devices are involved. Even if the computation and reconfiguration action time in the optical domain is negligible, the IP layer routing convergence and/or MPLS tunnel setup may take a relative long time compared to user traffic dynamics. Therefore, user traffic may not be shifted as quickly as desired.

4.2.3. Interactions with upper layers

In [86], TCP transmission experiments were performed over a reconfigurable optical access network. The results showed that without proper modifications to TCP, network reconfiguration degraded the TCP throughput due to false detection of congestion by TCP congestion control and avoidance mechanisms. However, reconfigurations at WDM core networks impact on large number of TCP flows that involve different end systems. Modifications to various TCP implementations are impractical.

In [87], interactions of overlay routing (i.e., the application-layer routing on top of the IP layer shown in Fig. 8) and reconfiguration were studied. The simulation results showed that such interactions led to a high variance in the traffic demand. Selfish behaviours are generally observed in the overlay routing. Overlay routing highly degraded the performance of reconfiguration, and led to instability of reconfiguration. However, the study used the minimum delay logical topology design algorithm [5] and its extension [88] for reconfigurations, which did not consider reconfiguration constraints. Simply designing a virtual topology for each traffic matrix leads to a poor performance, which deteriorates even worse in the interaction with overlaying routing. By the time that the reconfigurations add bandwidth in congested links, the overlay routing may already move away from the congested links and possibly move to the supposedly less congested links, where the bandwidth could have just been reduced. In [87], using the hysteresis concept, several reconfiguration algorithms were proposed. It showed that a combination of hysteresis and filtering with fine-tuned parameters stabilized the reconfigurations, even when reconfiguration constraints were ignored in the topology design algorithms.

For the methods that react to individual lightpath load changes, the correlation of lightpath load is an issue. In grooming networks, traffic demands usually traverse multiple lightpaths. In [89], the effectiveness of multi-layer traffic engineering was examined for correlated traffic.

4.3. Performance evaluations

Performance evaluations of the adaptive strategy are very difficult, due to its complicated interactions with upper layers and signalling mechanisms for lightpath setup. The properties of different topologies and traffic models also contribute to the difficulty. To obtain realistic results, studies need to be conducted on practical scale networks, making simulation the commonly used method. Various assumptions were made in the simulations, mainly related to input traffic model, traffic shaping in response to reconfigurations, and lightpath setup time (summarized in Table 4).

Only a few literatures reported very limited results on the IP traffic dynamics during reconfiguration. In [90], an experiment was conducted on a simple 4-node network,

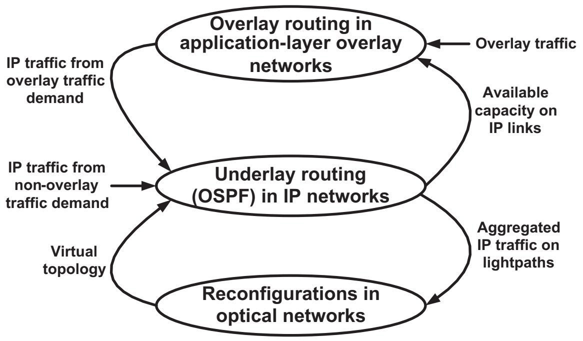


Fig. 8. Interaction of application-layer overlay routing and reconfiguration.

Table 4
Major assumptions used in the performance evaluations of the adaptive strategy.

Input traffic model	Traffic shaping in response to reconfigurations	Lightpath setup time	References
Sampled from real networks over 24-h period. In [52], traffic between two sampling points is created using a linear interpolation	Not considered	Not considered	[52,65]
Measured traffic	Not considered	Not considered	[57]
Scale up measured traffic by 10 times	Not considered	Not considered	[58]
Randomly generated or hypothetical traffic changes	Not considered	Not considered	[41,53–55,59–64,67–74,93]
Randomly generated or hypothetical traffic changes	Not considered	Fixed lightpath setup time of 100 ms	[75]

where nodes are 5–10 km apart to each other. Experimental results showed that the overall time for a routing protocol (OSPF) to converge was 19.37 s, where the major time was used to establish the adjacent relations. In [91], experiments on a network with regular topology showed that as nodes increase from 8 to 16, OSPF convergence time linearly grew from approximately 4 to 8 s, while reconfiguration action time linearly grew from approximately 20 to 125 s. In [18], experiments on a testbed network with 4 nodes connected by fibres in a ring topology showed that the convergence time of reconfiguration (including the new topology setup and IP routing OSPF convergence) was between 10–20 s.

In [92], experimental results showed the traffic dynamics and the benefits of lightpath-on-demand and reconfiguration for three data-intensive distributed applications. In a distributed computing application, computing facilities were located in three clusters, while the data center was located in one cluster. Experiment results showed the traffic over the links between clusters varies during the lifecycle of the application. The traffic peaks occurred during the start and end phase, when many computing facilities fetched data simultaneously. There was very little traffic at other time. Such a traffic pattern poses a big challenge for the adaptive reconfiguration strategy. In an ultra-high resolution distributed video processing application, an adaptive reconfiguration strategy was feasible due to the constant traffic load. Another application had a property of irregular all-to-all traffic pattern, being a mix of constant and burst traffic.

5. Third strategy: proactively a topology

The third strategy is to proactively design a virtual topology for future changes of traffic. For short, we call it the "proactive strategy". In the first branch of the proactive strategy, future traffic is predicted based on the trend of traffic changes and the statistics of past traffic dynamics. The second branch of the proactive strategy aims at designing virtual topologies insensitive to traffic changes, i.e., traffic uncertainty proof.

5.1. Traffic prediction-based proactive reconfiguration

5.1.1. Feed-forward control model

With prediction-based proactive reconfiguration, virtual topologies are designed and deployed, in hope of the new virtual topologies taking effect just in time for the occurrence of the predicted traffic patterns. The reconfiguration strategy based on traffic prediction may be modeled as a feed-forward control, where traffic changes are treated as disturbance, shown in Fig. 9. In [94,95], an online multi-stage reconfiguration method incorporated a user traffic prediction function. Based on the predicated future traffic for a fixed time period known as the prediction horizon, the reconfiguration rewards and costs were evaluated for all possible combinations of decisions.

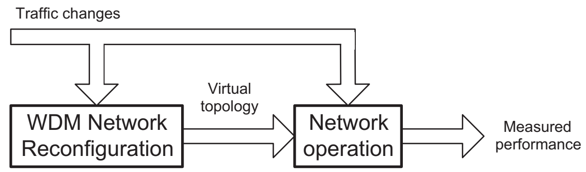


Fig. 9. A feed-forward control model for the reconfiguration strategy based on traffic prediction.

In [30], predicted traffic was used to trigger gradual reconfigurations, which consisted of small reconfiguration steps by limiting the number of lightpaths that could be reconfigured in each step. Its reconfiguration heuristic algorithm is shown in Fig. 10. It pointed out that sudden traffic changes were unpredictable and could greatly increase prediction errors if they are not identified. Sudden traffic changes may be caused by many reasons, i.e., route changes in the IP layer. Then, it used a method to identify sudden traffic changes, and applied the traffic prediction only when there was no sudden traffic change. In a simulation environment, its reconfiguration performed well with the traffic prediction calibrated for steady traffic. Its performance did not deteriorate when traffic suddenly changes.

The robustness of prediction-based reconfiguration highly depends on the accuracy of the predicated traffic. As the prediction horizon increases, the accuracy tends to decrease. The prediction horizon is defined as the time from the moment that a prediction is made to the moment that the predicted traffic is expected to appear.

5.1.2. An extended state observer based control model

In [105,106], an extended state observer was used to increase the robustness of reconfigurations. The extended state observer provided an enhanced prediction-based control. A feedback loop control was added a special controller based on attractor selection, shown in Fig. 11. Its

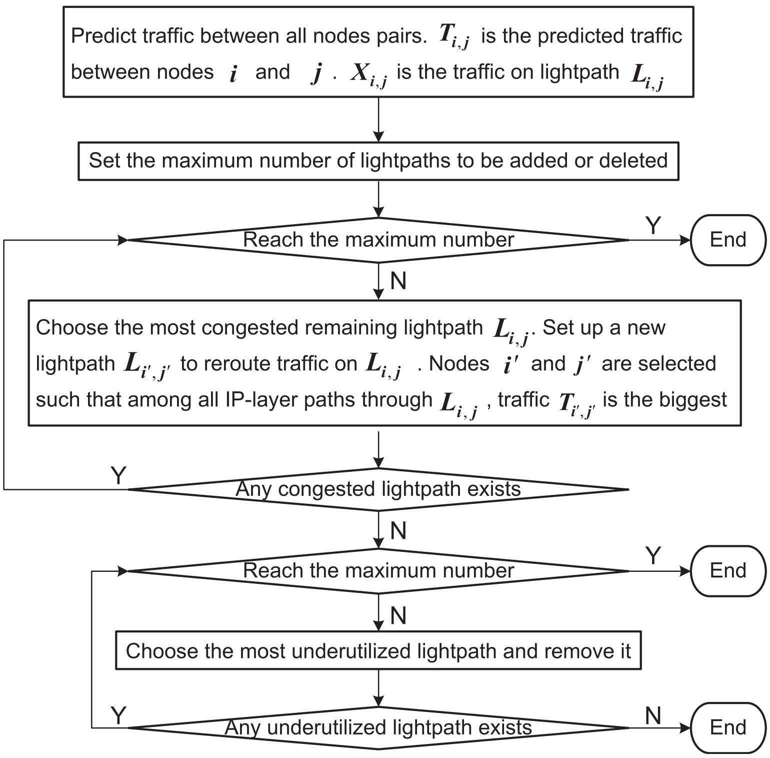


Fig. 10. The reconfiguration heuristic algorithm used in [30].

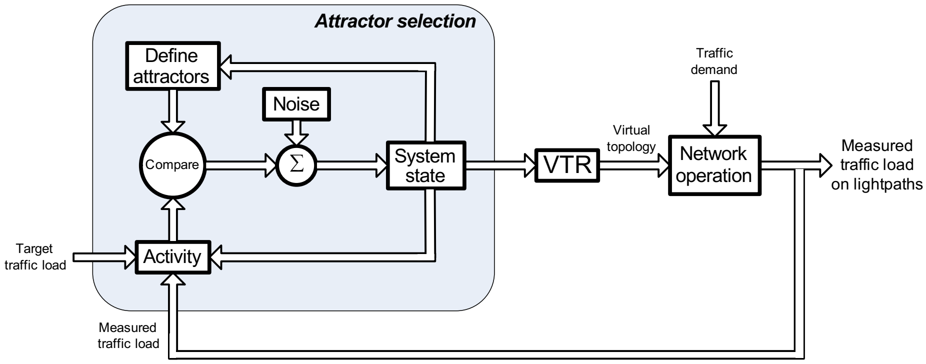


Fig. 11. Control architecture of the reconfiguration based on attractor selection.

fundamental idea was inspired by biological systems that are robust to environmental changes. Its behaviour is illustrated in Fig. 12. An attractor is an equilibrium point in the solution space when the network state is close to control target. When the network state was far away from the control target, random noise caused a new attractor being selected.

5.2. Virtual topology insensitive to traffic changes

Aiming at designing virtual topologies insensitive to traffic changes, the second branch of the proactive reconfiguration strategy can be classified in two flavours: universal virtual topology, and over-provisioning.

5.2.1. Universal virtual topology

A universal virtual topology aims at using the same virtual topology for many traffic patterns. Such a "one-fits-all" approach deals with traffic fluctuations using one single virtual topology. If the sequence of future traffic changes is known in advance, then in theory one single virtual topology could be designed to optimize a certain objective over long time as opposed to at each point of time. In practice, even though future traffic changes are unknown, a virtual topology could be used regardless of traffic pattern at a cost of sub-optimal network operation at most time. In this way, the need for reconfiguration as traffic changes is removed.

Reconfiguration can be reduced or even avoided, assuming all traffic patterns are known and taking advantage of the sharing of bandwidth between flows with increasing and decreasing bandwidth requirements. However, the effectiveness of this single virtual topology approach significantly depends on the allowed traffic patterns and other network properties such as topology. In [96], one single virtual topology was designed using a heuristic algorithm to optimize a complex objective. It did not allow lightpaths and IP layer flows to be reconfigured. Simulation results showed that only minor extra resources were required compared to using a perfect matching virtual topology for each traffic pattern, when most traffic was either between nodes within the same region or between nodes in different regions. Significant resource savings were achieved compared to a single virtual topology that was designed for the worst-case based on the capacities of all ingress-egress pairs. When one single virtual topology was used for the worst case, a maximum traffic pattern could be derived by setting each element of the traffic pattern to the maximum value over all traffic patterns, resulting in a very pessimistic performance.

IP-layer traffic adaptation may be added to the previous single virtual topology approach, so that unexpected traffic can be handled. This approach is motivated by the fact that IP-layer rerouting is easier, quicker and less disruptive than reconfiguration. In [97], one single virtual topology was designed, which did not necessarily provide sufficient bandwidth to support all traffic patterns. Instead, the objective was to maximize the acceptance probability of the expected traffic demands by using the cumulative distribution function over all traffic patterns. When bandwidth was insufficient on the direct lightpath between a given node-pair, IP-layer rerouting over existing lightpaths was used for the excess (a small amount) traffic. In [98], one single virtual topology was used to handle traffic fluctuations, assuming no lightpath is allowed to be reconfigured. It compared two policies, one with and the other without IP-layer flow reconfigurations. Different than the approach in [97] that only reroutes at the IP layer for new traffic flows, rerouting of existing IP-layer tunnels were used in [98].

One virtual topology may be used for a set of traffic patterns as opposed to one single traffic pattern, to avoid reconfiguration if the traffic changes within the set. If the

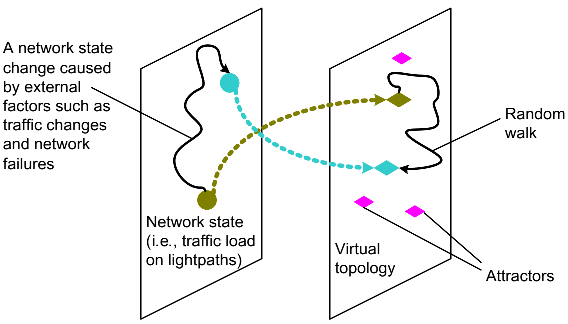


Fig. 12. Behaviour of the reconfiguration based on attractor selection.

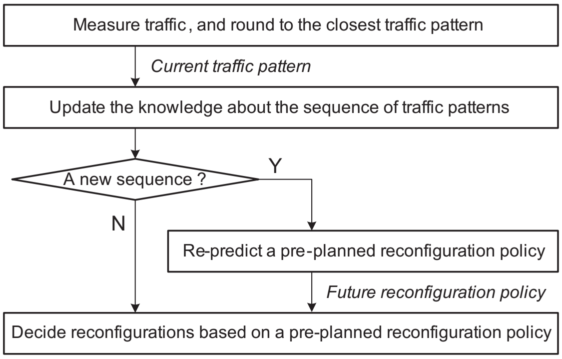


Fig. 13. Pre-planned reconfiguration for clusters of traffic patterns with updates on the reconfiguration policy.

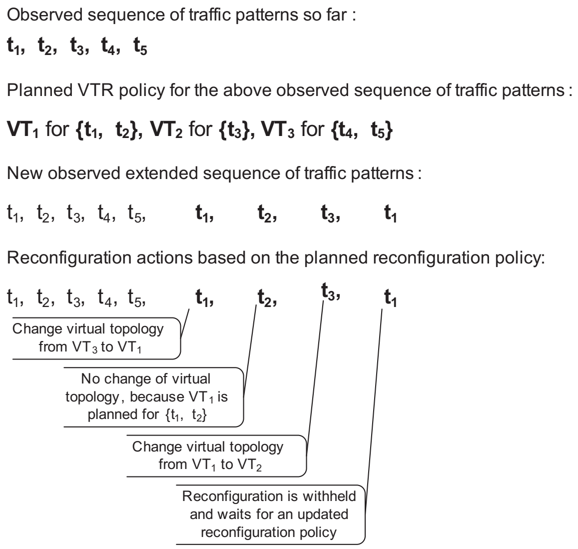


Fig. 14. Behaviours of using pre-planned reconfiguration for clusters of traffic patterns with updates on the reconfiguration policy.

complete sequence of traffic pattern is known in advance, reconfiguration could be optimized for the entire time horizon, instead of just for one point of time. In [107], with a goal of optimizing the reconfiguration performance gain over time, traffic patterns were divided into clusters, so that no reconfiguration was required within a cluster of traffic patterns. Realizing the difficulty of knowing the complete sequence of traffic pattern in advance, a traffic prediction method was used and the clusters were incrementally built up based on a learning process about the past traffic transition probability (shown in Fig. 13). The reconfiguration policy was updated with a goal of optimizing the probabilistic gain of using virtual topologies for traffic pattern clusters. The gain was computed as the saving on reconfiguration cost (i.e., return, which was saved by not changing virtual topology when the consecutive traffic patterns stay in the same cluster) minus the inferior resource utilization (i.e., investment, which was caused by not using the best virtual topology for each traffic pattern). Essentially, future traffic and reconfiguration policy were updated to increase the success probability of prediction. The behaviours of using pre-planned reconfiguration for clusters of traffic patterns with updates on the reconfiguration policy were illustrated in an example shown in Fig. 14. Distinct traffic patterns were defined from measured traffic matrices that are usually continuous. There is a trade-off between the complexity and the accuracy of the algorithm that determines the reconfiguration policy. The complexity of the algorithm in [107] was proportional to the cubic of the number of the total distinct traffic patterns. A total number of 60 distinct traffic patterns were used in its performance evaluation, which is a coarse representation of all possible measured traffic. For NSFNET, there were up to $14 \times 13 = 182$ traffic flows. If each traffic flow has only two states (low and high), $2^{182} = 6.1 \times 10^{54}$ total traffic patterns were required to distinguish all combinations; if each traffic flow has three states (low, normal, and high), $3^{182} = 6.9 \times 10^{86}$ total traffic patterns were required. So using discrete traffic patterns to represent traffic load is a big challenge for scalability.

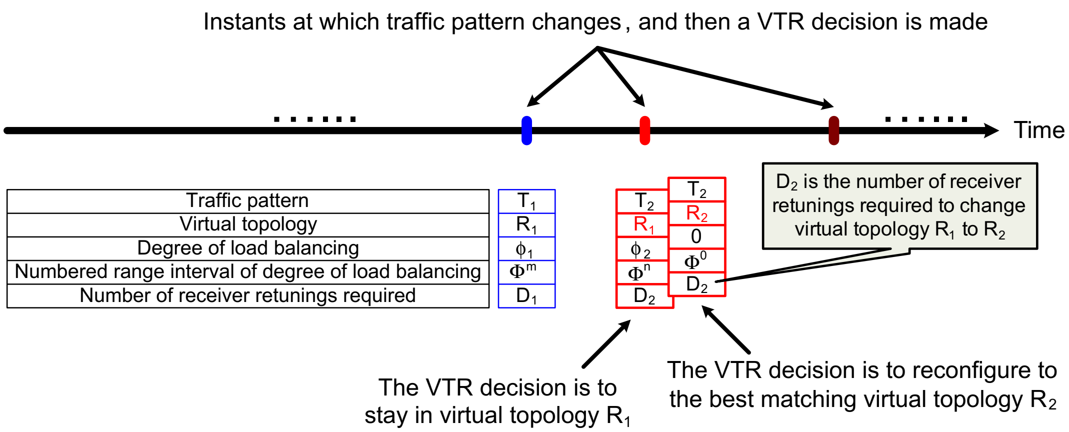


Fig. 15. Markov process model for reconfiguration, where the decisions in each state have two options: staying in the current virtual topology, or reconfiguring to the best matching virtual topology.

5.2.2. Markov decision process models

Assuming the transition probabilities among all traffic patterns are given and future traffic patterns only depend on the current traffic pattern (i.e., independent of past traffic patterns), the best reconfiguration policy can be pre-computed using dynamic programming techniques on Markov process models to maximize the long-term expected reward. The reward for one reconfiguration is measured by the performance gain of using a matching virtual topology minus its reconfiguration cost. With the best reconfiguration policy, the average reconfiguration reward achieves the maximal value over long time period. Once the best reconfiguration policy is pre-computed, it can be used to govern the reconfiguration in realtime by just identifying the current traffic pattern to a stored one. The challenge of applying a Markov process model is that if a state is defined by a virtual topology and a traffic pattern, the potential number of states is too huge to compute and store the best reconfiguration policy, even though the elements of a traffic matrix could be restricted to integers within an upper bound on their values. In [99–104], a Markov process model was formulated for single-hop star-topology passive broadcast WDM networks. It significantly reduced the number of states by using a new state defined by the number of receiver re-tunings required and a numbered range interval of degree of load balancing. The degree of load balancing characterized the efficiency of the network in meeting traffic demands for given traffic pattern and virtual topology. It may take any real value within a fixed range, and then for approximation, was divided into non-overlapping intervals and was given an index number. The decisions in each state had two options (shown in Fig. 15): staying in the current virtual topology, or reconfiguring to the best matching virtual topology that was designed by a heuristic algorithm. Each transition was associated with a probability and a reward (shown in Fig. 16). In both figures, when the decision was to reconfigure, it was assumed that the best matching virtual topology was able to achieve. The simulation results in [99,101,102] were obtained for a total number of states between 400 and 2000, where 20–40 intervals were used to estimate the degree of load balancing, and the number of receiver re-tunings was up to 100. In practice, besides the challenge of the number of states, a priori knowledge of traffic pattern transition probabilities is difficult to obtain. The robustness of a pre-computed reconfiguration policy is limited by the accuracy of transition probabilities of traffic patterns. In [19], it was pointed out that the near-neighbour traffic model was generally invalid over timescales of one day or longer, where traffic oscillations and long-term growth tended to occur.

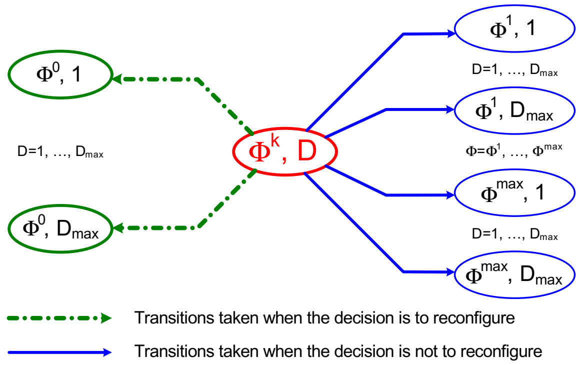
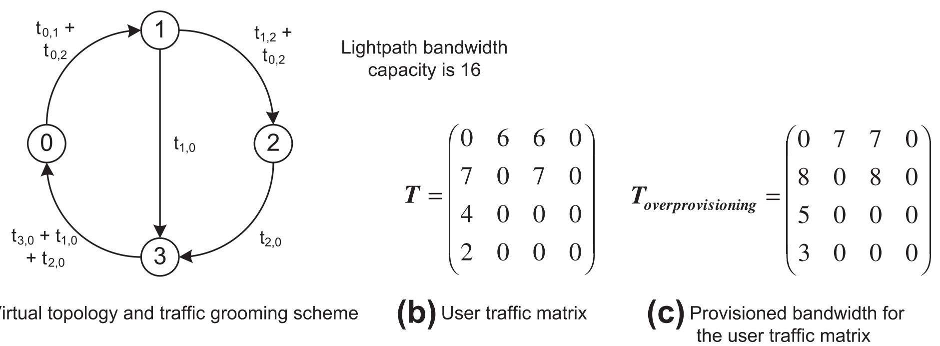


Fig. 16. Transitions out of state (Φ^k,D).

5.2.3. Proactive provisioning spare resources

Spare resources may be used to proactively provision virtual topologies that are robust to traffic changes. Proactive over-provisioning was used in [11,108,109]. For given virtual topology, user traffic matrix and grooming scheme, over-provisioning was applied to user traffic by utilizing spare bandwidth of lightpaths. This improved network agility and response time to traffic demand changes. We show an example in Fig. 17. In [11,108], it was assumed that the grooming scheme was fixed, and no new user traffic flow was allowed. Then, such over-provisioning reduced the need for reconfiguration. Assuming reconfiguration is too slow for realtime bandwidth provisioning, such over-provisioning reduced blocking of user traffic. However, if new user traffic flows are allowed, as opposed to only bandwidth changes of existing flows, the spare capacity may be unavailable and could result in higher blocking for new flows. The trade-off needs to be further investigated.



$$T = \begin{pmatrix} 0 & 6 & 6 & 0 \\ 7 & 0 & 7 & 0 \\ 4 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 \end{pmatrix} \qquad T_{overprovisioning} = \begin{pmatrix} 0 & 7 & 7 & 0 \\ 8 & 0 & 8 & 0 \\ 5 & 0 & 0 & 0 \\ 3 & 0 & 0 & 0 \end{pmatrix}$$

Fig. 17. An example of over-provisioning bandwidth for user traffic to accommodate user traffic changes and thus to postpone reconfiguration.

6. Distributed reconfiguration triggering methods and strategies

6.1. Distributed reconfiguration in a single domain

6.1.1. Distributed initiation of lightpath setup or removal (each node still decides global reconfiguration)

Reconfigurations may be triggered in a distributed manner. In [110], all nodes were assumed to use the same heuristic algorithm and identical traffic measurement when deciding a new virtual topology. As a result, all nodes should have a consistent decision of the new virtual topology. Then the originating nodes of the lightpaths that should be set up or removed independently initiated action procedures. The heuristic algorithm used for the distributed reconfiguration is shown in Fig. 18, which is very similar to its centralized counterpart heuristic algorithm used in [30]. To fit its distributed operation, the limitation on the total number of lightpaths to be added or deleted and the sequence of additions were removed. In [56], experimental results were given for a small network with six routers connected to four WDM switches. The consistence of reconfiguration relies on all nodes using identical traffic measurement, which is disseminated by a link-state routing protocol with traffic engineering extensions. However, in practice, different nodes have different versions of traffic measurement due to the distributed flooding mechanism that is used to disseminate link-state advertisement messages [111]. The update interval of link-state advertisement used in the experiments was very short, i.e., two seconds. In this way, the difference should not cause reconfiguration conflicts and inconsistency. The new lightpaths obtained from the heuristic algorithm in [110,56] may compete for resources. The competition could be naturally handled by a first-come-first-serve policy, which blocks the lightpath setup requests that use the same resource and arrive after the first one. However, there is an issue of avoiding repeat requesting the same lightpath after a failed attempt. Note that each node still decides global reconfiguration, although the initiation of lightpath setup or removal is distributed.

6.1.2. Distributed reconfigurations based using rerouting solicit messages (each node still needs global information about sub-lightpath connections)

In [112], a distributed reconfiguration method was proposed for traffic grooming WDM networks. It aimed at distributed triggering rerouting of connections with sub-lightpath bandwidth, and indirectly reconfiguring lightpaths. Arrival connection requests were dynamically rou-

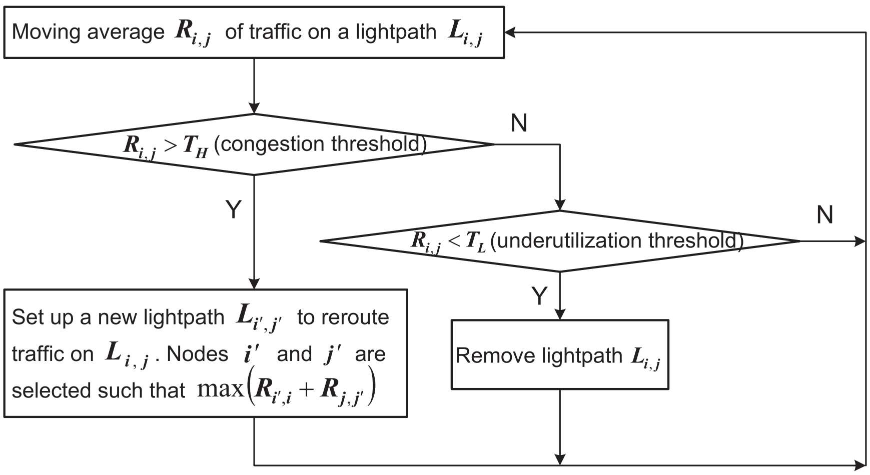


Fig. 18. The heuristic algorithm for a distributed reconfiguration used in [110].

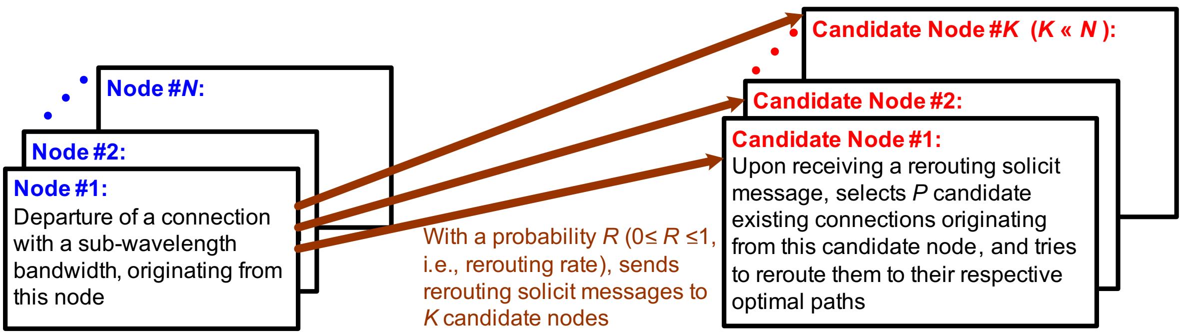


Fig. 19. The source node of a connection that is to be torn down sent rerouting solicit messages to candidate nodes [112].

ted using an auxiliary graph. If necessary and feasible, new lightpaths were dynamically set up. Connection departures trigger distributed connection rerouting, resulting in idle lightpaths being removed. It proposed the source node of a connection that is to be torn down triggered rerouting by sending rerouting solicit messages to a number of candidate nodes (shown in Fig. 19). Each candidate node evaluated the resource savings for rerouting of connections originating from this candidate node. The connections with the largest resource savings were chosen. It proposed a general case where K candidate nodes and P candidate connections at each candidate node were used. It does not solve the contentions when checking new routes in its CheckNewConn function, which limits the proposal to work only in a special case where $K = P = 1$ as in its simulations. Its heuristics for selecting candidate nodes and candidate connections relies on global connection information, which does not fit distributed operations.

6.1.3. A distributed election protocol controlled reconfigurations (each node still needs global information about optical layer resource availability)

In [113], a distributed reconfiguration method was proposed for SONET-over-WDM networks, aiming at automatic grooming of SONET circuits to dynamically established lightpaths. Each node independently and

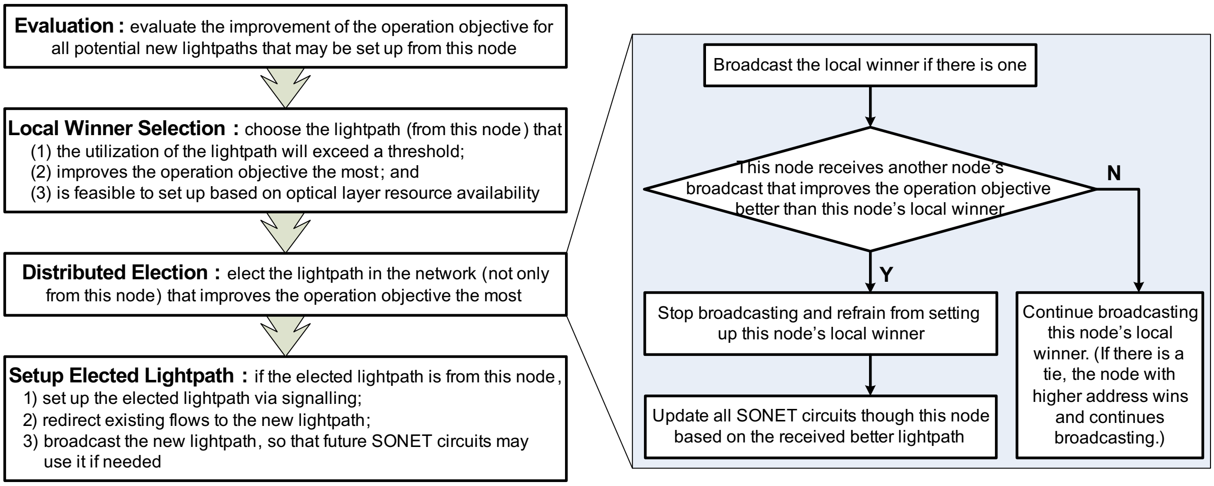


Fig. 20. Distributed addition of lightpaths used in [113].

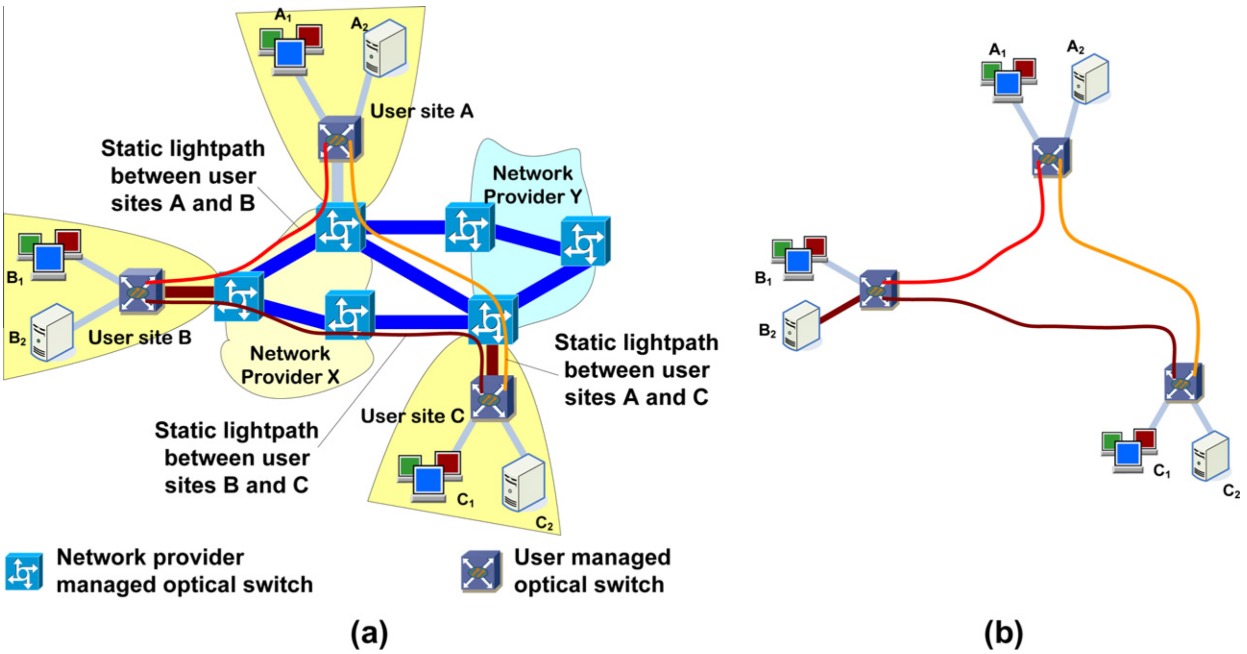


Fig. 21. Reconfiguration in an overlay network by using optical switches to dynamically connect different end-users to static inter-domain lightpaths. (a) Static inter-domain lightpaths; (b) The physical topology that virtual topologies can be built onto.

repeatedly executed the lightpath addition procedure as shown in Fig. 20. In the evaluation step, it was assumed that each node knew the route (list of traversed nodes) of every active SONET circuit that travels though this node. The computation complexity is $O(V \times F)$, where V is the total number of nodes and F is the total number of SONET circuits travelling through this node. In the local winner selection step, it was assumed that each node had global information about optical layer resource availability. A conceptual distributed election procedure was given, but a functional distributed election procedure would be more complicated, e.g., dealing with message loss, non-responding nodes, etc. When the utilization of a lightpath was below a threshold, a lightpath removal procedure was triggered and tried to reroute the SONET circuits carried over this lightpath. A distributed lightpath removal procedure can be derived from the centralized lightpath removal procedure given in [113]. It suggested that the lightpath utilization upper and lower threshold could be predefined or dynamically updated via a routing protocol. Experimental results on the thresholds were reported. How to determine sufficient gap between the upper and lower thresholds to prevent reconfiguration oscillations needs further study. Compared to the proposal in [112], the contention was resolved by the election procedure, and less global information was assumed known at each node.

Compared to the method in [110], the method in [113] is truly distributed since all nodes are not assumed to have the same version of traffic measurement for the whole network. However, a complex election process is introduced to achieve this true distributed feature. The method in [110] scales better than the method in [113], because when the number of traffic flows increase, the computation complexity of the method in [110] does not increase. The method in [113] results in more accurate lightpath setup decision, but at a cost of heavy state information maintenance at each node. Both methods suffer from their strong assumption on each node's knowledge of global optical layer resource availability.

6.2. Reconfiguration across multiple domains

6.2.1. Reconfigurations across multiple domains using overlay networks

Overlay networks are used to manage reconfiguration across multiple domains, where lightpaths are statically provisioned using resources from multiple domains and are provided to end users for reconfiguration. In [115–117], the challenges of reconfiguration over multiple domains were outlined, which require coordination among several network providers. As a result, despite years of research and development, the vision of a dynamically reconfigurable optical core across multiple domains (e.g., [118]) is far from reality. Due to administrative burden and strict time requirements of reconfiguration, inter-domain lightpaths typically are held in place for months or longer. To increase the utilization of such lightpaths, overlay networks were constructed by using optical switches to dynamically connect different end-users to the statically provisioned inter-domain lightpaths (illustrated in Fig. 21). In this way, the

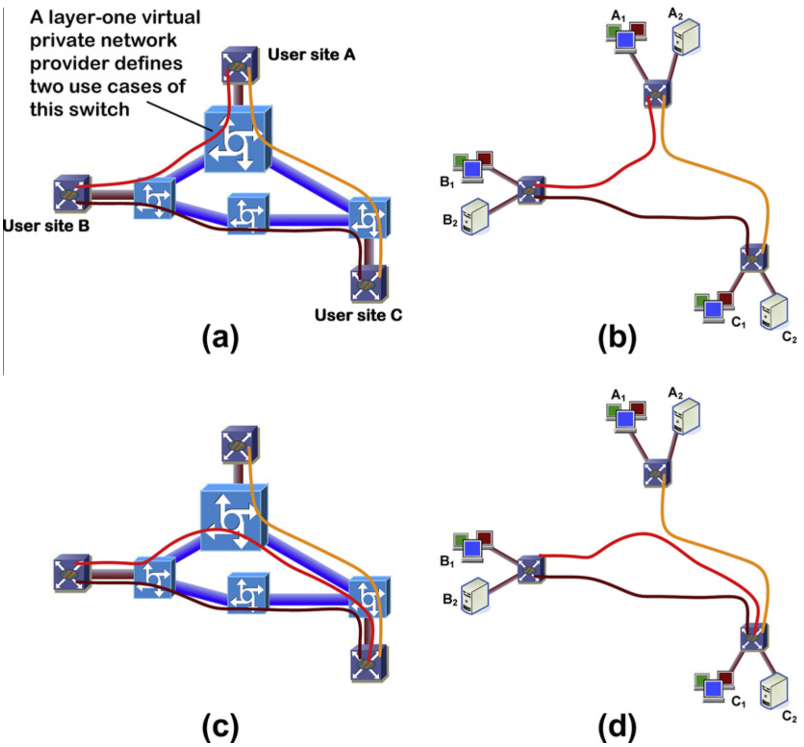


Fig. 22. Reconfigurations in an overlay network, in which inter-domain lightpaths are defined by use cases. (a) First use case of inter-domain lightpaths; (b) The physical topology corresponding to the first use case; (c) Second use case of inter-domain lightpaths; (b) The physical topology corresponding to the second use case.

problem of reconfiguration over multiple domains was transformed into a single-domain reconfiguration problem. Note that reconfiguration in an overlay network has additional constraints, i.e., pre-define wavelength channels must be used between user managed optical switches.

6.2.2. End user managed reconfigurations of layer-one virtual private networks

When resources and their associated management functions can be partitioned, end users are able to conduct more flexible reconfigurations. In [119], Layer-One Virtual Private Networks (L1-VPNs) were composed across multiple domains. L1-VPN providers defined use cases of acquired resources, and then offered to end users for on-demand activation and reconfigurations. For example, in Fig. 22, a network provider authorized an L1-VPN provider to use three ports on a given optical switch (other than the two ports used by the lightpath between user sites A and C) and a specific wavelength channel. The L1-VPN provider was given the management service for the three ports and switching unit. The L1-VPN provider defined two use cases as shown in Fig. 22(a) and (c). Unlike static lightpaths, reconfigurations could change the use of resources within a limited scope defined by the use cases. Thus, two physical topologies can be used to build virtual topologies, as shown in Fig. 22(b) and (d).

7. Other reconfiguration triggering methods and their related reconfiguration strategies

We would like to comment on the four types of triggering events that were given at the beginning of Section 2. Some reconfiguration policies are designed to deal with some (not all) of the triggering events.

7.1. Network failure triggered reconfigurations

In network failure recovery, new lightpaths are dynamically requested, which could be blocked and then trigger a WDM network reconfiguration. Such failure recovery triggered WDM network reconfiguration is a stretch of the WDM network reconfigurations in response to lightpath blockings that were proposed in [55,67,68]. However, a recovery lightpath has tighter time to be set up than a new regular lightpath. Normally, the upper layer applications of a new regular lightpath do not send traffic until a success confirmation is received from the WDM network. Thus, user traffic is not lost or disrupted, but is only delayed. But delays in setting up a recovery lightpath result in loss and disruption of user traffic. In summary, failure recovery triggered WDM network reconfiguration has little practical merit, unless additional coordinations with upper layer applications are used. In many cases, simple changing of wavelength channels but using the same route does not recover from failures that impact all wavelength channels on a link or connected to a node. Therefore, more complicated route changes and possibly combined with wavelength channel changes are required, resulting in much longer time for reconfigurations than simple wavelength retuning proposed in [55,67,68].

In [105], it acknowledged that network failures cause much larger performance degradations than gradual traffic changes do. Reconfigurations were used to handle both traffic changes and network failures, aiming at adapting virtual topology to network status without extensive monitoring of network status at different layers. Specifically, it assumed no mechanism to detect network failures and no monitoring of IP layer route changes. The condition of IP networks was indirectly monitored through the bandwidth utilization of lightpaths. Inspired by a biological adaptation process, a reconfiguration mechanism was proposed, which reacted properly to traffic changes and network failures in simulations. However, the network failures used in the simulations were fibre cuts. WDM network failures must be detected and located so that proper virtual topology can be reconfigured. Otherwise, a new virtual topology may attempt to use failed optical layer resources. The proposed mechanism may apply to IP network failures.

In [124], reconfigurations were used to handle both traffic changes and network failures. After a link or node failure, alternate lightpaths for restoration of the failed lightpaths may exist only if the network is reconfigured. Reconfigurations were used to accommodate new requests which may otherwise be blocked. The details of the triggering methods were not discussed in [124].

In [125], reconfiguration for failure restoration was compared with rerouting restoration. Even for a single-hop virtual topology, reconfiguration for failure restoration achieved better wavelength efficiency than rerouting restoration. However, the comparisons were made through offline optimization formulation, which did not consider the online performance such as reconfiguration or rerouting time and complexity. Its comparisons also showed that as the traffic load becomes heavy, the advantage of reconfiguration for failure restoration in wavelength efficiency became small. It concluded that the capability of tuning wavelength at the source node and converting wavelength at intermediate nodes was by far more important in wavelength efficiency in restoration.

Although failure recovery triggered WDM network reconfigurations have little practical merit, they could be used to protect a second subsequent failure [9,28]. Such techniques are out of the scope of this survey.

7.2. Resource upgrades triggered reconfigurations

When additional network resources are deployed, it is not urgent to conduct WDM network reconfigurations. In most cases, the added resources are gradually utilized as new lightpaths will consider using them. Since there are additional resources, likely the make-before-move migration methods are able to build new lightpaths and then move the existing traffic to the new lightpaths without much disruption.

In [123], a multi-period network planning and reconfiguration are used to incrementally increase network capacity to carry all predicted traffic. In [42], reconfiguration was conducted after topological changes such as new nodes and/or new link additions.

In [120], three network operation phases were considered: (1) initial call setup; (2) short/medium term reconfiguration, in which backup lightpaths were optimized while working lightpaths were not reconfigured; and (3) long term reconfiguration, in which working and backup lightpaths were reconfigured. Offline optimization was used in all three phases. The triggering of the second and third phase was not discussed.

In [121], three policies were used: (1) after the usage of wavelength channels on an overloaded link exceeded a threshold, then the lightpaths using this link were reconfigured; (2) after the usage of the wavelength channels in the whole network exceeded a threshold, then the lightpaths using busy links were reconfigured; (3) after the protection sharing on a backup path fell below a threshold, the corresponding working lightpaths were reconfigured. In [122], reconfiguration was conducted after establishments of a given number of new lightpaths. Four policies were compared: (1) reconfiguration of only the lightpaths that were established after the last reconfiguration; (2) reconfiguration of all lightpaths; (3) reconfiguration of the routes and wavelengths of protection lightpaths; (4) reconfiguration of the wavelengths (but not the routes) of working lightpaths, as well as the routes and wavelengths of protection lightpaths. In [114], two strategies to trigger reconfiguration were compared: (1) a reconfiguration-minimized strategy: after a given number of link additions or upgrades to accommodate additional user traffic; (2) an investment-minimized strategy: when a link runs out of capacity before upgrading the link.

8. Open issues for future research

For the known-demand strategy, how to determine the time intervals to conduct reconfigurations or the number of the accumulated lightpath demands to trigger reconfigurations remains an open issue. Lightpath demands may be allowed to slide within their time windows, but reconfiguration for scheduled lightpaths is not studied so far in the literature. The aggregated traffic is significantly impacted by the user traffic routing over virtual topology, which is simplified or neglected by the known-demand strategy. So far, the studies on WDM network reconfigurations for multicast traffic were very limited.

For the adaptive strategy, the transient behaviours during reconfigurations may cause further traffic fluctuations, and may trigger unnecessary reconfigurations or interfere with decisions on further reconfigurations. Oscillations of virtual topology could happen, if the transient behaviours of user traffic are not handled properly. The transient behaviours during reconfiguration remain an open area for future research.

The performance evaluations of the adaptive strategy are insufficient. When WDM network reconfiguration interacts with upper layers, the traffic will be shaped. Short-term transient behaviours and long-term trends are impacted. Unfortunately, the traffic shaping was largely ignored in most simulation studies. A few experiments were conducted on small scale networks (e.g. in [90–92,18]). However, some behaviours may not present in small scale networks.

For the proactive strategy, an unexplored area is that proactively provision lightpaths while not using the over-provisioned lightpaths to carry user traffic before there is a real need to do so. That means, the over-provisioned lightpaths are kept as a standby capacity, but are not used immediately. They will be activated when needed. Over-provisioned lightpaths can be reconfigured based on the updated network state. Because the over-provisioned lightpaths do not carry user traffic yet, their reconfigurations do not disrupt user traffic.

Reconfiguration based on partial traffic matrix needs further study. An attractive application would be distributed reconfigurations. Although the advantages of using distributed reconfigurations were briefly discussed in [114], only the benefits of centralized reconfigurations were studied in detail. It speculated that distributed reconfigurations could result in localizing traffic disruptions, but no detailed studies were available.

Reconfiguration in multiple domains with or without coordination is not well studied. So far, most reconfiguration is investigated in a single domain scenario, where all network resources are assumed to be managed by one authority. However, a domain may conduct reconfiguration for the purpose of attracting profitable traffic to itself and offloading non-profitable traffic to competitors. In such situations, reconfigurations are used as actions in a competitive market.

In general, the extensive academic research of WDM network reconfigurations has not yet resulted in a widespread deployment of the technologies. In our opinion, the understanding of the technologies needs major improvements so that the confidence of using them may grow gradually. The performance evaluations of most proposed mechanisms are rather simplified. Not sufficient results and analysis are available for key criteria, e.g., response time, resource overheads, service disruptions, ability to accommodate dynamic traffic, etc. Many simulation-based evaluations should be further verified and validated against test results. To bridge the gap between theory and practice of WDM network reconfigurations, more testbed experiments and field trials are required.

9. Summary

We identified the common purpose and the difference of network reconfiguration and traffic engineering. Their common purpose is to facilitate efficient and reliable network operations while simultaneously optimizing network resource utilization and traffic performance. But, in network reconfiguration, the goal is achieved by changing bandwidth capacity between node pairs. In contrast, in traffic engineering, the goal is achieved by changing the way that traffic uses bandwidth.

WDM network reconfiguration has great potentials to add significant flexibility in network operations. To realize such great potentials, enormous in-depth researches have been conducted, addressing diversified aspects of the problem.

Conceptually, WDM network reconfiguration consists of three phases: (1) making a reconfiguration policy decision whether a reconfiguration should be conducted; (2) selecting a new virtual topology based on a certain optimization objective; and (3) migrating from the current topology to the new topology. We surveyed the strategies and triggering methods of WDM network reconfiguration.

There are gaps in research and in field trials. It is important to further build up knowledge of understanding of the network behaviours under different scenarios and settings, thus to gradually increase confidence of introducing automated WDM network reconfigurations.

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