Lightpath Scheduling and Routing for Traffic Adaptation in WDM Networks

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***Abstract*—We study the benefits and trade-offs of using scheduled lightpaths for traffic adaptation. We propose a network planning model that allows lightpaths to slide within their desired timing windows with no penalty on the optimization objective and to slide beyond their desired timing windows with a decreasing tolerance level. Our model quantitatively measures the timing satisfactions or violations. We apply the Lagrangian relaxation and subgradient methods to the formulated optimization problem, with which great computational efficiency is demonstrated when compared with other existing algorithms. Our simulation results show how timing flexibility improves network resource utilization and reduces rejections.**

***Index Terms*—Networks; Assignment and routing algorithms; Combinatorial network design; Network optimization.**

I. Introduction

Network traffic at the optical layer periodically fluctuates. For core optical networks such as wavelength division multiplexing (WDM) networks, network traffic is observed following daily patterns [1] or weekly patterns [2]. Such traffic patterns can be predicated from historical statistics, which repeat every day (or week) with minor variations in timing and volume. The knowledge about traffic patterns provides an opportunity to schedule lightpaths to adapt to the changing traffic. Traffic adaptation is a network reconfiguration process to adapt to traffic fluctuations.

Using scheduled lightpaths for traffic adaptation has different timing requirements from the other lightpath scheduling problems. Existing methods for the scheduled routing and wavelength assignment (RWA) problems assume that a lightpath should be set up either at a given time or within a given time window, which makes the lightpath scheduling inflexible for traffic adaptation. For example, in [3–15], network planning was conducted for a set of lightpath requests, each having prespecified starting and ending times. In [16–24], static network planning was conducted for fixed holding-time lightpath requests, each one being allowed to slide within its given time window. But, for traffic adaptation, timing flexibility in lightpath scheduling is very important. Network operators are concerned about not only timing violations but also resource utilization and lightpath rejections and need a tool to make wise trade-offs between these goals. Network operators would rather adjust lightpath scheduling timing than reject lightpaths that cannot be accommodated due to their strict timing requirements or impractical timing windows.

For traffic adaptation, scheduled lightpaths are allowed to slightly slide in timing, without deteriorating the performance. Sliding-timing scheduling potentially provides better network resource utilization than fixed-timing scheduling. Since lightpaths are scheduled based on the statistical traffic characteristics, minor timing slides should not impact much on the performance of the traffic adaptation, while dramatic timing slides should be avoided.

For traffic adaptation, the extent of timing satisfaction or violation needs to be quantitatively measured. A timing window should not be used in a “binary” way, i.e., it can either be satisfied (thus the corresponding lightpath is accepted) or not (thus the corresponding lightpath is rejected). Network operators often would prefer scheduled lightpaths being centered on their desired timing, with a decreasing tolerance level as scheduled lightpaths move away from their desired timing windows. For example, a network operator wants to schedule offline large database backup operations at night when the network traffic is light. The ideal timing window would be after midnight and before 6:00 am. However, such operations may start earlier than midnight but cause increasing penalty as they move toward evening traffic peak from 7:30 pm to 9:30 pm, when the cost is higher. Similarly, the scheduled lightpaths could continue after 6:00 am but cause increasing penalty as they move toward morning traffic peak from 8:00 am to 10:00 am. This requires proper modeling of the extent of timing satisfaction or violation, which has not been done by the existing methods for the static lightpath scheduling, to our knowledge, and motivates this study. Furthermore, with the usage-based pricing [20], which is a time-wise variable, a lightpath should be penalized differently for the different time span being scheduled upon. However, this variation is not taken into consideration in [20].

Our study aims at planning scheduled lightpaths to adapt to relatively stable traffic patterns. Static scheduled lightpath demands are known as inputs to our network planning problem. Our problem is different from dynamic lightpath scheduling problems, which generally do not assume any *a priori* statistical information about traffic patterns

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[25–32]. In [33,34], static lightpath scheduling problems were called "advance lightpath reservation problems," while dynamic lightpath scheduling problems were called "immediate lightpath reservation problems." In our approach, once a lightpath is preplanned, it becomes available to carry traffic at its scheduled time. In contrast, dynamic lightpath scheduling cannot guarantee the availability of a lightpath. Only when a request arrives, the network operator makes real-time decisions depending on the network resource availability at the moment of the request. Our approach achieves a better coordination of lightpaths than dynamic lightpath scheduling by taking advantage of the extra information about traffic patterns.

Our method of using scheduled lightpaths for traffic adaptation has two major advantages over other virtual topology reconfiguration methods. First, our method provides a flexible framework to make trade-offs between the traffic adaptation and the network utilization. Second, we proactively coordinate lightpaths as the traffic changes, so that interruptions to the traffic are minimized. Essentially, we reconfigure the virtual topology by using scheduled lightpaths, which is the same method used in all related work on lightpath scheduling. Other virtual topology reconfiguration methods can be classified as reactive methods, prediction-based methods, etc. In [1,35,36], based on real-time traffic measurement, the online virtual topology is reconfigured to adapt to traffic fluctuations, where lightpaths are dynamically added or deleted. In [37], based on the predicted traffic, the virtual topology is reconfigured in time to adapt to traffic changes. In [38,39], the virtual topology is designed to fit a wide range of traffic patterns so that the need for reconfiguring the virtual topology is reduced.

This paper is organized as follows: in Section II, we summarize the assumptions used in our model; in Section III, we present our model, followed by a solution based on the Lagrangian relaxation and subgradient methods in Section IV; we evaluate the performance of our solution methods in experimental examples in Section V; and we conclude this paper in Section VI. Derivation details are included in Appendix A.

II. Network Operations, Modeling, and Assumptions

We consider wavelength-routed WDM networks with mesh topologies and capable of wavelength conversion. We model a general topology WDM mesh network of N nodes interconnected by E links. Each link consists of a pair of fibers, each fiber for one direction and having W noninterfering wavelength channels (WCs). Two nodes can be connected through a lightpath defined as a concatenated sequence of WCs [40]. The contribution of wavelength conversion has been highlighted in reconfigurable WDM networks [41]. We include wavelength conversion in our network model, so that its contributions can be evaluated in the context of scheduled lightpaths. Two lightpath segments that use different wavelengths are allowed to be chained together by using a wavelength converter installed at their junction node. In this way, a semilightpath is formed [42]. For simplicity, we use "lightpath" in this paper regardless of whether it uses the same wavelength all the way or not. We assume that all wavelength converters are capable of full-range conversion, which means any wavelength of an incoming lightpath segment can be converted into any wavelength of an outgoing lightpath segment. Each node has a predefined number of wavelength converters (could be zero if none). A node shares its wavelength converters among all its incoming and outgoing lightpath segments, i.e., if a wavelength converter is available at a given node, any incoming lightpath segment may choose to use it before entering any outgoing lightpath segment (see [43] for example node architecture).

Lightpaths are scheduled to be set up at the beginning of their starting time slots and be torn down at the end of their ending time slots. Network-wide synchronous time slots are used for resource allocations and lightpath scheduling. All time slots have the same fixed duration, which should be 5 min or longer. Many network management systems monitor network status every 5 min; thus a time slot shorter than this does not improve the performance but adds tremendous planning and operation overhead. As we will show shortly, the complexity of our scheduling problem directly relates to the number of time slots in the planning time horizon. We assume the time to set up or tear down a lightpath (i.e., signaling time) is negligible compared with the duration of a time slot. The holding time of a lightpath is fixed and known in advance, measured by the number of time slots. Without losing generality, we number the time slots in our planning time horizon sequentially from 0 to $Z-1$ ($0 \leq t < Z$).

We aim at scheduling and allocating network resources to lightpaths, i.e., planning network operations for scheduled sliding lightpath demands (SSLDs). The network resources primarily include WCs and wavelength converters. We provide an accepted SSLD with a RWA scheme, which is described as a list of allocated WCs and possibly together with wavelength converters. The same RWA scheme is used for the entire holding time of an SSLD, i.e., once an SSLD is accepted, it stays connected from its starting time slot to its ending time slot. If there are insufficient resources for an SSLD during its holding time, the SSLD is rejected. We allow multiple SSLDs being set up between a given node pair.

III. Problem Formulation

A. Notations

For the remainder of this paper, the following notations and variables are used:

Input Parameters:

$\mathcal{V}$	the set of all nodes in the network
e_{ij}	the fiber between node i ($i \in \mathcal{V}$) and node j ($j \in \mathcal{V}$)
$\mathcal{E}$	the set of all fibers in the network, i.e., $\{e_{ij}\}$, ($i \in \mathcal{V}, j \in \mathcal{V}$)
d_{ij}	the cost of using a WC on link e_{ij} ($e_{ij} \in \mathcal{E}$) for one time slot

o_i the cost of using a wavelength converter on node i ($i \in \mathcal{V}$) for one time slot

W the number of wavelengths used in the network

l_{sdn} the nth SSLD from node s ($s \in \mathcal{V}$) to node d ($d \in \mathcal{V}$). If it is accepted, we also use l_{sdn} to denote the RWA scheme for the SSLD.

$\mathcal{L}$ the set of all SSLDs, i.e., $\{l_{sdn}\}$

L the total number of SSLDs

t_{sdn} the holding time of l_{sdn}

$[b_{sdn}, b'_{sdn}]$ the desired window of starting time for l_{sdn}, $0 \leqslant b_{sdn} \leqslant b'_{sdn} < Z$

C_{sdn} the routing cost of l_{sdn}, i.e., the cost of resources used by l_{sdn}

F_i the number of wavelength converters installed on node i ($i \in \mathcal{V}$)

N the number of nodes in the network

P the penalty coefficient for rejecting an SSLD

Z the total number of time slots of our scheduling problem

y_{sdn} the weight for the earliness penalty of l_{sdn}

r_{sdn} the weight for the tardiness penalty of l_{sdn}

DECISION VARIABLES:

α_{sdn} a binary integer variable indicating the admission status of l_{sdn}. It is one, if l_{sdn} is accepted. Otherwise, it is zero.

β_{sdn} the starting time slot of l_{sdn}, $0 \leqslant \beta_{sdn} < Z$.

δ_{ijct}^{sdn} a binary integer variable representing the use of the cth WC ($0 \leqslant c < W$) on fiber e_{ij} ($e_{ij} \in \mathcal{E}$) at time slot t by l_{sdn} ($l_{sdn} \in \mathcal{L}$). It is one, if l_{sdn} uses such the WC at such a time slot. Otherwise, it is zero.

ϕ_{it}^{sdn} a binary integer variable representing the use of a wavelength converter on node i ($i \in \mathcal{V}$) at time slot t ($0 \leqslant t < Z$) by l_{sdn} ($l_{sdn} \in \mathcal{L}$). It is one, if l_{sdn} uses such a wavelength converter at such a time slot. Otherwise, it is zero.

A the set of admission status of all l_{sdn}'s, i.e., $\{\alpha_{sdn}\}$

B the starting time slots of all l_{sdn}'s, i.e., $\{\beta_{sdn}\}$

Δ_{sdn} the RWA scheme of l_{sdn} ($l_{sdn} \in \mathcal{L}$), i.e., $\{\delta_{ijct}^{sdn}\}_{sdn}$

Φ_{sdn} the allocation of wavelength converters to l_{sdn} ($l_{sdn} \in \mathcal{L}$), i.e., $\{\phi_{jt}^{sdn}\}_{sdn}$

Δ the RWA schemes of all l_{sdn}'s, i.e., $\{\Delta_{sdn}\}$

Φ the usage of wavelength converters by all l_{sdn}'s, i.e., $\{\Phi_{sdn}\}$

INTERMEDIATE VARIABLES FOR COMPUTATION AND RESULT EVALUATIONS:

D_{sdn} the dual routing cost of l_{sdn}

E_{sdn} the overall timing violation penalty of l_{sdn}

ξ_{ijct} Lagrange multipliers corresponding to using a WC c ($0 \leqslant c < W$) on fiber e_{ij} ($e_{ij} \in \mathcal{E}$) at a time slot t ($0 \leqslant t < Z$)

π_{it} Lagrange multipliers corresponding to using a wavelength converter on node i ($i \in \mathcal{V}$) at a time slot t ($0 \leqslant t < Z$)

$\hat{\xi}_{ijc}^{\beta,T}$ the accumulated dual cost of using a WC c ($0 \leqslant c < W$) on fiber e_{ij} ($e_{ij} \in \mathcal{E}$)

$\hat{\pi}_{i}^{\beta,T}$ the accumulated dual cost of using a wavelength converter on node i ($i \in \mathcal{V}$)

$\hat{\delta}_{ijc}^{\beta,T}$ the continuous availability of a WC c ($0 \leqslant c < W$) on fiber e_{ij} ($e_{ij} \in \mathcal{E}$)

$\hat{\phi}_{i}^{\beta,T}$ the continuous availability of using a wavelength converter on node i ($i \in \mathcal{V}$)

$\hat{d}_{ij}^{\beta,T}$ the accumulated cost of using a WC on fiber e_{ij} ($e_{ij} \in \mathcal{E}$)

$\hat{o}_{i}^{\beta,T}$ the accumulated cost of using a wavelength converter on node i ($i \in \mathcal{V}$)

SL_{sdn} a sorted list of all the possible β_{sdn}'s for l_{sdn} based on its dual profit in the dual solution.

B. Objective Function

Our objective is to minimize the summation of the rejection of requests, the resource usage, and the timing violation of lightpaths. We want to accept as many profitable requests as possible, and for the accepted requests, we want to find lightpath schedules that respect their timing preference as much as possible, while at the same time provide them with RWA schemes that use as few resources as possible. In order to achieve this, we introduce a term in the objective function to penalize the timing violation, if l_{sdn} is not scheduled to start at time slot b_{sdn}.

Our objective function is to minimize the function J, i.e., $\min_{A,B,\Delta,\Phi}\{J\}$, where

$$J \equiv \sum_{l_{sdn} \in \mathcal{L}} [(1-\alpha_{sdn})P + \alpha_{sdn}(C_{sdn} + E_{sdn})]. \quad (1)$$

The overall penalty consists of the rejection penalty (i.e., P; in practice, it generally equals the revenue of a given lightpath), the resource usage cost (i.e., C_{sdn}), and the timing violation penalty (i.e., E_{sdn}). The readers are referred to [44] for examples for the penalty assignment. The timing violation penalty could be either an earliness penalty or a tardiness penalty. When l_{sdn} is scheduled sooner than its desired starting time, the lightpath will be removed sooner than the desired ending time, causing a shortage of the effective service time after the lightpath is removed. This is because we strictly respect the holding time of l_{sdn}, i.e., if l_{sdn} is accepted, its holding time will be exactly as requested. On the other hand, when l_{sdn} is scheduled later than its desired starting time of l_{sdn}, there will be a shortage of effec-

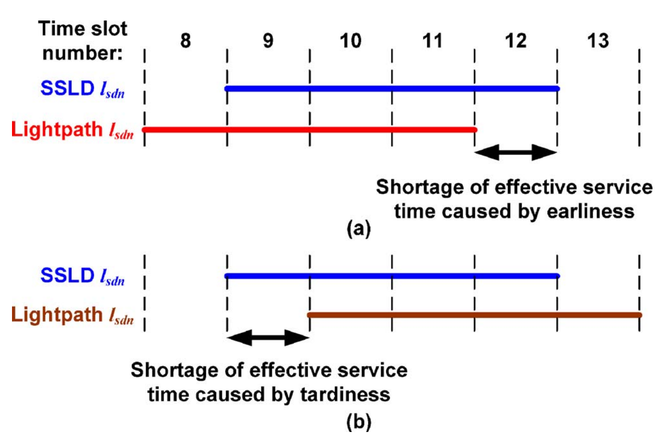

Fig. 1. (Color online) Shortage of effective service time caused by schedule earliness and tardiness.

tive service time before the lightpath starts. The shortage of effective service time caused by schedule earliness and tardiness is shown in Fig. 1. The penalty margin should reflect the network operator's decreased tolerance level as the timing of the lightpaths moves away from their desired timing windows. In this paper, we adopt earliness and tardiness penalties defined in [45]:

$$E_{sdn} = \begin{cases} y_{sdn} \times (b_{sdn} - \beta_{sdn})^2 & \text{if } \beta_{sdn} < b_{sdn} \\ \text{(i.e., earliness penalty)} & \\ 0 & \text{if } b_{sdn} \leqslant \beta_{sdn} \leqslant b'_{sdn} \\ \text{(i.e., no penalty, since the lightpath starts} & \\ \text{within its desired starting time window)} & \\ r_{sdn} \times (\beta_{sdn} - b'_{sdn})^2 & \text{if } \beta_{sdn} > b'_{sdn} \\ \text{(i.e., tardiness penalty)} & \end{cases}, \quad l_{sdn} \in \mathcal{L}, \tag{2}$$

where y_{sdn} and r_{sdn} are the weights for earliness and tardiness penalties of l_{sdn}. Our earliness and tardiness penalties reflect a decreasing tolerance level as a scheduled lightpath moves away from its desired timing window (shown in Fig. 2). When y_{sdn} and r_{sdn} are set to infinitely large positive values and the resource costs are set to zero, this formulation then becomes the same as the fixed time-window scheduling problem in [14], which does not allow any timing violation. Note that other forms of the earliness and tardiness penalty functions can also be used within our framework.

The cost of routing l_{sdn} is denoted as C_{sdn} and defined as the total cost of using WCs and wavelength converters. We use this definition to illustrate that the cost of routing a lightpath is a weighted summation of certain parameters related to links and nodes. Such a definition may be extended to incorporate other parameters without changing the solution method proposed later in this paper.

$$C_{sdn} = \sum_{\beta_{sdn} \leqslant t < (\beta_{sdn}+t_{sdn})} \left(d_{ij} \times \sum_{e_{ij} \in \mathcal{E}} \sum_{0 \leqslant c < W} \delta_{ijct}^{sdn} + o_i \times \sum_{i \in \mathcal{V}} \phi_{it}^{sdn} \right), \quad l_{sdn} \in \mathcal{L}. \tag{3}$$

Our design variables are the admission status of all SSLDs (A), the starting time slots of all lightpaths (B), the RWA schemes for all lightpaths (Δ), and the allocations of the wavelength converter to all lightpaths (Φ). Our design variables are not completely independent. They represent three interrelated subproblems, i.e., lightpath request admissions, lightpath scheduling, and RWAs. Based on our assumption of the wavelength converter's installation structure, the allocations of wavelength converters to all lightpaths may be derived from the RWA schemes for all lightpaths.

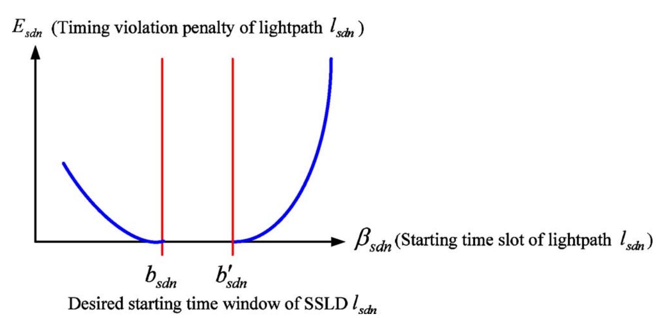

Fig. 2. (Color online) Example of earliness and tardiness penalties reflecting a decreasing tolerance level as a scheduled lightpath moves away from its desired timing window.

C. Constraints

1) Flow Conservation Constraints: If l_{sdn} is admitted, its RWA must be continuous along its path and be terminated at its two end nodes:

$$\sum_{j \in \mathcal{V}} \sum_{0 \leqslant c < W} \delta_{ijct}^{sdn} - \sum_{j \in \mathcal{V}} \sum_{0 \leqslant c < W} \delta_{jict}^{sdn} = \begin{cases} \alpha_{sdn} & \text{if } \beta_{sdn} \leqslant t < \beta_{sdn} + t_{sdn},\ i = s \\ -\alpha_{sdn} & \text{if } \beta_{sdn} \leqslant t < \beta_{sdn} + t_{sdn},\ i = d \\ 0 & \text{otherwise} \end{cases},$$

$$\forall l_{sdn} \in \mathcal{L}, \quad i \in \mathcal{V}. \tag{4}$$

If l_{sdn} is accepted (i.e., $\alpha_{sdn}=1$), at the source node (i.e., $i=s$), there is one lightpath going out; at the destination node (i.e., $i=d$), there is one lightpath coming in; at any intermediate node, this lightpath does not contribute to the number of lightpaths that terminate at this node. For any node that is not related to this lightpath, or when l_{sdn} is rejected (i.e., $\alpha_{sdn}=0$), this lightpath does not contribute to the number of lightpaths that terminate at the node. These constraints confine that, if and only if $\alpha_{sdn}=1$, during the lifespan of l_{sdn} (i.e., $\beta_{sdn} \leqslant t < (\beta_{sdn}+t_{sdn})$), there must be a lightpath from node s to node d.

2) Wavelength Conversion Constraints:

$$\phi_{jt}^{sdn} = \begin{cases} 1 & \text{if } \exists (m \in \mathcal{V},\ k \in \mathcal{V},\ b \neq c),\ \delta_{mjbt}^{sdn} = \delta_{jkct}^{sdn} = 1 \\ 0 & \text{otherwise} \end{cases},$$

$$\forall l_{sdn} \in \mathcal{L}, \quad j \in \mathcal{V}, \quad 0 \leqslant t < Z. \tag{5}$$

One wavelength converter on an intermediate node j is used only when different wavelengths are assigned to l_{sdn} for the incoming and outgoing wavelengths at this node.

3) Exclusive WC Usage Constraints:

$$\sum_{l_{sdn} \in \mathcal{L}} \delta_{ijct}^{sdn} \leqslant 1, \quad \forall e_{ij} \in \mathcal{E}, \quad 0 \leqslant c < W, \quad 0 \leqslant t < Z. \tag{6}$$

Every WC at any time slot t cannot be used by more than one lightpath.

4) Converter Quantity Constraints:

$$\sum_{l_{sdn} \in \mathcal{L}} \phi_{jt}^{sdn} \leqslant F_j, \quad \forall j \in \mathcal{V}, \quad 0 \leqslant t < Z. \tag{7}$$

The number of occupied converters on node j at any time slot t must not be more than the number of converters installed on the node.

5) Lightpath Persistency Constraints:

$$\delta_{ijcx}^{sdn} = \delta_{ijcy}^{sdn}, \quad \forall\, l_{sdn} \in \mathcal{L}, \quad e_{ij} \in \mathcal{E}, \quad \beta_{sdn} \leqslant x < \beta_{sdn} + t_{sdn}, \quad \beta_{sdn} \leqslant y < \beta_{sdn} + t_{sdn} \tag{8}$$

During the lifespan of l_{sdn}, its RWA scheme must remain the same for all time slots. Note that when combined with wavelength conversion constraints, the allocation of the wavelength converters ϕ_{jt}^{sdn} stays the same, too.

IV. A Solution Based on the Lagrangian Relaxation and Subgradient Methods

A. Overview of Existing Solution Methods for Static Lightpath Scheduling Problems

Existing static lightpath scheduling problems are solved by different methods such as heuristics. As explained in our introduction, the existing problems assume simple cases where a lightpath starts either at its given time or within its given time window. Our problem is different from these problems by allowing a lightpath to slide beyond its desired time window but with an increasing penalty as it moves further away. Therefore, solving our problem is more challenging due to the additional flexibility in allowing extra timing violation. In Table I, we summarize the solution methods for the static lightpath scheduling problems where an SSLD must start at its specified starting time; otherwise the SSLD is rejected. In Table II, we summarize the solution methods for the static lightpath scheduling problems where an SSLD is allowed to slide within its specified time window; otherwise it is rejected.

The Lagrangian relaxation and subgradient methods (LRSM) have demonstrated their potential in solving large-scale optimization problems such as the static RWA problem [46–49], traffic grooming and multicast routing [50], network reconfiguration [41], the grade-of-service differentiated static RWA problem [44], the virtual path planning and packet routing problems in a layered network [51], and the two-layer routing problem [52,53]. For example, the pure static RWA problem in a mesh network with limited wavelength conversion capability was studied in [46]. A link-based formulation was proposed, considering the fairness of demand acceptance among different node pairs. The LRSM framework was used to solve the proposed network recon-

TABLE I
Solution Methods for the Static Lightpath Scheduling Problems Where a Lightpath Must Start at its Specified Starting Time

Solution Methods	References	Description of Solution Methods
Heuristic algorithm (for the joint problem)	[3]	Separately solving two subproblems: (1) routing and (2) wavelength assignment. For the routing subproblem, the branch-and-bound method is used to obtain the optimal solution, while Tabu search is used to obtain approximate solutions. For the wavelength assignment subproblem, a greedy vertex coloring algorithm is used. A heuristic algorithm is used to jointly solve the two subproblems, where demands are sorted first and then apply the fixed-alternate routing, followed by a first fit wavelength assignment to each demand.
Heuristic algorithm	[4]	A global random search algorithm to compute RWA schemes that minimize the number of rejected SSLDs
Simulated-annealing-based method	[5]	A simulated-annealing algorithm iteratively explores the solution space until a stopping condition is satisfied
Branch-and-bound method	[6]	Use the branch-and-bound method for solving integer linear programming problems, provided by the CPLEX software package
Heuristic algorithm	[7,8]	Sort demands by one of the four policies and then assign costs to wavelength links before searching for working and protection paths. Demand sorting policies: earliest-setup demand first, earliest-teardown demand first, most-conflicting demand first, least-conflicting demand first
Heuristic algorithm assisted by CPLEX	[9]	Precompute candidate paths for each demand and then use CPLEX to obtain the best path selection from the candidate paths for all demands
Heuristic algorithm	[10]	Partition demands into disjoint (in time or in edge) groups. The demands in the same group are routed at the same time and are assigned the same wavelength.
Heuristic algorithm	[11]	Sort demands in ascending order of their starting time, then use greedy heuristics to allocate resources to each demand
Heuristic algorithm	[12]	Partition demands into groups (time-disjoint in one algorithm, time-overlapping in the other algorithm) and then route groups of demands
Heuristic algorithm	[13]	Partition demands into time-disjoint groups and then search for paths sharing links of previously selected paths for the demands in the same group to increase the number of link-disjoint paths available to the demands in other groups
Lagrangian-relaxation-based method	[14,15]	The constraints of no overbooking on any WC at any time slot are relaxed to create a dual problem. The solution to the dual problem is a performance bound of the original problem. Then, the solution to the dual problem and the generated Lagrangian multipliers are used to develop heuristic algorithms for achieving a near-optimal solution to the original problem.

TABLE II
SOLUTION METHODS FOR THE STATIC LIGHTPATH SCHEDULING PROBLEMS WHERE A LIGHTPATH IS ALLOWED TO SLIDE WITHIN ITS SPECIFIED TIME WINDOW

Solution Methods	References	Description of Solution Methods
Heuristic algorithm assisted by CPLEX	[16,17]	Schedule demands optimally in time by CPLEX and then use existing methods (e.g., methods in Table I) for the subproblem where a lightpath must start at its specified starting time
Heuristic algorithm	[18,19]	Three steps: (1) dividing SSLDs into disjoint windows, (2) using a greedy-window-based RWA algorithm on all SSLDs, and (3) rearranging the SSLDs that are not satisfied in step (2)
Heuristic algorithm	[20]	Heuristic algorithm to schedule SSLDs and to assign wavelength to lightpaths in a single-fiber
Heuristic algorithm	[21]	Partitioning SSLDs into time-disjoint groups
Heuristic algorithm	[22–24]	Heuristic algorithm to jointly schedule lightpaths and to allocate resources

figuration problem. Great computational efficiency has been demonstrated when compared with other existing algorithms. Despite the advances made by the LRSM in the static RWA problems, lightpath scheduling cannot directly adopt the same approach because the static RWA problem does not consider the timing attribute.

A simple formulation employing the LRSM for lightpath scheduling was presented in [14,15] to maximize the network revenue. However, the formulation provided only allows simple network decisions, i.e., to reject/accept a lightpath demand if the time constraint is not satisfied without any tolerance of the timing violation, which makes network scheduling inflexible. Moreover, no wavelength conversion or the penalty of network resource usage was considered, and thus only limited network parameters can be controlled in the scheduling.

B. Application of the Lagrangian Relaxation and Subgradient Methods to the Static Lightpath Scheduling and RWA Problem

Our formulated problem faces a big challenge in computing its optimal solution because of the large number of design variables and constraints. For a network with N nodes, E links, W wavelengths, Z time slots, and L SSLDs, our formulation uses $|A|+|B|+|\Delta|+|\Phi|=L+L+L\times Z\times E\times W+L\times Z\times N$ binary integer variables, where $|\cdot|$ denotes the number of elements in the set. The number of constraints in our formulation is very large too (shown in Table III). Consequently, finding the exact optimal solution for a medium-size problem is infeasible even for the static RWA problem

TABLE III
NUMBER OF CONSTRAINTS IN OUR FORMULATION

Type of Constraints	Number of Constraints
Flow conservation constraints in Eq. (4)	$L\times N\times Z$
Wavelength conversion constraints in Eq. (5)	$L\times N\times Z$
Exclusive WC usage constraints in Eq. (6)	$E\times W\times Z$
Converter quantity constraints in Eq. (7)	$N\times Z$
Lightpath persistency constraints in Eq. (8)	$L\times E\times Z\times(Z-1)$

[46], which is only a simplified version of our current problem by setting Z (the number of time slots) to 1. Thus, we aim at obtaining near-optimal solutions to our problem, while providing a tight performance bound that can be used to evaluate the optimality of our solutions.

We propose a method based on the LRSM and derive a dual problem (DP) by using the Lagrangian relaxation (LR) method. We solve the DP using the subgradient method. Then, we project the DP's solution to a feasible solution to the original problem by using a proposed heuristic algorithm. The overall flow chart is shown in Fig. 3. The advantage of solving the problem in the dual space first is that the DP is a convex integer problem, which can be efficiently solved by the subgradient method, while there is no convenient way to solve the original problem directly [54]. The application of the subgradient method is illustrated in Fig. 4. Note that the solution space and dual space use different variables and might have different dimensions of the solution space as well.

The computational time complexity of our proposed method is polynomial with respect to all design variables, in contrast to the exponential time complexity of the branch-and-bound method used in CPLEX, e.g., $O(K^L)$, where K is a predefined integer constant ($K\geqslant 2$). Unlike heuristic algorithms, our LRSM provides a theoretical performance bound and a feasible near-optimal solution at the same time. The duality gap, which indicates the optimality of a near-optimal solution, is well controlled.

The LR method is used to derive the DP of the original problem. The derivation details are given in Appendix A. We define the dual routing cost of l_{sdn} as D_{sdn}:

$$D_{sdn}=\min_{\beta_{sdn},\Delta_{sdn},\Phi_{sdn}}\Bigg(E_{sdn}+\sum_{e_{ij}\in\mathcal{E}}\sum_{0\leqslant c<W}\sum_{\beta_{sdn}\leqslant t<\beta_{sdn}+t_{sdn}}\delta_{ijct}^{sdn}(\xi_{ijct}+d_{ij})+\sum_{i\in\mathcal{V}}\sum_{\beta_{sdn}\leqslant t<\beta_{sdn}+t_{sdn}}\phi_{it}^{sdn}(\pi_{it}+o_i)\Bigg),$$

$$\forall l_{sdn}\in\mathcal{L}. \tag{9}$$

Then, the dual problem in Eq. (A7) (see Appendix A) may be simplified as

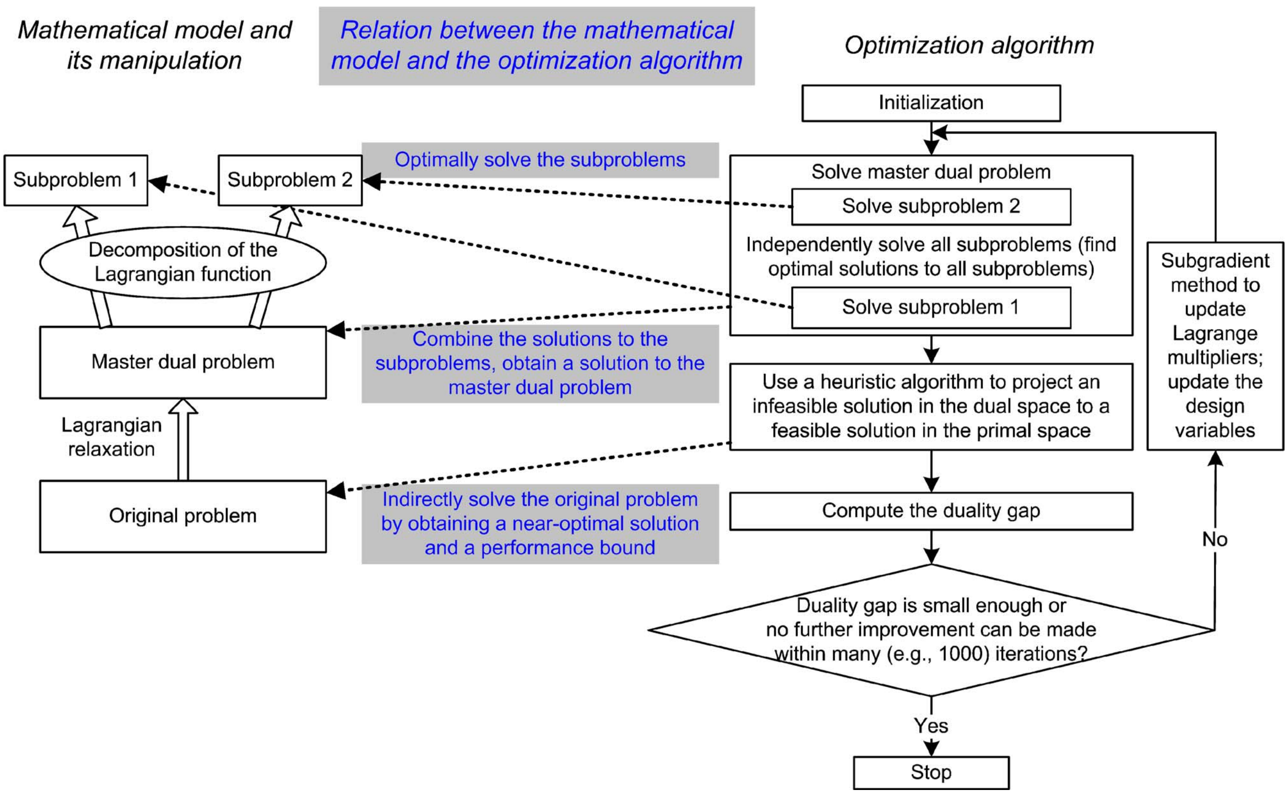

Fig. 3. (Color online) Illustration of our solution framework and its relation to the mathematical model.

$$\sum_{l_{sdn}\in\mathcal{L}} \{\min_{\alpha_{sdn}}[(1-\alpha_{sdn})P_{sdn}+\alpha_{sdn}D_{sdn}]\}, \qquad (10)$$

which we refer to as the relaxed problem.

We are able to decompose the overall relaxed problem into independent subproblems. The total number of the subproblems is L, each corresponding to l_{sdn}. The decision on α_{sdn} is straightforward based on the penalty P_{sdn} for rejecting l_{sdn} and dual routing cost D_{sdn} of l_{sdn} (may be thought of as the penalty for accepting l_{sdn}). A lower penalty should be chosen: if $P_{sdn} > D_{sdn}$, we set α_{sdn} to 1 (i.e., l_{sdn} is accepted); otherwise, we set α_{sdn} to 0. We break a tie arbitrarily.

C. Algorithm for Obtaining Dual Routing Cost

The dual routing cost D_{sdn} in Eq. (9) may be simplified as

$$D_{sdn} = \min_{\beta_{sdn}}\left\{E_{sdn} + \min_{\Delta_{sdn},\Phi_{sdn}}\left[\sum_{e_{ij}\in\mathcal{E}}\sum_{0\leq c<W}\sum_{\beta_{sdn}\leq t<\beta_{sdn}+t_{sdn}} \delta_{ijct}^{sdn}(\xi_{ijct} + d_{ij}) + \sum_{i\in\mathcal{V}}\sum_{\beta_{sdn}\leq t<\beta_{sdn}+t_{sdn}} \phi_{it}^{sdn}(\pi_{it}+o_i)\right]\right\} \quad \forall\, l_{sdn}\in\mathcal{L}, \qquad (11)$$

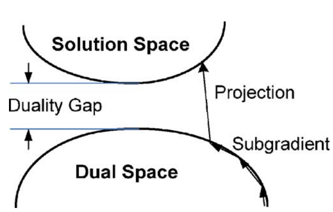

Fig. 4. (Color online) Application of the subgradient method in the dual space.

subject to the constraints (4) and (5).

To obtain the dual routing cost D_{sdn} for a given l_{sdn}, we propose an algorithm to optimize the scheduling and RWA for the lightpath, i.e., to decide its starting time slot β_{sdn}, as well as its RWA scheme Δ_{sdn} and Φ_{sdn}. Our proposed algorithm calculates an augmented property attribute (called "accumulated dual cost" or ADC) of each resource, and then uses the shortest path algorithm on wavelength graph (SPAWG) to solve the second part of D_{sdn} in Eq. (11), i.e., the RWA scheme optimization:

$$\min_{\Delta_{sdn},\Phi_{sdn}}\left[\sum_{e_{ij}\in\mathcal{E}}\sum_{0\leq c<W}\sum_{\beta_{sdn}\leq t<\beta_{sdn}+t_{sdn}} \delta_{ijct}^{sdn}(\xi_{ijct}+d_{ij}) + \sum_{i\in\mathcal{V}}\sum_{\beta_{sdn}\leq t<\beta_{sdn}+t_{sdn}} \phi_{it}^{sdn}(\pi_{it}+o_i)\right]. \qquad (12)$$

For a given resource (e.g., a WC or a wavelength converter), its accumulated dual cost relates to its two usage parameters: the starting time and the duration of using it. When a resource's corresponding Lagrange multiplier is given, its accumulated dual cost is fixed and is represented by a trimmed two-dimensional array. No matter which lightpath uses the resource, the accumulated dual cost does not change. Thus for a given set of all resources' Lagrange multipliers, the accumulated dual costs are calculated once and are presented to all lightpaths for the lightpaths. When solving the DP, we choose resources for lightpaths based on the accumulated dual costs of the resources. The competition among lightpaths for the same resource is reflected by the Lagrange multiplier of the resource, which will be discussed shortly in Subsection IV.D.

The accumulated dual cost $\hat{\xi}_{ijc}^{\beta,T}$ of using a WC c ($0 \leq c < W$) on fiber e_{ij} ($e_{ij} \in \mathcal{E}$) is

$$\hat{\xi}_{ijc}^{\beta,T} = \sum_{\beta \leq t < \beta+T} (\xi_{ijc,t} + d_{ij}), \quad \forall e_{ij} \in \mathcal{E}, \quad 0 \leq c < W, \quad (13)$$

where β denotes the starting time slot of using the WC, and T denotes the duration of using it.

Similarly, the accumulated dual cost $\hat{\pi}_i^{\beta,T}$ of using a wavelength converter on node i ($i \in \mathcal{V}$) is

$$\hat{\pi}_i^{\beta,T} = \sum_{\beta \leq t < \beta+T} (\pi_{i,t} + o_i), \quad \forall i \in \mathcal{V}. \quad (14)$$

We incrementally calculate $\hat{\xi}_{ijc}^{\beta,T}$ and $\hat{\pi}_i^{\beta,T}$ as the starting time slot β increases by reusing the calculated results from the previous time slot, except for the initial time slot (i.e., $\beta=0$).

To obtain the dual routing cost in Eq. (11), we compare the dual routing cost for all possible starting time slots. Since the accumulated dual cost of all resources are calculated, we use the SPAWG to solve the second part of D_{sdn} in Eq. (11), which is now simplified as $\min_{\Delta_{sdn},\Phi_{sdn}}[\Sigma_{e_{ij}\in\mathcal{E}}\Sigma_{0\leq c<W}\hat{\xi}_{ijc}^{\beta,T} + \Sigma_{i\in\mathcal{V}}\hat{\pi}_i^{\beta,T}]$ by using the definition of the accumulated dual cost of WCs in Eq. (13) and wavelength converters in Eq. (14). Essentially, the SPAWG is a shortest path algorithm customized for WDM networks [46]. In this way, the optimal scheduling and RWA scheme for a given lightpath is obtained by solving the dual routing cost in Eq. (11).

For each l_{sdn}, we define its *dual profit* to be $(P_{sdn} - D_{sdn})$. We sort all the possible β_{sdn}'s for l_{sdn} based on its *dual profit* in the dual solution and create a list SL_{sdn}. This sorted list will be used in our heuristic algorithm later in Subsection IV.E.

D. Updating Lagrange Multipliers

We employ the subgradient method to solve the DP maximization. The subgradient method [54] is only useful for integer programming problems. Since all our variables are integers, the subgradient method is applicable to our problem.

The variables of the DP are Lagrange multipliers, which we represent as a multiplier vector $z=(\xi,\pi)$. The vector is updated by the following formula:

$$z^{(h+1)} = z^{(h)} + \alpha^{(h)} g(z^{(h)}), \quad (15)$$

where $z^{(h)}$ denotes the value of the vector z obtained at the hth iteration, and $\alpha^{(h)}$ denotes the step size of the hth iteration. The vector $g(z)$ is the subgradient of the dual function q with respect to z, i.e., $g(z)=(g(\xi),g(\pi))$. The vectors $g(\xi)$ and $g(\pi)$ are composed of $g(\xi_{ijct})$ and $g(\pi_{it})$, respectively, where

$$g(\xi_{ijct}) = \sum_{l_{sdn}\in\mathcal{L}} \delta_{ijct}^{sdn} - 1, \quad \forall e_{ij} \in \mathcal{E}, \quad 0 \leq c < W, \quad 0 \leq t < Z, \quad (16)$$

$$g(\pi_{it}) = \sum_{l_{sdn}\in\mathcal{L}} \phi_{it}^{sdn} - F_i, \quad \forall j \in \mathcal{V}, \quad 0 \leq t < Z. \quad (17)$$

The updating process of the vector is illustrated in Fig. 5, where in each iteration, the variables move along the direction of their subgradient for a distance determined by its step size. Z^* denotes the optimal solution. The step size is calculated by

$$\alpha^{(h)} = \mu \times \frac{q^U - q^{(h)}}{g^T(z^{(h)})g(z^{(h)})}, \quad (18)$$

where q^U is an estimate of the optimal solution (which we take the best value of the objective function J obtained), $q^{(h)}$ is the value of q at the hth iteration, and g^T is the transpose of g. The parameters μ and q^U are changed adaptively as the algorithm converges. Convergence can also be speeded up by using the method in [46].

E. Constructing a Feasible RWA Scheme

The DP's solution may be infeasible for the original problem because some of the original constraints are relaxed. In other words, the exclusive WC usage constraints in Eq. (6) and the converter quantity constraints (7) might be violated in the DP's solution. Note that all other constraints are satisfied, which is ensured by the DP's solution procedure provided in Subsections IV.B and IV.C.

To facilitate our heuristic algorithm, we define two attributes for each resource: continuous availability and accumulated cost. Similar to the definition of the ACD described in Subsection IV.C, the two new attributes relate to a given resource's two usage parameters, i.e., the starting time and the duration of using this resource, Moreover, both attributes are independent of the routing of lightpaths and may be represented by a trimmed two-dimensional array.

The continuous availability of a resource is defined as its minimal capacity from a given starting time through the duration of using it. The continuous availability of a WC c ($0 \leq c < W$) on fiber e_{ij} ($e_{ij} \in \mathcal{E}$) is denoted as $\hat{\delta}_{ijc}^{\beta,T}$ and is calculated as

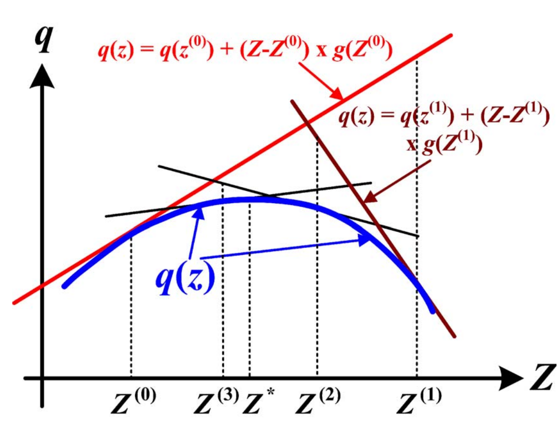

Fig. 5. (Color online) Updating the variables by using the subgradient method.

$$\hat{\delta}_{ijc}^{\beta,T} = \min_{\beta \le t < \beta+T}\left(1 - \sum_{l_{sdn}\in\mathcal{L}} \delta_{ijc,t}^{sdn}\right), \quad \forall\, e_{ij} \in \mathcal{E}, \quad 0 \le c < W, \tag{19}$$

where β denotes the starting time slot of using the WC, and T denotes the duration of using it.

Similarly, the continuous availability of a wavelength converter on node i ($i \in \mathcal{V}$) is denoted as $\hat{\phi}_i^{\beta,T}$ and is calculated as

$$\hat{\phi}_i^{\beta,T} = \min_{\beta \le t < \beta+T}\left(F_i - \sum_{l_{sdn}\in\mathcal{L}} \phi_{i,t}^{sdn}\right), \quad \forall\, i \in \mathcal{V}. \tag{20}$$

As the counterpart of the accumulated dual cost defined in the dual problem space, we define the accumulated cost in the primal problem space. The accumulated cost of using a WC on fiber e_{ij} ($e_{ij} \in \mathcal{E}$) is denoted as $\hat{d}_{ij}^{\beta,T}$ and is calculated as

$$\hat{d}_{ij}^{\beta,T} = \sum_{\beta \le t < \beta+T} d_{ij}, \quad \forall\, e_{ij} \in \mathcal{E}. \tag{21}$$

Similarly, the accumulated cost of using a wavelength converter on node i ($i \in \mathcal{V}$) is denoted as $\hat{o}_i^{\beta,T}$ and is calculated as

$$\hat{o}_i^{\beta,T} = \sum_{\beta \le t < \beta+T} o_i, \quad \forall\, i \in \mathcal{V}. \tag{22}$$

We propose a heuristic algorithm to construct a feasible scheduling and RWA scheme based on the obtained DP's solution. Using our heuristic algorithm, we determine

- which SSLDs should be rejected, rescheduled, or rerouted;
- which starting time slots the rescheduled lightpaths should take;
- which paths and WCs the rerouted lightpaths should take.

We sort SSLDs according to our proposed SSLD priority rules and then sequentially search for feasible scheduling and RWA schemes for the sorted SSLDs. We set two SSLD priority rules: (1) an accepted SSLD in the dual solution has higher priority over a rejected SSLD in the dual solution, and (2) the priority of accepted SSLDs in the dual solution is determined based on their dual profit (defined in the solution to the relaxed problem in Subsection IV.B). We break a tie arbitrarily. Our algorithm is shown in the flow chart in Fig. 6. For l_{sdn}, we decide its best scheduling based on its dual profit, which is stored in the sorted list SL_{sdn}. Then, for a given starting time slot of l_{sdn}, we adopt the heuristic algorithm called the feasible route searching algorithm (FRSA) proposed in [46] to obtain a feasible RWA scheme. If no feasible RWA scheme is found, the next-best scheduling for the same l_{sdn} is tried until all possible starting time slots are searched or a feasible scheduling and RWA scheme is found. The FRSA is implemented on the wavelength graph of the network, which is formed by separating every node into W vertices representing the wavelengths available on the node and connecting these vertices with arcs representing the WCs and the wavelength converters. The details to form the wavelength graph can be found in Appendix B of [46], while the availability and the weight (WE_{ijc}) of a resource should be replaced by the continuous availability and the accumulated cost, respectively.

F. Analysis of Computation Complexity

The total computation complexity of our algorithm is determined by two factors: the total number of iterations and the complexity of computing solutions within each iteration. Our algorithm uses iterations to improve the quality of solutions. The convergence of the iterations is very efficient. Because in the worst case the total number of iterations is limited to a constant, we are able to simplify the analysis of computation complexity to a single iteration. Within each iteration, the computation complexity is determined by two factors: the complexity of computing the DP's solution and the complexity of the heuristic algorithm in constructing a feasible solution.

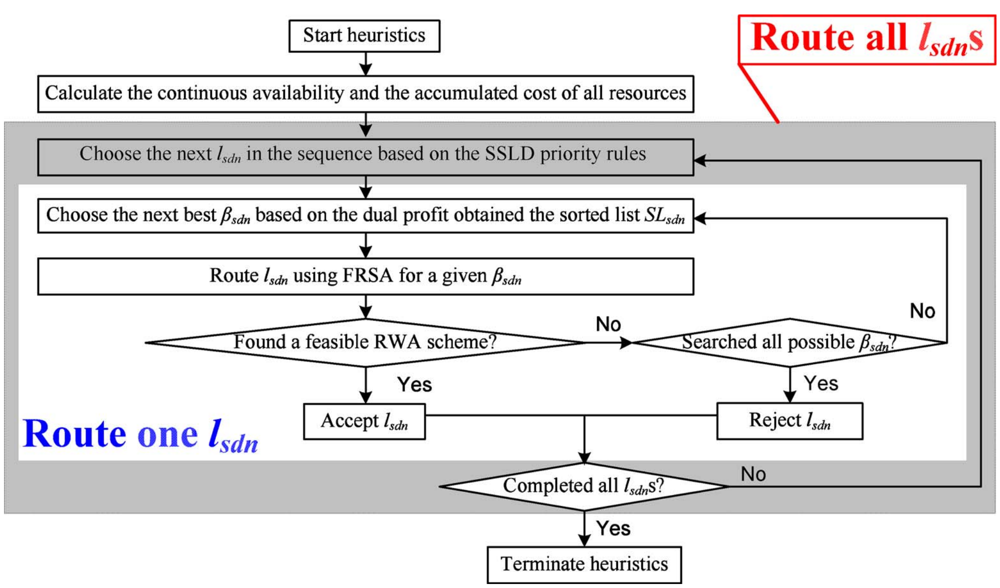

Fig. 6. (Color online) Flow chart of our heuristic algorithm to obtain a feasible scheduling and RWA solution.

The computation of the DP's solution has the computation complexity of $O((N+W)N^2WZ+(N+WE)Z^2)$. The optimal dual solution is achieved when all the subproblems are minimized. The computation complexity of the accumulated dual cost for a given starting time and a given holding time is $O(N+WE)$. There are altogether $Z(Z-1)$ combinations of starting time and holding time, which result in a computation complexity of $O((N+WE)Z^2)$ in calculating all combinations of the accumulated dual cost. The complexity of solving each dual routing cost D_{sdn} for a given starting time β_{sdn} is the same as the complexity of the modified minimum-cost semilightpath [46], i.e., $O((N+W)NW)$. By grouping the D_{sdn}'s with the same source node, the complexity of solving all D_{sdn}'s is $O((N+W)N^2W)$. We need to solve it for every possible starting time β_{sdn}, and thus the overall complexity to solve all dual routing costs is $O((N+W)N^2WZ)$. The total complexity of solving the DP is $O((N+W)N^2WZ+(N+WE)Z^2)$.

The heuristic algorithm to construct a feasible solution has the computation complexity of $O(L^3\log L+L^2(NW)^2+L(N+WE)Z^3+LZ\log Z)$. The computation complexity of the continuous availability for a given starting time and a given holding time is $O((N+WE)Z)$. There are altogether $Z(Z-1)$ combinations of starting time and holding time, which result in a computation complexity of $O((N+WE)Z^3)$ in calculating all combinations of the continuous availability. The complexity of the FRSA is $O(L^2\log L+L(NW)^2)$, which was analyzed in [46]. The time complexity for the sorting operation is $O(Z\log Z)$. Therefore the overall complexity of the heuristic algorithm is $O(L^3\log L+L^2(NW)^2+L(N+WE)Z^3+LZ\log Z)$.

Our algorithm has a polynomial computation complexity with respect to all design variables. The total complexity of our algorithm is dominated by the total number of SSLDs and the total number of time slots. In Table IV, we show a comparison with some solution methods for the static lightpath scheduling problems where a lightpath must start at its specified starting time. Since our problem allows sliding in the time window and scheduling beyond the desired time window, our computation complexity highly depends on the total number of time slots.

TABLE IV
COMPUTATION COMPLEXITY FOR THE STATIC LIGHTPATH SCHEDULING PROBLEMS WHERE A LIGHTPATH MUST START AT ITS SPECIFIED STARTING TIME

Solution Methods	References
Branch and bound	In [3], $O((K_{MAX})^L)$ for the lightpath routing subproblem, where K_{MAX} denotes the maximum number of alternative paths between a given node pair. Note that its complexity is exponential with respect to the number of SSLDs.
Heuristic algorithms	In [10], $O(N^3+L\log(L)+L^2N^2)$ for its constructive heuristics (which end deterministically); in [18], $O(L^2(EW+N\log N))$.

G. Evaluation of a Feasible Scheduling and RWA Scheme

We use the duality gap to evaluate the quality of our solutions. The duality gap is defined as (J^*-q^*), where J^* denotes the optimal value of the optimization objective, and q^* denotes the optimal value of the dual function. The value of the objective function J of any feasible solution obtained is an upper bound on the optimal objective J^*. The DP's optimal solution q^*, on the other hand, is a lower bound of J^*. The value of the dual function q of any DP's solution is a lower bound of q^*. In conclusion, the value $(J-q)$ provides an upper bound of the duality gap. Even without obtaining the exact optimum, we are able to estimate the distance of our suboptimal solution to the optimal solution. We are ensured, by using the duality gap, that our near-optimal solution is within a certain range from the optimum. The readers are referred to [46] for the performance comparison of LR with other methodologies.

V. PERFORMANCE EVALUATION

We evaluate the performance of our algorithm in a network example operating under randomly generated traffic patterns. Our example network is a mesh topology network (i.e., NSFNET) with 14 nodes and 21 links. Its topology is shown in Fig. 7, which marks the sequence number of nodes and links. In this section, we present results for one particular traffic pattern. Please note that the performance of our optimization framework is not contingent upon the statistical property of the traffic and the same trends are observed under several other traffic matrices, as well as various network topologies. The number of SSLDs for all node pairs is shown in Table V, where the number on the ith row and the jth column represents the total number of SSLDs from node i to j over all the time slots. We randomly assign their values between 0 and 3. The total number of SSLDs is 286. Their timing requirement is shown in Table VI, which is also randomly generated. The array at the ith row and the jth column represents the timing and duration requirements of SSLDs from node i to j. In an array, each row represents one SSLD, where the first number is its earliest desired starting time slot, the second number is its latest desired starting time slot, and the third number is its duration.

In our first example, we study how timing flexibility improves network resource utilization and reduces rejections. We first fix the tardiness penalty and study the impact of the earliness penalty. We vary the weight of the earliness penalty for SSLDs, so that when an SSLD's starting time is

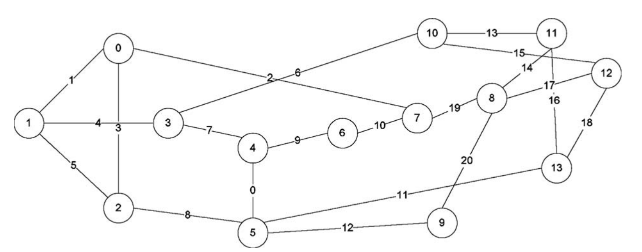

Fig. 7. Example network for performance evaluation (NSFNET with 14 nodes and 21 links).

TABLE V
NUMBER OF SSLDS FOR ALL NODE PAIRS

0	1	3	1	3	1	3	0	2	0	3	2	0	3
0	0	0	2	0	1	0	0	1	0	1	0	0	3
3	0	0	3	0	1	2	3	2	3	1	2	3	0
3	1	0	0	1	1	2	3	2	2	3	2	0	3
1	0	1	2	0	3	3	2	0	3	3	1	1	3
1	2	1	3	2	0	1	3	3	1	2	1	0	2
3	1	2	3	3	3	0	3	3	1	3	2	3	3
0	0	0	0	1	0	3	0	0	1	3	0	2	0
3	0	1	3	3	3	3	0	0	2	3	1	1	2
0	0	0	1	2	0	2	0	1	0	1	0	0	3
1	0	0	2	0	3	1	1	0	3	0	3	0	3
2	3	1	1	3	2	3	2	2	2	3	0	1	3
2	0	0	0	0	1	2	0	3	0	2	0	0	3
1	3	0	2	3	2	3	3	1	2	3	3	3	0

earlier than its desired starting time, an earliness penalty is incurred. We introduce two measurements of timing violation: the sum of earliness violations (SEV) and the sum of tardiness violations (STV), defined as

Sum of Earliness Violations (SEV)

$$= \sum_{l_{sdn} \in \mathcal{L}} \min\{0, (b_{sdn} - \beta_{sdn})\}, \tag{23}$$

Sum of Tardiness Violations (STV)

$$= \sum_{l_{sdn} \in \mathcal{L}} \min\{0, (\beta_{sdn} - b'_{sdn})\}. \tag{24}$$

In Fig. 8, we present the trade-off between SEV and the number of rejected SSLDs, as the weight of the earliness penalty y_{sdn} increases. The SEV decreases as the number of rejections increases, which indicates that fewer time violations may be achieved at the cost of more rejections. For a total of 286 SSLDs, an increase of SEV from 0 to 55 results in a reduction of rejected SSLDs from 9 to 3. If no timing violation is allowed, the weight of earliness penalty y_{sdn} needs to be above 50 with the current parameter setting (shown on the top of the figure). In such a situation, the result is the same as the traditional sliding window scheduling. As the earliness penalty varies, the achieved optimization objective and its bound remain almost unchanged (shown in Fig. 9). The duality gap is constantly lower than 5%, and the values have some minor changes only when the weight of the earliness penalty y_{sdn} approaches 0.

We fix the earliness penalty and study the impact of the tardiness penalty by varying the weight of the tardiness penalty r_{sdn} for SSLDs. In Fig. 10, we show the trade-off between STV and the number of rejected SSLDs as the weight of the tardiness penalty r_{sdn} increases. The achieved optimization objective and its bound are shown in Fig. 11. We observe a similar trend as shown in Figs. 8 and 9, which indicates that we may adjust either one of the two parameters or both to control timing violations, with minimal impact on the achieved optimization objective. Note that the optimality of the results is ensured by their tight lower bounds.

In our second example, we study the impact of the cost of WCs (denoted by d_{ij}). We set the parameters ($F_i=4$, $W=14$, $o_i=0$, $P_{sdn}=100$, $y_{sdn}=49$, $r_{sdn}=20$) and vary the cost of WCs. We grouped the SSLDs into three groups based on their holding time. We can see in Fig. 12 that as d_{ij} increases from

TABLE VI
TIMING AND DURATION REQUIREMENTS OF SSLDS FOR ALL NODE PAIRS

	0	1	2	3	4	5	6	7	8	9	10	11	12	13
0		0 3 4	6 8 3 2 9 5 5 9 3	5 8 4	0 3 3 1 6 3 3 5 3	0 5 4	4 8 4 1 6 4 2 6 3		6 9 3 2 8 5		7 9 3 1 5 4 6 9 3	6 9 3 4 7 4		2 6 5 3 7 3 0 5 3
1				2 6 3 5 9 4		3 7 3			3 9 4		5 8 3			3 8 5 4 7 4 1 8 4
2	4 9 5 2 6 3 3 7 3			4 9 3 1 8 5 2 5 4		7 9 3	7 9 3 1 6 3	3 7 3 5 7 3 4 9 5	5 7 3 2 6 5	4 8 4 0 9 5 4 8 4	2 7 5	3 8 3 2 8 5	1 9 5 3 9 4 0 7 5	
3	0 3 4 6 9 3 1 5 5	0 5 5			7 9 3	1 9 5	5 9 4 2 4 3	0 9 5 1 5 3 0 3 3	6 9 3 0 4 4	5 8 3 1 6 4	5 8 3 7 9 3 1 4 4	7 9 3 0 3 4		3 7 5 7 9 3 6 8 3
4	5 8 4		3 8 4	6 9 3 5 8 4		1 7 5 7 9 3 4 9 5	2 5 4 5 9 4 5 8 4	4 9 5 4 8 5		5 8 4 4 6 3 0 9 5	5 7 3 0 4 3 6 8 3	3 6 3	4 7 3	5 9 3 7 9 3 2 6 5
5	0 7 5	4 8 5 7 9 3	0 4 4	2 8 5 5 8 3 3 9 4	4 9 4 4 8 4		0 4 5	4 8 5 5 8 3 6 8 3	7 9 3 2 6 3 7 9 3	2 6 3	1 9 5 4 9 5	0 4 3		4 6 3 1 5 4
6	2 8 4 6 9 3 4 9 5	1 6 4	2 7 3 0 5 4	2 6 4 2 7 3 1 6 3	7 9 3 4 9 4 1 6 5	1 8 4 0 4 3 3 6 3		7 9 3 1 5 5 0 3 3	7 9 3 7 9 3 6 8 3	2 6 3	7 9 3 4 8 3 7 9 3	0 7 5 6 8 3	1 4 4 3 7 3 6 9 3	5 9 4 4 8 5 5 9 4
7					0 7 5		5 8 3 7 9 3 1 8 5			2 7 5	5 7 3 1 8 4 0 6 5		0 5 5 7 9 3	
8	1 4 4 6 8 3 2 6 5		2 4 3	1 8 4 7 9 3 5 9 4	3 8 5 1 6 4 3 8 5	4 7 4 3 6 4 6 8 3	3 6 4 1 5 3 3 8 4			3 8 5 6 8 3	7 9 3 7 9 3 4 8 4	5 7 3	2 9 4	5 9 4 3 9 4
9				2 7 4	2 8 5 5 8 4		1 5 3 7 9 3		0 5 5		4 8 4			5 7 3 0 3 3 2 6 5
10	3 7 3			5 9 3 4 8 4		0 3 4 7 9 3 5 9 4	5 8 3	0 5 5		0 5 3 1 4 3 0 5 4		4 8 5 2 9 5 4 8 5		4 8 5 2 4 3 4 7 4
11	0 7 4 7 9 3	4 9 5 4 7 4 6 9 3	4 9 4	5 7 3	2 6 4 6 9 3 0 7 5	7 9 3 7 9 3	1 8 5 7 9 3 5 8 3	2 6 3 6 9 3	3 8 3 6 8 3	4 9 4 1 9 5	0 6 4 1 4 3 5 9 4		2 6 5	5 7 3 7 9 3 6 8 3
12	0 6 4 2 7 4					0 6 4	2 9 4 4 7 4		3 6 3 6 8 3 4 9 5		6 8 3 6 9 3			6 9 3 7 9 3 3 6 3
13	6 8 3	0 6 4 0 3 3 5 8 4		1 4 3 0 7 5	0 7 5 3 5 3 3 9 4	0 4 5 5 9 4	3 6 3 6 8 3 4 9 3	6 8 3 5 9 4 5 9 4	5 8 3	2 8 4 1 6 4	7 9 3 4 9 4 5 8 4	5 9 4 7 9 3 3 9 5	1 3 3 5 9 4 0 3 4	

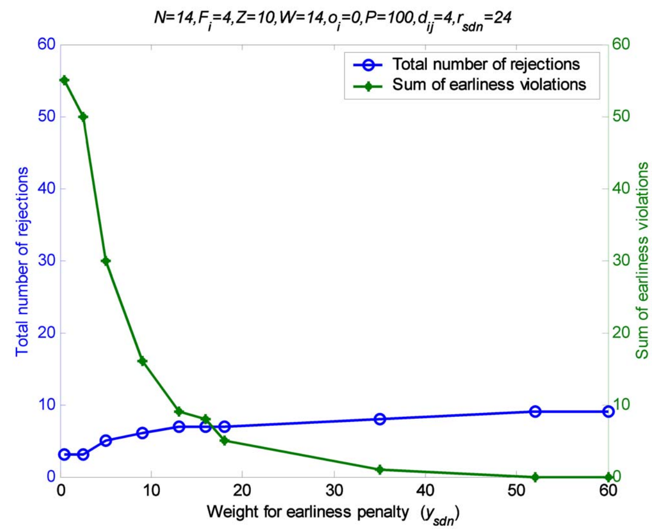

Fig. 8. (Color online) Number of rejected SSLDs versus the earliness violations as y_{sdn} varies.

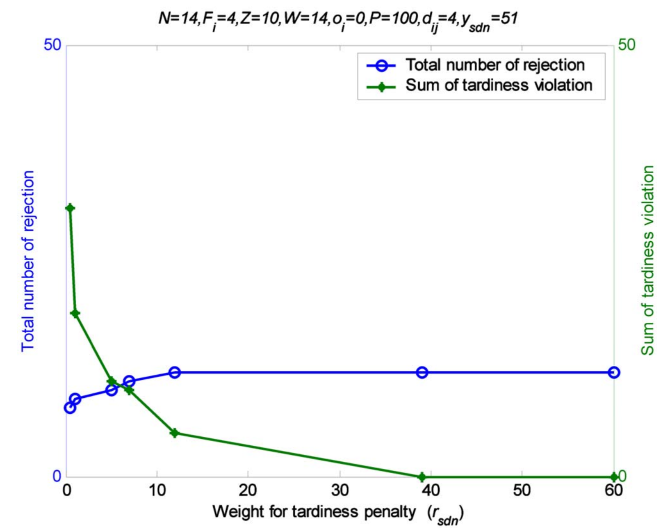

Fig. 10. (Color online) Number of rejected SSLDs versus the tardiness violations as r_{sdn} varies.

0 to 40, the average hop counts of each group drop at different rates. We use hop count zero to denote the status at which all the associated SSLDs are rejected. As d_{ij} increases, the number of rejected SSLDs increases as shown in Fig. 13. In Fig. 14, we demonstrate that the performance of our scheduling results is mostly optimal for this study. The network operator can thus easily control the hop number of the routings by adjusting the d_{ij} value. Please note that we only set all P_{sdn}'s to the same value for the simplicity of our numerical experiments. Our model allows the easy control of fairness of the rejection/acceptance by adjusting the P_{sdn} values. The readers are referred to [44] for a complete study on the assignments of the P_{sdn}'s.

In our third example, we study wavelength conversion's impacts on the design objective and the reduction of rejected SSLDs. We set the cost of all wavelength converters to zero, i.e., $o_i = 0$, so that if a wavelength converter is available, there is no cost for a lightpath to use it. In each parameter setting, we compare two cases: no wavelength conversion and four wavelength converters available at each node. We show the achieved value of the design objective and its bound, the number of rejected SSLDs in Table VII. Our results show that wavelength conversion does not significantly improve the LR bound, but it helps our heuristic algorithm in finding a better feasible solution; thus a slightly better value of the design objective is achieved. In summary, the contribution of wavelength conversion for lightpath scheduling is minimal. Note that the total number of SSLDs is 286. Although fewer SSLDs are rejected with wavelength converters than without wavelength converters, the impact of wavelength converters on the optimization objective is insignificant considering the total number of SSLDs.

Our algorithm demonstrates consistent near-optimum optimized solutions under various network settings and traffic patterns. Duality gaps on other network topologies and traf-

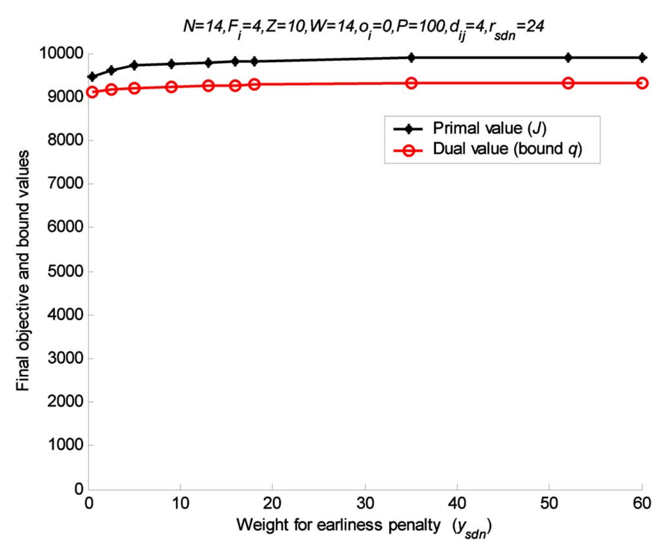

Fig. 9. (Color online) Achieved optimization objective and its bound as y_{sdn} varies.

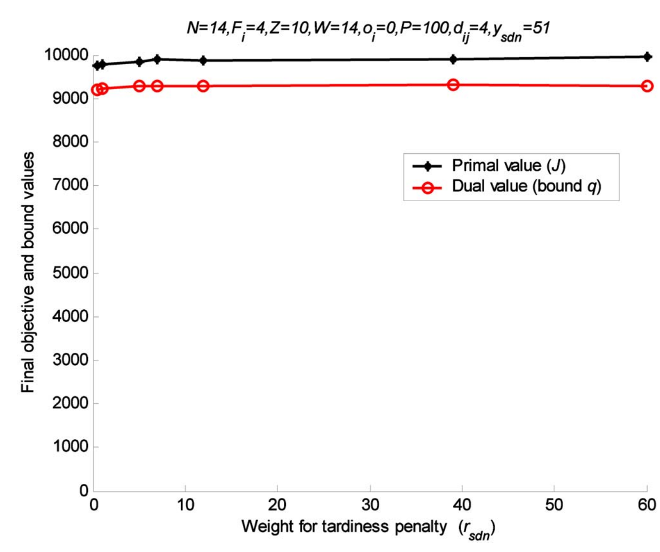

Fig. 11. (Color online) Achieved optimization objective and its bound as r_{sdn} varies.

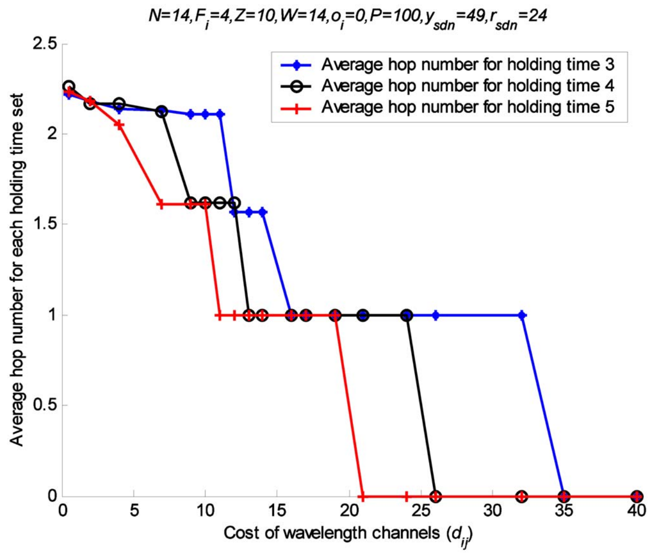

Fig. 12. (Color online) Impact of d_{ij} on the average hop count.

fic matrices are shown in Table VIII. Our simulation results for different network and traffic scenarios show the same trend of improvement of network resource utilization and rejection reductions by timing flexibility.

Most of our results for the NSFNET example are obtained within 3 hours of computation on a personal computer with Windows XP, Centrino 1.99 GHz CPU, and 1 GB RAM. The computation time complexity is much higher (although still polynomial) than the RWA algorithm in [46] due to the extra time dimension.

VI. Conclusions

In this paper, we have studied the benefits and trade-offs of using scheduled lightpaths for traffic adaptation. Knowing traffic patterns allows us to schedule lightpaths adaptively to the changing traffic at the network planning stage.

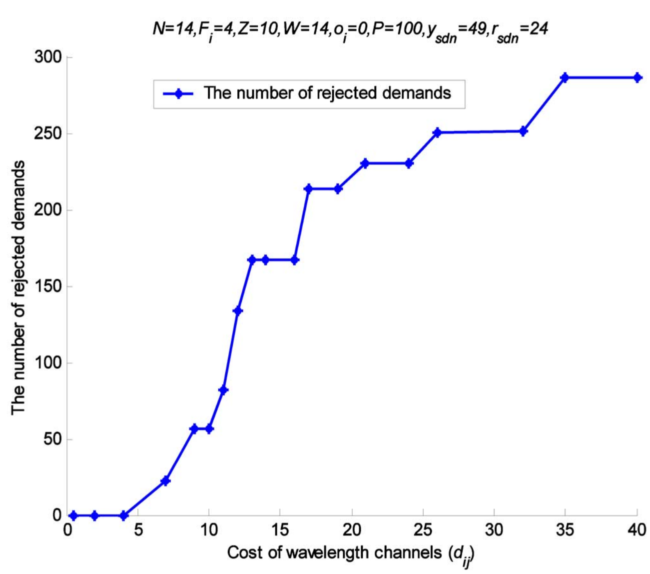

Fig. 13. (Color online) Impact of d_{ij} on the rejection of SSLDs.

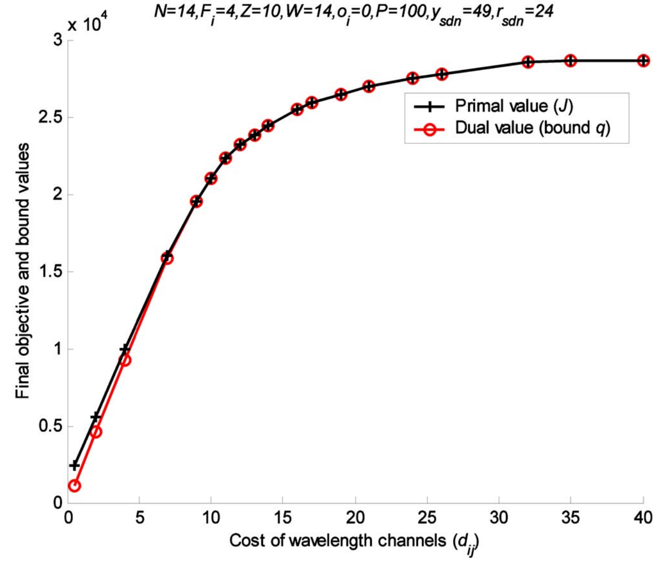

Fig. 14. (Color online) Achieved optimization objective and its bound as d_{ij} varies.

We proposed a network planning model as an optimization problem. Our model allows lightpaths to slide within their desired timing windows with no penalty on the optimization objective and to slide beyond their desired timing windows with a decreasing tolerance level. Our model quantitatively measures the timing satisfaction or violation.

We applied the Lagrangian relaxation and subgradient methods to the formulated optimization problem. Our methods demonstrated great computational efficiency when compared with other existing algorithms. We aimed at obtaining near-optimal solutions to our problem, while providing a tight performance bound that can be used to evaluate the optimality of our solution.

Our simulation results show how timing flexibility improves network resource utilization and reduces rejections. We also studied the impact of the cost of network resources on the optimization objective. Our future work includes studying the variable holding time.

Appendix A

We choose to relax the exclusive WC usage constraints (6) and converter quantity constraints (7). The reason for choosing these constraints to relax is that the derived DP can thus be decomposed into independent subproblems, whose optimal solutions can be easily obtained. Associated with the Lagrangian relaxation, additional elements are added into the primal function J by using the corresponding Lagrange multipliers ξ_{ijct} ($e_{ij} \in \mathcal{E}$, $0 \leq c < W$, $0 \leq t < Z$) and π_{it} ($j \in \mathcal{V}$, $0 \leq t < Z$). In this way, the "hard" constraints (6) and (7) are transformed into a "soft" price in the DP, which leads to the following Lagrangian dual problem:

TABLE VII
USING WAVELENGTH CONVERSION TO IMPROVE THE ACHIEVED DESIGN OBJECTIVE AND TO REDUCE THE NUMBER OF REJECTED SSLDS

Parameters					Results		
W	y_{sdn}	r_{sdn}	d_{ij}	F	q	J	Number of Rejected SSLDs
12	49	24	4	4	9122	9256	2
				0	9146	9414	5
8	49	24	4	4	10165	11178	31
				0	10174	11762	37
10	49	24	4	4	9263	10005	14
				0	9287	10330	19
10	49	24	8	4	17820	17862	30
				0	17829	17922	37
12	20	20	4	4	9278	9781	9
				0	9288	10145	15
12	20	20	8	4	17723	17882	35
				0	17726	17942	41

$$\max_{\xi,\pi\geqslant 0}(q) = \min_{A,B,\Delta,\Phi}\Bigg\{\sum_{l_{sdn}\in\mathcal{L}}[(1-\alpha_{sdn})P_{sdn}+\alpha_{sdn}(C_{sdn}+E_{sdn})] + \sum_{e_{ij}\in\mathcal{E}}\sum_{0\leqslant c<W}\sum_{0\leqslant t<Z}\xi_{ijct}\Bigg(\sum_{l_{sdn}\in\mathcal{L}}\delta_{ijct}^{sdn}-1\Bigg) + \sum_{i\in\mathcal{V}}\sum_{0\leqslant t<Z}\pi_{it}\Bigg(\sum_{l_{sdn}\in\mathcal{L}}\phi_{it}^{sdn}-F_i\Bigg)\Bigg\}, \tag{A1}$$

subject to constraints (4), (5), and (8). We use ξ to denote $\{\xi_{ijct}\}$ and π to denote $\{\pi_{it}\}$.

After regrouping the relevant terms, the dual function leads to the following problem:

$$\min_{A,B,\Delta,\Phi}\Bigg\{\sum_{l_{sdn}\in\mathcal{L}}\Bigg[(1-\alpha_{sdn})P_{sdn}+\alpha_{sdn}(C_{sdn}+E_{sdn}) + \sum_{e_{ij}\in\mathcal{E}}\sum_{0\leqslant c<W}\sum_{0\leqslant t<Z}\delta_{ijct}^{sdn}\xi_{ijct}+\sum_{i\in\mathcal{V}}\sum_{0\leqslant t<Z}\pi_{it}\phi_{it}^{sdn}\Bigg] - \sum_{e_{ij}\in\mathcal{E}}\sum_{0\leqslant c<W}\sum_{0\leqslant t<Z}\xi_{ijct}-\sum_{i\in\mathcal{V}}\sum_{0\leqslant t<Z}\pi_{it}F_i\Bigg\}. \tag{A2}$$

By using the fact that

$$\delta_{ijct}^{sdn}=\alpha_{sdn}\delta_{ijct}^{sdn}, \quad \forall\, l_{sdn}\in\mathcal{L}, \quad e_{ij}\in\mathcal{E}, \quad 0\leqslant c<W, \quad 0\leqslant t<Z, \tag{A3}$$

$$\phi_{it}^{sdn}=\alpha_{sdn}\phi_{it}^{sdn}, \quad \forall\, l_{sdn}\in\mathcal{L}, \quad j\in\mathcal{V}, \quad 0\leqslant t<Z. \tag{A4}$$

We further rewrite Eq. (A2) as

$$\min_{A,B,\Delta,\Phi}\Bigg\{\sum_{l_{sdn}\in\mathcal{L}}\Bigg[(1-\alpha_{sdn})P_{sdn}+\alpha_{sdn}\Bigg(C_{sdn}+E_{sdn} + \sum_{e_{ij}\in\mathcal{E}}\sum_{0\leqslant c<W}\sum_{0\leqslant t<Z}\delta_{ijct}^{sdn}\xi_{ijct}+\sum_{i\in\mathcal{V}}\sum_{0\leqslant t<Z}\pi_{it}\phi_{it}^{sdn}\Bigg)\Bigg] - \sum_{e_{ij}\in\mathcal{E}}\sum_{0\leqslant c<W}\sum_{0\leqslant t<Z}\xi_{ijct}-\sum_{i\in\mathcal{V}}\sum_{0\leqslant t<Z}\pi_{it}F_i\Bigg\}. \tag{A5}$$

TABLE VIII
COMPUTATION RESULTS USING VARIOUS TOPOLOGIES AND TRAFFIC MATRICES

Network Settings							
Network Name	Number of Nodes (N)	Number of Links (E)	Number of Wavelength Channels (W)	Total Number of SSLDs in Traffic Matrix	J	q	Duality Gap (%)
NSFNET	14	21	12	231	11653	11344	2.72
	14	21	4	105	5379	5081	5.86
	14	21	7	165	8198	8035	2.03
Random Network	22	35	10	352	18278	17641	3.61
	22	35	6	211	11015	10715	2.80
	22	35	8	263	13708	13346	2.72
European Network	28	61	8	403	19421	19162	1.35
	28	61	10	605	28180	27222	3.52
	28	61	4	201	9673	9217	4.95
	28	61	12	807	37837	35434	5.43
Average Duality Gap (%)							**3.50**

Since the last two terms are independent of the decision variables, the problem can be further simplified as

$$\min_{A,B,\Delta,\Phi}\left\{\sum_{l_{sdn}\in\mathcal{L}}\left[(1-\alpha_{sdn})P_{sdn}+\alpha_{sdn}\left(C_{sdn}+E_{sdn}+\sum_{e_{ij}\in\mathcal{E}}\sum_{0\leq c<W}\sum_{0\leq t<Z}\delta_{ijct}^{sdn}\xi_{ijct}+\sum_{i\in\mathcal{V}}\sum_{0\leq t<Z}\pi_{it}\phi_{it}^{sdn}\right)\right]\right\}, \quad (A6)$$

subject to constraints (4), (5), and (8).

Due to constraints (8), for every l_{sdn}, if $\beta_{sdn}\leq t<(\beta_{sdn}+t_{sdn})$, we may set variables δ_{ijct}^{sdn} and ϕ_{it}^{sdn} to constants (denoted by δ_{ijc}^{sdn} and ϕ_{i}^{sdn}, respectively); otherwise, set them all to zero. Considering the cost of routing a lightpath in Eq. (3), we thus rewrite Eq. (A6) as

$$\min_{A}\left\{\sum_{l_{sdn}\in\mathcal{L}}\left[(1-\alpha_{sdn})P_{sdn}+\alpha_{sdn}\min_{\beta_{sdn},\Delta_{sdn},\Phi_{sdn}}\left(E_{sdn}+\sum_{e_{ij}\in\mathcal{E}}\sum_{0\leq c<W}\sum_{\beta_{sdn}\leq t<\beta_{sdn}+t_{sdn}}\delta_{ijct}^{sdn}(\xi_{ijct}+d_{ij})+\sum_{i\in\mathcal{V}}\sum_{\beta_{sdn}\leq t<\beta_{sdn}+t_{sdn}}\phi_{it}^{sdn}(\pi_{it}+o_{i})\right)\right]\right\}. \quad (A7)$$

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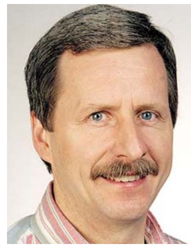

Michel Savoie is the research program manager for the Broadband Applications and Optical Networks group of the Broadband Network Technologies Research Branch at the Communications Research Centre Canada (CRC), an Agency of Industry Canada. He maintains expertise in broadband systems and related technologies such as user-controlled lightpaths (UCLP), infrastructure as a service (IaaS), green ICT, application-oriented networking (AON), advanced IP, and ATM- and WDM-based optical networks in order to provide advice on important national initiatives and to demonstrate the application of CRC technologies in a real operational environment. He has managed two UCLP projects funded under CANARIE's directed research program and was involved with EUCALYPTUS: a Service-oriented Participatory Design Studio project funded under the CANARIE Intelligent Infrastructure Program (CIIP). He was involved with PHOSPHORUS: a Lambda User Controlled Infrastructure for European Research integrated project funded by the European Commission under the IST 6th Framework. He is also involved with the Health Services Virtual Organization (HSVO) project under CANARIE's Network-Enabled Platforms program, the High Performance Digital Media Network (HPDMnet) research initiative, and the GreenStar Network project under CANARIE's Green IT Pilot program. CRC and its partners are currently engaged in the further development of the Argia/UCLP and the IaaS Framework software. Mr. Savoie holds a B.Sc. and M.Sc. in electrical engineering from the University of New Brunswick.