Lightpath Scheduling and Routing for Traffic Adaptation

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Abstract - We study the benefits and trade-off of using scheduled lightpaths for traffic adaption. We propose a network planning model, which allows lightpaths to slide within its desired timing window with no penalty on the optimization objective, and to slide beyond its desired timing window with a decreasing tolerance level. Our model quantitatively measures the timing satisfaction or violation. We apply the Lagrangian Relaxation and Subgradient Method to the formulated optimization problem. Our method demonstrated great computational efficiency when compared with other existing algorithms. Our simulation results show how timing flexibility improves network resource utilization and reduces rejections.

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 predicted from historical statistics, which repeat very day (or week) with a little variation in timing and volume. Knowing traffic patterns provides an opportunity to schedule lightpaths to adapt to the changing traffic.

Using scheduled lightpaths for traffic adaptation has different timing requirements from the other lightpath scheduling problems. Existing methods for the lightpath scheduling, 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 [3,4,5,6,7], network planning was conducted for a set of lightpath requests, each having pre-specified starting and ending time. In [8,9,10,11], static network planning was conducted for lightpath requests with fixed holding-time, 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 concern about not only timing violation but also resource utilizations and lightpath rejections, and need a tool to make wise trade-offs between these goals. Network operators would rather adjust lightpaths scheduling timing, than reject lightpaths that cannot be accommodated due to their strict timing requirement 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 slide should not impact much on the performance of the traffic adaptation, while dramatic timing slide should be avoided. For example, due to a traffic increase between two given nodes between 5:30pm and 6:30pm everyday, the network operator needs to add a lightpath between the two nodes for the extra traffic. It usually does not make much difference if the timing slide is far below the variance of the traffic, e.g., starting the lightpath from 5:20pm or 5:40pm. However, setting up the lightpath at 4:30pm or at 6:30pm cannot relieve the traffic congestion.

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 normally 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. This requires proper modelling of the extent of timing satisfaction or violation, which has not been done by the existing methods for the static lightpath scheduling, and motivates this study.

Our study aims at planning scheduled lightpaths to adapt to relatively stable traffic patterns. Static scheduled lightpath demands are known as input 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 [12,13,14]. In our approach, once a lightpath is pre-planned, 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 known 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 virtual topology by using scheduled lightpaths, i.e., we pre-plan virtual topology reconstructions.

This paper is organized as the following: In section 2, we summarize the assumptions used in our model. In section 3, we present our model, followed by its performance evaluation in section 4. We conclude this paper in section 5.
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 fibres, each fibre for one direction and having \( W \) non-interfering Wavelength Channels (WCs). Two nodes can be connected through a lightpath defined as a concatenated sequence of WCs [15]. Two lightpath segments that use different wavelengths are allowed to be chained together by using a wavelength converter installed at their junction node. For simplicity, we use “lightpath” in this paper regardless of whether it uses the same wavelength all the way or not.

Lightpaths are scheduled to be set up at the beginning of its starting time slot and be torn down at the end of its finishing time slot. 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 minutes or larger. Many network management systems monitor network status every 5 minutes, thus a time slot shorter than it 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., signalling time) is negligible compared to 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 \( Z-1 \) (\( 0 \leq i < Z \)).

We aim at scheduling and allocating network resources to lightpaths, i.e., planning network operations for Scheduled Sliding Lightpath Demands (SSLD). The network resources primarily include WCs and wavelength converters. We provide an accepted SSLD with a Routing and Wavelength Assignment (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 finishing time slot. If there is insufficient resource 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:
- \( \psi \) the set of all nodes in the network;
- \( e_{ij} \) the fibre between node \( i \) (\( i \in \psi \)) and node \( j \) (\( j \in \psi \));
- \( \Xi \) the set of all fibres in the network, i.e., \( \{ e_{ij} \} \), \(( i \in \psi , j \in \psi )\);
- \( d_{ij} \) the cost of using a WC on link \( e_{ij} \) (\( i \in \Xi \)) for one time slot;
- \( O_i \) the cost of using a wavelength converter on node \( i \) (\( i \in \psi \)) for one time slot;
- \( W \) the number of wavelengths used in the network;
- \( l_{sd} \) the \( n \)-th SSLD from node \( s \) (\( s \in \psi \)) to node \( d \) (\( d \in \psi \)). If it is accepted, we use the same notation to refer to the lightpath that is provided to the SSLD; the set of all SSLDs, i.e., \( \{ l_{sd} \} \);
- \( L \) the total number of SSLDs;
- \( t_{sd} \) the holding time of SSLD \( l_{sd} \). Based on our assumption, it is the same as the lifespan of lightpath \( l_{sd} \), if SSLD \( l_{sd} \) is accepted;
- \( [b_{sd}, b_{sd}'] \) the desired window of starting time for SSLD \( l_{sd} \), i.e., \( 0 \leq b_{sd} \leq b_{sd}' < Z \);
- \( C_{sd} \) the routing cost of lightpath \( l_{sd} \), i.e., the cost of resources used by lightpath \( l_{sd} \);
- \( D_{sd} \) the dual routing cost of lightpath \( l_{sd} \);
- \( F_s \) the number of wavelength converters that are installed on node \( i \) (\( i \in \psi \));
- \( N \) the number of nodes in the network;
- \( P \) the penalty coefficient for rejecting an SSLD;
- \( Z \) total time slots of our scheduling problem;
- \( \alpha_{sd} \) a binary integer variable indicating the admission status of SSLD \( l_{sd} \). It is one, if SSLD \( l_{sd} \) is accepted. Otherwise, it is zero;
- \( \beta_{sd} \) the starting time slot of lightpath \( l_{sd} \), \( 0 \leq \beta_{sd} < Z \);
- \( y_{sd} \) the weight for earliness penalty of lightpath \( l_{sd} \);
- \( r_{sd} \) the weight for tardiness penalty of lightpath \( l_{sd} \);
- \( \delta_{sd} \) a binary integer variable representing the use of the \( e_{ij} \)-th WC on fibre \( e_{ij} \) (\( i \in \Xi \), \( 0 \leq c < W \)) at time slot \( t \) by lightpath \( l_{sd} \) (\( l_{sd} \in \psi \)). It is one, if lightpath \( l_{sd} \) uses such WC at such time slot. Otherwise, it is zero;
- \( \phi_{sd} \) a binary integer variable representing the use of a wavelength converter on node \( i \) (\( i \in \psi \)) at time slot \( t \) (\( 0 \leq t < Z \)) by lightpath \( l_{sd} \) (\( l_{sd} \in \psi \)). It is one, if lightpath \( l_{sd} \) uses such wavelength converter at such time slot. Otherwise, it is zero;
- \( A \) the set of admission status of all SSLDs, i.e., \( \{ \alpha_{sd} \} \);
- \( B \) the starting time slots of all lightpaths, i.e., \( \{ \beta_{sd} \} \);
- \( \Delta_{sd} \) the RWA scheme of lightpath \( l_{sd} \) (\( l_{sd} \in \psi \)), i.e., \( \{ z_{ij}^{sd} \} \);
- \( \Phi_{sd} \) the allocation of wavelength converters to lightpath \( l_{sd} \) (\( l_{sd} \in \psi \)), i.e., \( \{ \phi_{sd} \} \);
- \( \Lambda_{sd} \) the RWA schemes of all lightpaths, i.e., \( \{ \Delta_{sd} \} \);
- \( \Phi \) the usage of wavelength converters by all lightpaths, i.e., \( \{ \Phi_{sd} \} \);
- \( E_{sd} \) the overall timing violation penalty of lightpath \( l_{sd} \).

B. Objective Function

Our objective is to minimize 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 timing violation, if lightpath $l_{sdnl}$ is not scheduled to start at time slot $b_{sdnl}$.

Our objective function is to minimize the function $J$, i.e.,

$$\min_{A,A,\phi} J = E\left[1 - \alpha_{sdnb}P + \alpha_{sdnb}(C_{sdnl} + E_{sdnl})\right].$$

The overall penalty consists of the rejection penalty (i.e., $P$), the resource usage cost (i.e., $C_{sdnl}$) and the timing violation penalty (i.e., $E_{sdnl}$). The timing violation penalty could be either an earliness penalty or a tardiness penalty. When SSLD $l_{sdnl}$ 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 starts. This is because we assume the lifespan of lightpath $l_{sdns}$ is exactly the same as the holding time of SSLD $l_{sdnl}$. On the other hand, when lightpath $l_{sdnl}$ is scheduled later than its desired starting time of SSLD $l_{sdnl}$, there will be a shortage of effective service time before the lightpath starts. In this paper, we adopt earliness and tardiness penalties defined in [18]:

$$E_{sdnl} = \begin{cases} y_{sdnl} \times (b_{sdnl} - \beta_{sdnl})^2 & \text{if } \beta_{sdnl} < b_{sdnl} \\
0 & \text{if } b_{sdnl} \leq \beta_{sdnl} < \beta'_{sdnl} \\
( i.e., \text{earliness penalty}) & \text{if } b_{sdnl} \geq \beta'_{sdnl}, \text{(i.e., no penalty, since the lightpath starts within its desired starting time window)} \\
y_{sdnl} \times (\beta_{sdnl} - \beta'_{sdnl})^2 & \text{if } \beta_{sdnl} > \beta'_{sdnl} \\
0 & \text{if } b_{sdnl} \geq \beta'_{sdnl}, \text{(i.e., tardiness penalty)} \end{cases}$$

where $y_{sdnl}$ and $r_{sdnl}$ are the weights for earliness and tardiness penalty of lightpath $l_{sdnl}$. Our earliness and tardiness penalties reflect a decreasing tolerance level as a scheduled lightpath moves away from its desired timing window (shown in Figure 1). When $y_{sdnl}$ and $r_{sdnl}$ 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, which does not allow any timing violation.

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

$$C_{sdnl} = \sum_{\beta_{sdnl} \in \beta_{sdnl} + \Delta \beta_{sdnl}}^2 \left( d_{ij} \times \sum_{c_{j} \in \text{con}_{j}} \delta_{sdnc} + e_{ij} \times \sum_{c_{j} \in \text{con}_{j}} \delta_{sdnc} \right), \quad l_{sdnl} \in L$$

(2)

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 ($\phi$), and the allocations of wavelength converter to all lightpaths ($\phi$). Our design variables are not completely independent. They represent three inter-related sub-problems, i.e., lightpath request admissions, lightpath scheduling, and RWAs. Based on our assumption of the wavelength converter’s installation structure, the allocations of wavelength converter to all lightpaths may be derived from the RWA schemes for all lightpaths.

C. Constraints

a) Lightpath continuity constraints:

If SSLD $l_{sdnl}$ is admitted, its RWA must be continuous along its path and be terminated at its two end nodes.

$$\sum_{j \in V} \sum_{c_{j} \in \text{con}_{j}} \delta_{sdns} = \sum_{j \in V} \sum_{c_{j} \in \text{con}_{j}} \delta_{sdn}, \quad s \neq i \neq d, \quad s \neq j \neq d$$

(3)

If $l_{sdnl}$ is accepted (i.e., $\alpha_{sdnl} = 1$), 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 $l_{sdnl}$ is rejected (i.e., $\alpha_{sdnl} = 0$), this lightpath does not contribute to the number of lightpaths that terminate at the node. These constraints confine that if and only if $\alpha_{sdnl} = 1$, during the lifespan of lightpath $l_{sdnl}$ (i.e., $\beta_{sdnl} \leq t < (\beta_{sdnl} + \Delta_{sdnl})$), there must be a lightpath from node $s$ to node $d$.

b) Wavelength conversion constraints:

$$\phi_{sdnl} = \begin{cases} 1 & \text{if } \exists (m \in V, \forall k \in V, h \neq c), \delta_{sdns} = \delta_{sdn} + 1, \\
0 & \text{otherwise} \end{cases}$$

$$\forall l_{sdnl} \in L, \quad j \in V, \quad 0 \leq t < Z$$

(4)

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

c) Exclusive WC usage constraints:

$$\sum_{l_{sdnl} \in L} \delta_{sdnc} \leq 1, \quad \forall e_{ij} \in E, \quad 0 \leq c < \delta_{sdn}, \quad 0 \leq t < Z$$

(5)

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

da) Converter quantity constraints:

$$\sum_{l_{sdnl} \in L} \phi_{sdnl} \leq F_{j}, \quad \forall j \in V, \quad 0 \leq t < Z$$

(6)

The number of occupied converters on node $j$ at any time slot $t$ must not be more than the number of the converters installed on the node.
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e) Lightpath persistency constraints:
\[ \delta_{i,j}^{\text{on}} = \delta_{i,j}^{\text{off}}, \quad \forall l_{i,j} \in L, \quad \epsilon_j \in \mathcal{E}, \quad \phi_{i,j} \leq x, \quad y < \beta_{i,j} + t_{i,j} \]  

During the lifespan of lightpath \( \lambda_{i,j} \), its RWA scheme must remain the same for all time slots. Note that when combined with constraints (b), the allocation of wavelength converters \( \phi_{i,j} \) remains the same for all time slots. Note that when combined with constraints (b), the allocation of wavelength converters \( \phi_{i,j} \) stays the same, too.

IV. 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 Figure 2, which marks the sequence number of nodes and links. In this section, we present results for one particular traffic pattern, while the same trends are observed under several other traffic patterns. The number of SSLDs for all node pairs are shown in Table 1, where the number on the \( i^{th} \) row and the \( j^{th} \) column represents the total number of SSLDs demands from node \( i \) to \( j \) over the entire time slots. We randomly assign their values between 0 and 3. The total number of SSLDs is 286, and heir timing requirement is also randomly generated.

![Example network for performance evaluation (NSFNET)](image)

Figure 2. Example network for performance evaluation (NSFNET)

We applied a Lagrangian Relaxation and Subgradient Method (LRSM) to the formulated optimization problem. Great computational efficiency is demonstrated when compared with other existing algorithms. We aim at obtaining near-optimal solutions to our problem, while providing a tight performance bound that can be used to evaluated the optimality of our solution. Details on LRSM can be found in [19].

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<th>TABLE I. NUMBER OF SSLDS FOR ALL NODE PAIRS</th>
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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 earlier than its desired starting time, a earliness penalty incurs. We introduce two measurements of timing violation: the Sum of Earliness Violations (SEV), and the Sum of Tardiness Violations (STV), defined as:

\[
\text{Sum of Earliness Violations (SEV)} = \sum_{l_{i,j} \in \mathcal{L}} \min[0, (\beta_{i,j} - \phi_{i,j})] \tag{8}
\]

\[
\text{Sum of Tardiness Violations (STV)} = \sum_{l_{i,j} \in \mathcal{L}} \min[0, (\phi_{i,j} - \beta_{i,j} + t_{i,j})] \tag{9}
\]

![Achieved optimization objective and its bound as \( y_{sl} \) varies](image)

Figure 4. Achieved optimization objective and its bound as \( y_{sl} \) varies

In Figure 3, we present the trade-off between SEV and the number of rejected SSLDs, as the weight of the earliness penalty \( y_{sl} \) 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 \( y_{sl} \) needs to be above 50 with the current parameter setting. 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 Figure 4). The duality gap is constantly lower than 5%, and the values have some minor changes only when the weight of the earliness penalty \( y_{sl} \) approaches 0.

We now fix the earliness penalty and study the impact of the tardiness penalty. We vary the weight of the tardiness penalty \( r_{sl} \) for SSLDs. In Figure 5, we show the trade-off between STV and the number of rejected SSLDs, as the weight of the
earliness penalty $r_{sdn}$ increases. The achieved optimization objective and its bound are shown in Figure 6. We observe a similar trend as shown in Figure 3 and Figure 4, which indicates that we may adjust either one of the two parameters or both to control timing violations, without changing 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 available network resources on the optimization objective. We vary the number of WCs on each fibre (denoted by $W$). The impact on the number of rejected SSLDs is shown in Figure 7. The achieved optimization objective and its bound are shown in Figure 8. In this example, we set parameters $F_i=4$, $d_{ij}=5$, $o_i=0$, $P_{sdn}=100$, $y_{sdn}=20$ and $r_{sdn}=20$. In this way, a lightpath may be scheduled up to one time slot ahead or behind of its desired timing, which causes a penalty of $20 \times 2^1 = 80$ within its total budget of 100. In Figure 7, we can see that as $W$ reduces, the number of rejected SSLD reduces too. We do not observe any obvious change in the timing violations as $W$ changes. In Figure 8, we can see again that our algorithm consistently produces near-optimal solution that is very close to the lower bound.

In our third example, we study the impact from the cost of WCs by fixing the other parameters and varying the cost of WCs (denoted by $d_{ij}$). The results are shown in Figure 9 and Figure 10. We divided the SSLDs into three groups based on their holding time. We can see in Figure 9 that as $d_{ij}$ increases from 0 to 40, the average hop counts of each group drop at different rates. In Figure 10, we demonstrate the performance of our scheduling results are 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 to the simplicity of our numerical experiments. Our model allows the easy control over the fairness of the rejection / acceptance by adjusting the $P_{sdn}$ values.
In this paper, we study the benefits and tradeoffs of using scheduled lightpaths for traffic adaptation. Knowing traffic patterns provides an opportunity to schedule lightpaths to adapt to changing traffic at the network planning stage. We proposed a network planning model as an optimization problem. Our model allows lightpaths to slide within its desired timing window with no penalty on the optimization objective, and slide beyond its desired timing window with a decreasing tolerance level. Our model quantitatively measures the timing satisfaction or violation.

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

V. CONCLUSIONS

REFERENCES