SRLG-Diverse Routing of Multiple Circuits in a Heterogeneous Optical Transport Network

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Abstract—Network planners are often requested to provision multiple physically-diverse high-speed circuits over a large carrier's core (inter-city) DWDM network, which consists of multiple layers and heterogeneous vendor systems. Optimally provisioning such circuits while avoiding shared risk link group (SRLG) failures is an NP-hard problem. In this paper, we propose a novel hybrid two-step approach: pre-processing with Integer Linear Programming (ILP) for diverse routing and post-processing for regenerator placement and wavelength assignment. This approach has been implemented in a prototype network planning tool. According to our experiments, most of the cases for a typical large carrier's core transport network can be solved within 1 minute, even with tens of thousands of binary decision variables, which allows interactive use by network planners.

Keywords: Diverse Routing, SRLG, ILP, Heterogeneous Optical Network.

Fig. 1. A point-to-point DWDM system.

I. INTRODUCTION

A large carrier's core transport network may include Dense Wavelength Division Multiplexing (DWDM) systems from different vendors. A typical point-to-point (unidirectional) DWDM system consists of two terminals connected by a pair of fibers. Each terminal contains an optical wavelength multiplexer and demultiplexer, amplifier, and transponders that interface client signals. The number of inline amplifiers placed between the terminals depends on the length and quality of fiber. Each transponder re-transmits its incoming client signal onto a particular wavelength of the optical grid (also called a channel) and the optical multiplexer combines n of these signals at different wavelengths together and transmits the multiplexed signal over a fiber to the demultiplexer at the other end. The demultiplexer decomposes the multiplexed signal back into n signals at their respective wavelengths, which are re-transmitted by each receiving transponder into its client signal. Client signals are typically generated by a packet switch, such as a large router, and the transmit/receive pair forms a link in the router topology.

For example, in Fig. 1, the top router on the left transmits a client signal with a short-reach wavelength λ_0. Before entering the optical multiplexer, this signal is converted to λ_1 using an optical transponder (OT). The λ_1 signal is combined with other wavelength signals and transmitted via the fiber to the optical de-multiplexer. The optical de-multiplexer decomposes the combined signal into different wavelengths. Then the λ_1 signal is converted into the short-reach wavelength λ_0 via
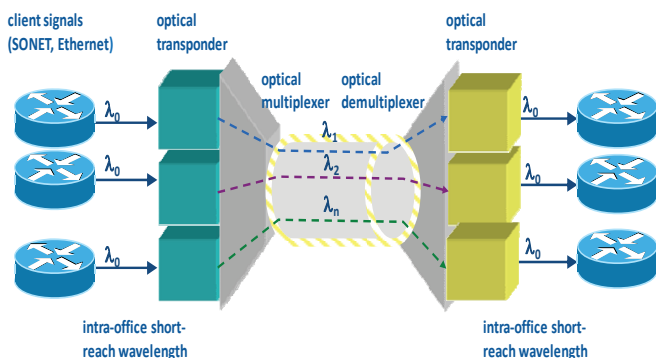
another OT and the λ_0 signal can be received by the top router on the right.

For simplicity we have not depicted amplifiers and other optical components. A point-to-point DWDM system consists of two fibers, one fiber for each direction. When a network point-to-point connection (also called circuit) is transported over two DWDM systems, two OTs are needed: the first OT converts the first DWDM system wavelength into the common short-reach wavelength (λ_0), and the second OT converts λ_0 into the second DWDM system wavelength. However, when the two DWDM systems are of the same technology from the same vendor, one regenerator can be used to replace the two back-to-back OTs, avoiding the conversion to the common short-reach wavelength, and thus reducing the component costs. With the same technology from the same vendor, a regenerator is usually less expensive than two back-to-back OTs.

Recently, Reconfigurable Optical Add Drop Multiplexer (ROADM) technologies for DWDM transport networks have been deployed due to their high capacity and capital savings. A ROADM network typically includes a set of multi-degree nodes connected via fibers to form a mesh topology. Traffic may be added or dropped, regenerated, or expressed through at ROADMs.

For some ROADM systems, a signal is able to travel a long distance such as 1500 km or more without requiring Optical to Electronic to Optical (OEO) regeneration (such an optical

signal is called a lightpath). This is referred to as the *optical reachability*. A regenerator is needed when a circuit length is longer than the optical reach or wavelength conversion is required. An optical path without regeneration is also called an *express link*.

Today, the channels of most ROADM-based systems support 10 Gigabits per second (Gbps) or 40 Gbps. But a large portion of circuits are still provisioned using lower speeds such as 2.5 Gbps. A network carrier needs to be able to multiplex multiple low-speed signals into a high speed channel of ROADM links. For example, four 2.5 Gbps signals are multiplexed into a single 10 Gbps signal; each 2.5 Gbps signal is carried on a subchannel of the 10 Gbps signal. It is analogous when four 10 Gbps signals are multiplexed into a 40 Gbps signal. A signal that multiplexes lower rate signals is called channelized; a signal that does not is called unchannelized. A channelized lightpath is called a *multiplex link*.

Multiple fibers are built in cables and cables can be laid inside of PVC (Polyvinyl chloride) ducts inside of concrete conduits or on power/telephone poles (called aerial). Fiber junctions are locations where fibers are spliced or cross-connected via patch panels. Fiber paths between two neighboring fiber nodes are called fiber spans. We represent DWDM systems by two DWDM nodes connected by a DWDM link. Each DWDM link traverses one or more fiber spans, and each fiber span may be traversed by one or more DWDM links. Fiber spans are also termed a Shared Risk Link Group (*SRLG*) in the industry since a fiber span outage can affect all the DWDM links routed over the fiber span.

For the purposes of this paper, we model the network of interest as decomposed into five layers, as shown in Fig. 2: 1) circuit layer, 2) multiplex link layer, 3) express link layer, 4) DWDM (ROADM) link layer and 5) fiber span layer.
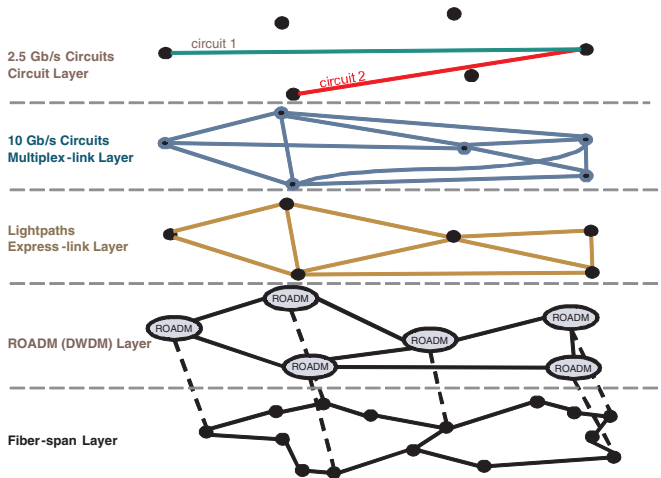

Fig. 2.   Multi-layer optical transport network

Problem Setting

Network planners are often requested to provision multiple physically-diverse optical routes with different source, different destination, and different rate requirements. Each route

may require the inclusion and/or exclusion of certain DWDM nodes. For example, an enterprise customer may ask for an optical Virtual Private Network (VPN) connecting multiple sites and require that the optical VPN routes be mutually diverse at the fiber layer. Fiber diversity means no sharing of fiber spans, fiber junctions, and other optical facilities among the routes. This problem becomes more complicated due to optical networks' multiple layers and heterogeneous vendor systems. Finding two fiber-diverse routes between two DWDM nodes is NP-Hard [1]. Furthermore, planners also need to add constraints to include or exclude DWDM nodes in the diverse routes, which is also NP-Hard.

The optical network diverse routing problem is defined as follows:

Given a network configuration that includes multiple vendor DWDM systems, fiber spans for each DWDM link, the cost of DWDM system terminal OT and regenerator, available DWDM link capacity, optical reachability, multiplexing capability and unused subchannels of the existing multiplex links, and a set of pairwise demands plus routing constraints (source, destination, required rate, a list of nodes to be avoided and a list of nodes to be included), we are required to find the set of routes in the heterogeneous network such that those routes are physically diverse from each other, meet the constraints and to ensure that the total capital cost or the total distance is minimized.

The total capital cost includes both common cost and terminal OT/regenerator cost. The common cost is defined as shared DWDM system cost, optical amplifier cost and fiber cost; it is often modeled as the product of unit common cost per wavelength-mileage and the total wavelength-mileage. Different DWDM systems have different unit common costs.

To the best of our knowledge, there is no publicly known work to solve this complicated real-world problem for a large-scale carrier network. Instead, network planners from most carriers rely on their judgment (aided by spreadsheets and PowerPoint slides) to find feasible solutions.

In this paper,

- We present a very efficient two-step method to solve this problem. We first formulate the optical diverse routing problem using Integer Linear Programming (ILP) to find feasible routes with the minimum estimated cost. The ILP problem could contain tens of thousands of binary decision variables, and we adopt many modeling tricks to solve it using a commercial ILP solver within 1 minute (real-time).

- To expand to specific solutions for the actual multi-layer problem, we create a cost-based auxiliary graph for the specific routes generated above. This optimizes DWDM system selection, regenerator placement, subchannel routing over multiplex links, and wavelength assignment.

- We implement the above two-step method as an online interactive optical network planning tool, which has been actively used by network planners since 2009. Most problems have been solved within 1 minute with near-

optimal results.

The rest of the paper is organized as follows. In Section II, we describe a simple example of a heterogeneous multi-layer core DWDM network. Section III describes the ILP model to find the feasible routes with the minimum estimated cost or geographic distance. Section IV presents our auxiliary graph model and describes how to apply this auxiliary graph to choose DWDM systems, optimize regenerator placement, and assign wavelengths. Software implementation and experiments are presented in Section V. Some related work is discussed in Section VI. We conclude the paper in Section VII.

II. A SIMPLE EXAMPLE OF A HETEROGENEOUS CORE DWDM NETWORK

As we mentioned in Section I, a large carrier's optical transport network may consist of multiple DWDM nodes, including point-to-point DWDM systems, point-to-point DWDM systems with limited OADM (optical add/drop multiplexing) or more modern ROADM nodes that have more through or add/drop cross-connection flexibility. Fig. 3 shows a sample optical transport network, which consists of 9 offices, marked as A to I, 14 DWDM links, 3 SRLGs (fiber spans), where OT refers to an optical transponder. Here the network consists of 3 different DWDM systems: Type 1 system is point-to-point DWDM including links A-B, B-C and A-I; Type 2 system is OADM system including C-D-H and I-B-D; Type 3 system is a ROADM system including A-C-E-F-G-H-I.
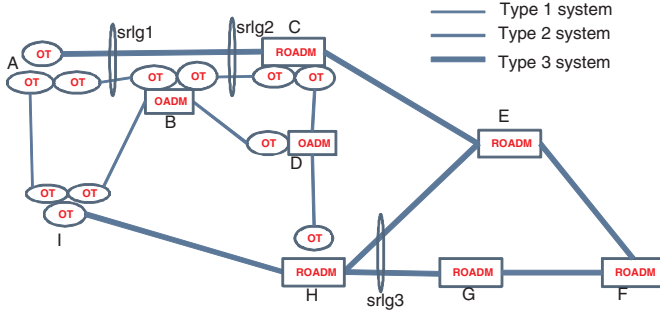

Fig. 3. An Example of an Optical Transport Network

In such a heterogeneous optical transport network, different types of systems can support different capacities per wavelength. For example, Type 1 system only supports 2.5 Gbps per wavelength, Type 2 system supports both 2.5 Gbps and 10 Gbps per wavelength, and Type 3 system supports 10 Gbps per wavelength. Furthermore, Type 3 system may also support sub-wavelength/channel grooming using de-multiplexing, i.e., a single wavelength can be de-multiplexed into four 2.5 Gbps sub-channels.

A wavelength can traverse multiple DWDM links without regeneration, which is referred to as *reachability*. For example, in Fig. 3, an optical signal can travel directly from I to D (through B) on Type 2 system. The reachability depends on fiber type, fiber distance, and other physical characteristics, which are provided by the system vendor via complicated

BE	Set of basic edges, i.e., DWDM links
PE	Set of bypassing edges (express and multiplex links)
$EE[u,v]$	Set of basic edges for the bypassing edge $(u,v) \in PE$
E	Full set of edges, i.e. $BE \cup PE$
RV	Set of ROADM
MV	Set of virtual nodes
JV	Set of fiber span network junction nodes
$VV[u]$	Set of virtual nodes of node u
$OL[u]$	Set of adjacent nodes of node u
G	Set of basic SRLG
$GE[g]$	Set of basic edges in SRLG g
XG	set of extended SRLG
$XE[g]$	Set of bypassing edges using extended SRLG, $g \in XG$
FG	Full set of SRLG, i.e., $G \cup XG$
$FE[g]$	Set of edges passing $g \in FG$
$P[u]$	Set of basic edges passing ROADM $u \in RV$
$VE[u]$	Set of edges passing nodes $u \in RV \cup JV$
$A[t]$	Set of nodes to be avoided for the t-th route
$I[t]$	Set of nodes to be included for the t-th route
$x[t,u,v]$	Binary variable to indicate if edge (u,v) is used in the t-th route
$y[t,g]$	Binary variable to indicate if SRLG $g \in FG$ is used in the t-th route
$z[t,u]$	Variable for the label of vertex u in the t-th route
$O[t,u]$	# of links containing vertex u in the t-th route

measurement and computation. Long distance reachability can reduce capital cost by saving regenerators.

During diverse routing modeling, we need to pay attention to some special cases, such as implied node inclusion and parallel diverse links. For the first case, if we need to find two diverse paths between I and D, I-A-C-D and I-B-D cannot be used since link A-C includes node B; For the second case, between offices C and H, we have express links C-D-H and C-E-H, which are physically diverse. In a large core transport network, such cases are not rare.

For ROADM systems with wavelength de-multiplexing capability, the network may have some existing multiplex links with some unused sub-channels. Since the de-multiplexing optical transponders have been installed, no extra capital cost is required to use these sub-channels. In diverse routing, such available sub-channel usage is preferred to minimize the cost incurred.

III. ILP MODEL FOR DIVERSE ROUTING

In this section, we define the ILP mathematical model for optical network diverse routing problem. We first introduce the network model to represent the above complicated optical transport network and demand specifications, then define decision variables and constraints to ensure physically-diverse routing, and finally describe the objective function to complete the ILP mathematical model. Note that, the terms of "edge" and "link" are usually used interchangeably, whereas in this section, we differentiate between "edge" which is used for abstract graphs, whereas "link" is used for the multi-layer optical network model. The key notation used in this paper is shown in Table I.

Basic Network Information

The optical network graph is made of a set of basic edges (BE) and bypassing edges (PE), and thus the full set of edges is the union of these, i.e., $E \triangleq BE \cup PE$. RV is defined as the set of DWDM nodes connecting edges in E. As described in Section II, there could be multiple systems between two DWDM nodes. If they are on the same fiber span route, the minimal distance and minimal 2.5 Gbps/10 Gbps/40 Gbps costs are chosen in the network graph. If they are on different fiber span routes, for each *additional* fiber span route, we create a virtual node and two virtual edges (from the two DWDM nodes to the virtual node) in the optical network graph to distinguish them. One virtual edge represents the physical optical link and the other virtual edge has a zero cost. MV is defined as the set of virtual nodes. JV is defined as the set of fiber span network junction nodes and $OL[u]$ is defined as the set of adjacent nodes of node u. $VV[u]$ is defined as the set of virtual nodes of node u.

SRLG Information

Since optical network links are routed over the fiber span network, each fiber span failure or fiber span joint failure could cause multiple optical network link failures. This defines an SRLG. Some SRLGs may share the same set of links. From the detailed route of each optical network link, we compute the minimal set of SRLGs such that no SRLG consists of the same set or the subset of the links of another SRLG. This SRLG set is called the basic SRLGs G. Each basic SRLG g is related to a set of basic edges $GE[g]$, i.e., the set of basic edges $GE[g]$ share the common potential failure g.

Similar to optical links routed over a fiber span network to form a basic SRLG set, express links and multiplex links routed over optical links can be used to form an extended SRLG set XG, which is the minimal set of optical links such that no two optical links will cause the same set of express/multiplex links to fail. To reduce the problem size, the extended SRLG set XG does not include any optical link passing any basic SRLG. For any extended SRLG g, $XE[g]$ is the set of bypassing edges PE sharing the common extended SRLG g.

The basic SRLG set G and the extended SRLG set XG are combined into a full set of SRLGs $FG \triangleq G \cup XG$. $FE[g]$ is defined as the set of edges sharing the same risk $g \in FG$. For a basic SRLG g, $FE[g]$ includes the basic edges in $GE[g]$ and those bypassing edges using any edge in $GE[g]$. For an extended SRLG, g, $FE[g]$ includes g itself (a basic edge) and those bypassing edges using g.

Node Passing

In an optical network, an optical link may pass through some DWDM nodes besides its terminal nodes. For example, Fig. 3 shows DWDM link A-C passes through node B. Such information also needs to be considered for diverse routing. For example, to provision two physically-diverse 10 Gbps routes, a pair of candidate routes, A-C and I-D, is not a feasible solution since in the DWDM link layer they both pass through office B. Here, $P[u]$ is defined as a set of DWDM links passing DWDM node $u \in RV$. u cannot be treated as a fiber joint (an SRLG) since it can terminate a route. $VE[u \in RV]$ is defined as those basic or bypassing edges passing through node u. This information is used to ensure node-diversity or prevent loops in the ILP outputs. A loop is defined as a route crossing the same node more than once.

Routing Demands

The user specifies a set of route demands. For the t-th route, the user specifies the source $S[t]$, destination $D[t]$, required rate $n[t]$, a set of DWDM nodes to be avoided $A[t]$ as well as a set of DWDM nodes to be included $I[t]$.

Data Model Optimization

ILP is a computationally intensive approach. To accelerate the computation, the problem size needs to be reduced. For the demand set $< S[t], D[t], n[t], A[t], I[t] >$, the optical links without enough capacity are removed to reduce the number of basic BE and bypassing PE edges. SRLGs related to only a single link are removed and SRLGs related to a same link failure set are consolidated to reduce the size of the SRLG set. $x[t, u, v]$ is a binary variable to indicate if edge (u, v) is used in the t-th route and $y[t, g]$ is a binary variable to indicate if SRLG g is used in the t-th route.

Constraints

$$EC[u] = \sum_{v \in OL[u]} x[t, u, v] - x[t, v, u], \forall t, u \in RV \quad (1)$$

$$\sum_{(u,v) \in FE[g]} x[t, u, v] + x[t, v, u] \leq 2|g|y[t, g] \quad (2)$$

$$\sum_t y[t, g] \leq 1, \forall g \in FG \quad (3)$$

$$\sum_t O[t, u] = EC[u], \forall u \in RV : EC[u] > 0 \quad (4)$$

$$\sum_t O[t, u] \leq 2, \forall u \in RV : EC[u] = 0 \quad (5)$$

$$O[t, u] = 0, \forall t, u \in A[t] \quad (6)$$

$$O[t, u] \geq 1, \forall t, u \in I[t] \quad (7)$$

$$z[t, v] - z[t, u] \leq M(1 - x[t, u, v]) - 1, \forall t, (u, v) \in BE \quad (8)$$

$EC[u] \triangleq |\{t : S[t] = u\}| + |\{t : D[t] = u\}|$ is the number of times vertex u being the source or destination for all the routes. A flow conservation constraint (1) ensures flow conservation at each node, at the source, at the destination, or at an intermediate node for the t-th route, where $S[t]$ and $D[t]$, are the source and destination of the t-th route. For example, if u is the source node of the t-th route, then for one of its neighboring nodes v, the link (u, v) will be chosen on the solution route, i.e., $x[t, u, v] = 1$.

Constraints (2) and (3) provide SRLG diversity. Constraint (2) ensures that variable $y[t, g]$ is 1 if any edge (u, v) in SRLG g is used in the t-th route. If $y[t, g]$ is 0, then no edge (u, v) in SRLG g can be used in the t-th route. Constraint (3) ensures that SRLG g cannot be used in more than one route, i.e., up to one $y[t, g]$ can be 1.

$$O[t, u] \triangleq \sum_{v \in OL[u]} (x[t, u, v] + x[t, v, u])$$
$$+2 \sum_{(u', v') \in VE[u]} (x[t, u', v'] + x[t, v', u'])$$
$$+ \sum_{w \in VV[u]} \left(\left(\sum_{v \in OL[w]} x[t, w, v] + x[t, v, w] \right) - 2(x[t, w, u] + x[t, u, w]) \right)$$

$O[t, u]$ is used to represent the number of links containing vertex u in the t-th route. If a bypassing edge traversing u is chosen, then $O[t, u]$ of u increases by a value of two. The definition of $O[t, u]$ combines the occurrences of a virtual node into that of its corresponding DWDM node but excludes the virtual link between the DWDM node and its virtual node.

Constraint (4) ensures that if vertex u is specified as the source or destination of any route, the sum of its occurrences in the solution should equal the total instances of using it as source or destination since network planners would not allow sources or destinations to be used as an intermediate node for other routes. For non-terminal nodes, Constraint (5) shows the sum of occurrences should be less than 2 to prevent more than one route from traversing it (i.e. node-diversity among routes).

A node exclusion constraint (6) ensures that vertex u is avoided in the t-th route. A node inclusion constraint (7) ensures that vertex u is included in the t-th route. Enforcing node inclusion introduces a new issue in the ILP formulation - the unadjusted ILP may return an invalid solution. For example, for a route from A to B to include C, the ILP may return a path A to B, and a separate loop containing C. If there is no requirement on node inclusion, a false solution can be avoided automatically since the solution without the loop has a lower/better objective value.

To prevent an invalid solution, a linear label variable for each vertex $z[t, u]$ is introduced. If an edge (u, v) is selected for t-th route, the label variable value $z[t, v]$ must be 1 smaller than label variable value $z[t, u]$, otherwise the two values have no relationship. To satisfy this constraint, a constant M is introduced as the maximum number of hops allowed. One value of M could be the number of DWDM nodes. To accelerate ILP computation, $|RV|/5$ is normally used as the default. Constraint (8) ensures that if edge (u, v) is used in the t-th route, i.e., $x[t, u, v] = 1$, the label of u must be greater than that of v by at least one. Therefore, any solution with loops is not allowed.

Finally, an objective function is created,

$$\Phi \triangleq \sum_{t, (u,v) \in E} (x[t, u, v] + x[t, v, u]) c[u, v]$$

where $c[u, v]$ is a user defined weight on edge (u, v). The user can choose the metric of all the routes to be minimized, therefore, $c[u, v]$ could be the cost of allocating a channel on (u, v) to minimize total capital cost, or geographical distance of (u, v) to minimize total distance, or 1 unit to minimize total hop count.

The diverse route with minimized cost or minimized distance (shortest path) through the network is output from the ILP, i.e., the set of binary values (1 or 0) to show if edge (u, v) is chosen on the t-th route.

IV. Auxiliary Graph Model for Second Step

The output of ILP produces a feasible solution without considering DWDM system selection, regenerator placement or wavelength assignment. In the second step, we construct an auxiliary weighted graph for each selected route as shown in [2]. The final results will be reviewed and confirmed by planners before being entered as a circuit provisioning job.

For the t-th selected route, $P[t] \triangleq < S[t], ..., D[t] >$ (node sequence), we create an auxiliary weighted graph $G_t(V_t, E_t)$. At a node (office location), k, along route P[t], if there are N_k types of links (DWDM systems or multiplex/express link) terminated at k and routed along P[t], we create $N_k + 1$ vertices in V_t. One vertex for terminating the real traffic and N_k vertices for the N_k link types. We create an edge from the traffic termination vertex to each of the other N_k vertices with a weight of terminal_OT_cost - regenerator_cost/2 or 0 for multiplex links. The edge weight is always non-negative since a half regenerator cost should be less than one OT cost of the same system type. For each link along route $P[t]$, we identify the corresponding two system-related vertex within V_t and connect them with an edge weighted as the regenerator_cost + common_cost for DWDM links and express links or multiplex link cost for multiplex links.

Then we search for the shortest path in the auxiliary weighted graph between the two terminating vertices corresponding to the original source and destination nodes of route $P[t]$. On the shortest path found, we first identify the inter-office edges since each inter-office edge corresponds to a DWDM link, express link, or multiplex link. If two consecutive inter-office links are of the same system type, we place a regenerator on their common office. If they are of different system types, one terminal OT of each system type is required on the common office to bridge the two system types. Finally, at each end of the route, one terminal OT of the corresponding system type is needed.

Afterward, for each DWDM link, express link, or multiplex link chosen on the shortest path, we assign the wavelength according to its own system-specific policy, such as a first-fit policy, i.e., allocating from the available wavelengths with the increasing order of frequency. Then we can report user the real capital cost based on the above terminal OT and regenerator placement and wavelength assignment.

We demonstrate the above procedure with the following example. Assuming the ILP model outputs two diverse routes from A to F for the network shown in Fig. 3: A-C-E-F with 10 Gbps route and A-I-H-G-F over 2.5 Gbps route. Fig. 4 shows the first route and the corresponding auxiliary weighted graph $G_1(V_1, E_1)$. It has 8 nodes and 9 edges, where the dashed lines represent the links derived from express links. The edges A-A3, C-C3, E-E3 and F-F3 are weighted as the terminal_OT_cost - regenerator_cost/2 of Type 3 system. The remaining edges are all weighted as one regenerator cost. If the least-cost path in $G_1(V_1, E_1)$ is A-A3-E3-F3-F, it means the optical signal will bypass ROADM C and be regenerated at ROADM E. Thus the total capital cost would be the cost

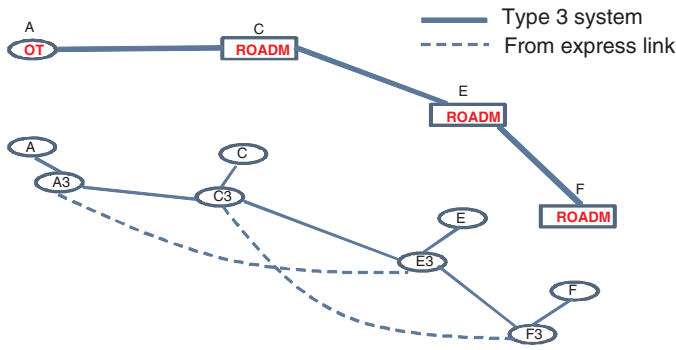of two terminal OTs plus one regenerator.

Fig. 4. First Route and the Corresponding Auxiliary Graph $G_1(V_1, E_1)$

Fig. 5 shows the second route and its auxiliary weighted graph. There are 11 nodes and 13 edges in $G_2(V_2, E_2)$, where the dashed-dot lines represent the links derived from multiplex links. At office A, there are only nodes A and A1 since there is only one system type, Type 1. Given Type III system does not directly support 2.5 Gbps, multiplexing 2.5 Gbps over 10 Gbps is needed. For this case, office I has two system types: Type 1 and multiplex link. Offices H, G and F all have one system type: multiplex link. Edges A-A1 and I-I1 are weighted as terminal_OT_cost - regenerator_cost/2 of Type 1 system. Edges I-I4, H-H4, G-G4 and F-F4 have zero weights. Edge A1-I1 is weighted as one regenerator cost of a Type 1 system. Edges I4-H4, I4-G4, I4-F4, H4-G4, H4-F4 and G4-H4 are weighted with their partial real regenerator costs plus common costs [3]. If the least-cost path in $G_2(V_2, E_2)$ is A-A1-I1-I-I4-F4-F, we may end up with a wavelength over edge A-I of Type 1 system and a subchannel of the multiplexed 10 Gbps route I-H-G-F.
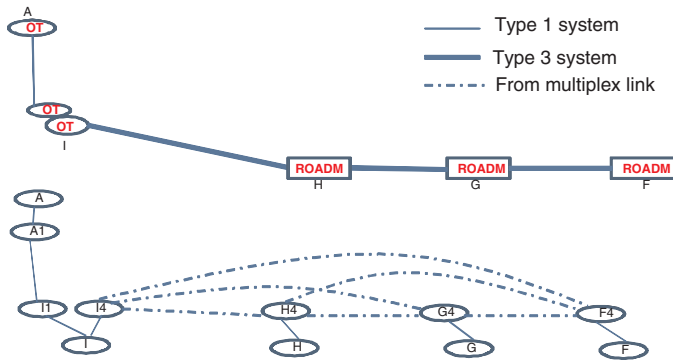

Fig. 5. Second Route and the Corresponding Auxiliary Graph $G_2(V_2, E_2)$

V. IMPLEMENTATION AND PERFORMANCE ANALYSIS

We implemented the two-step method described in Sections III and IV and prototyped a core DWDM routing tool with a web-based graphic user interface (GUI) to provision multiple physically-diverse optical circuits. A network planner can request diverse routes for up to four circuits: The input is

the circuit endpoints, circuit rates, and the lists of nodes to be avoided or included. He/she also can specify 1) whether to minimize the total cost or distance, 2) whether to constrain node or edge diversity, and 3) the circuit deployment date. Then the prototype tool 1) finds the near-optimal feasible diverse routes over the heterogeneous systems via integer linear programming (ILP), then 2) for each route selects DWDM systems, identify regenerator locations, and assign wavelengths. The final routes are displayed on the GUI, including the detailed information about OTs, regenerator locations and wavelength assignment.

The second step usually requires less than 1 second running time, and thus we focus the performance of the first step of routing for the tasks requiring ILP computation. If the user demands diverse routes and/or node-inclusion feature, the front-end GUI will prepare the ILP model and data files in AMPL format [4], and forward them to an ILP-computing server. The computing server is equipped with 2.5 GHZ Quad-Core AMD Opteron 8380 Processors, and has installed AMPL/Gurobi 4.0 [5] (with the comparable performance as AMPL/CPLEX [6]) for ILP computation. Over a 9-month period (June 1st, 2010-Feb 28th, 2011), the server executed 868 ILP tasks initiated from the network operators in addition to hundreds of test instances. 84.2% real tasks require two diverse routes, 3.2% tasks require three or four diverse routes, and the remaining tasks (12.6%) require single routing but with node inclusion.

The sizes of the resulting ILP problems vary with route numbers, and are usually very large. A real case of provisioning three physically-diverse 10 Gbps routes in a large commercial heterogeneous optical network consists of 507 DWDM nodes, 930 basic edges, 4609 express/multiplex edges and 474 non-redundant SRLGs. The resulting ILP instance has 31872 binary variables and 4483 constraints. It was very surprising that such a large ILP problem could be solved in a very short time (5.1 seconds), which thus enables it to be used in interactive network planning.

Fig. 6 shows the single-thread running-time (in seconds) of those real-world tasks with ILP computation. The default setting of target running time for Gurobi is 60 seconds. The ILP computation will stop earlier if the relative gap between the best (integer) solution found and the best boundary (i.e., the potential optimal result) is less than 1%. Otherwise, it returns the best solution found after the target time. Fig. 6 also indicates up to 1.5 seconds for AMPL pre-processing besides 60 seconds for Gurobi.

It shows that 16.0% instances require less than 0.5 second, 39.6% instances require 0.5-1 second, and 39.7% instances require 1-10 seconds. Only 2.1% instances exceed 60 seconds. Moreover, those sluggish instances correspond to 4 unique tasks (excluding the repeated tests for the same task). Interestingly, all the four tasks require node-inclusion *AND* minimization of the total distance. It is easy to understand that a task case demanding more routes needs more time, and a task case with node-inclusion creates more variables/constraints, and thus the ILP also takes more time. Additionally, requir-

ing node-inclusion makes a simple routing problem NP-hard since it becomes a variation of the well-known NP-Complete problem, The travelling salesman problem (TSP) problem: finding a shortest tour that visits each node exactly once in a weighted graph [7]. However, under the same constraints, we observe that minimizing total distance can take more time than minimizing total cost. Our preliminary explanation for this phenomenon is that for a hybrid network, most recent DWDM systems can go through a long distance without regeneration such that their common costs per bandwidth per mile will be much lower than the legacy systems. In searching for the routes with the minimum total cost, the ILP solver (usually using branch and bound methods) can easily identify those low-cost routes. However, in searching the routes with the minimal total distance, there is no such advantage; the ILP solver needs to search a large space and requires more time to explore it.
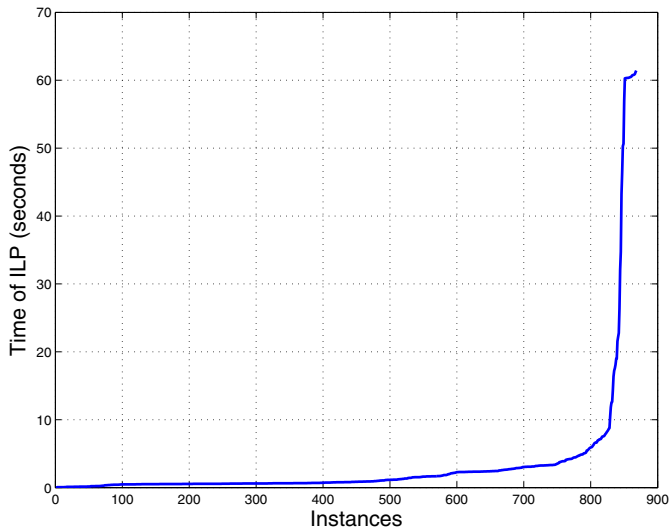

Fig. 6. ILP Running Time Distribution for 868 real tasks

We further analyze one of the four above tasks that did not find the optimal result within 60 seconds. The instance is for two diverse 10 Gbps circuits to minimize the total distance and include one intermediate node. The resulting ILP problem has 21875 binary variables. We rerun the instance for 10 minutes. Fig. 7 shows the trajectories of the best (integer) solution and the best boundary reported by Gurobi. The relative gap between the best solution found and the best boundary reaches 64.0% after 35 seconds, and reaches 44.3% after 131 seconds. Thereafter, the improvement is very slow. A faster heuristic method for this particular type of problem (including nodes and minimizing distance) would be useful.

We also observe that formulating the ILP problem plays a critical role in speeding up the computation. Different AMPL formulations with an equivalent functionality could end up with totally different running time. For example, defining an auxiliary linear variable w, adding a constraint $w = x + y + z$, and replacing all the occurrences of $x + y + z$ in other
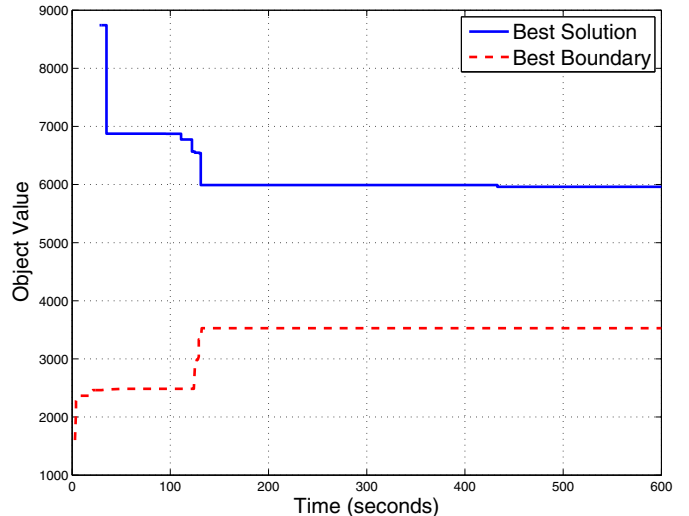

Fig. 7. Evolution of objective value for best solution and best boundary of a difficult diverse routing case with ILP

constraints and the objective function with w could make the problem unsolvable within the target time.

Finally, commercial ILP solvers, such as AMPL+Gurobi/CPLEX, are very expensive and we need to deploy our software in various environments, including test sites, production sites and disaster recovery sites. To reduce the deployment cost, we made our AMPL modeling compatible with the open-source modeling language, GMPL [8], which is a subset of AMPL but less powerful. We also customized the kernel of open-source ILP solver, Cbc [9], for our application. GMPL 4.31/Cbc 2.2.2 is deployed in non-production environments, and is usually 4 times slower than its commercial counterpart.

VI. RELATED WORK

There are some related studies dealing with diverse routing [1], [10]–[13] assuming homogeneous networks. Hu in [1] proved that finding two SRLG-diverse paths is NP-Hard. Suurballe [10] developed an efficient algorithm for finding k-(node or link)-diverse paths with the minimum total length between two end-points. A related problem is the k-diverse paths problem (k-DPP). In this problem [14], we are given a tuple $(s_1, t_1; ...; s_k, t_k)$ of $2k$ vertices and we want to construct k diverse paths pi ($1 \leq i \leq k$), from s_i to t_i. The k-DPP can be further split into k-VDPP, if diverse refers to vertex-diverse, and k-EDPP, if diverse refers to edge-diverse. Both the k-VDPP and k-EDPP problems can be solved in polynomial time. However, in our optical diverse routing problem, the k circuits should also be SRLG diverse, which introduces additional complexity. There also exist systems providing diverse routing services that compute physically-diverse circuits in digital transport networks. For example, a universal diverse circuit route finder model [15] was described to route physically-diverse circuit requests with different required rates under opaque optical networks, i.e., no express link or multiplex

link involved. But to the best of our knowledge, there is no tool available that supports real time diverse routing over heterogeneous optical networks.

VII. CONCLUSION

We introduced the Optical Network Diverse Routing problem and its application in the planning of a core (inter-city) transport network of a large commercial telecommunications carrier. We proposed a novel hybrid two-step approach to solve this NP-hard problem: Step 1) Integer Linear Programming to find Fiber-diverse routes and Step 2) construction of a cost-based auxiliary graph of the routes to do more refined optimization over the true multi-layered network model (including multiplex optimization, regenerator placement and wavelength assignment). We implemented these algorithms and models in a prototype planning tool which enables network planners to make more informed and intelligent decisions quickly and significant cost savings to the carrier.

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