

Circuit Planning Tool over Heterogeneous Networks

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Abstract—currently, there is no existing solution or tool to efficiently route a high-speed circuit over heterogeneous DWDM networks under multi-vendor environment, although each vendor may provide a planning tool to route a circuit within its own sub-network domain. This is mainly due to the lack of common technology for optical reachability calculation across vendor sub-networks. Each sub-network has its own proprietary parameters or formulas to calculate whether an optical path is reachable or not. To route a circuit across heterogeneous networks, we rely on the common function provided by each vendor tool to determine all reachable paths within each sub-network, i.e., the reachability matrix for each sub-network. Here reachability matrix is defined as a list of all reachable paths within the sub-network. Then we build a weighted cost graph based on the reachability matrices and apply the shortest path algorithm to find a cost efficient route. Finally we address the DWDM (Dense Wavelength Division Multiplex) sub-network selection, regenerator placement, and wavelength assignment on the selected route. The systematical methodology has been implemented in a circuit planning tool for high-speed circuits (up to 100Gbps) and used in a real heterogeneous DWDM network since 2009.

Keywords—DWDM network, heterogenous network, high-speed network, reachability, reachability matrix

I. INTRODUCTION

With technology evolution and industry consolidation, a large carrier's DWDM (Dense Wavelength Division Multiplexing) network may include several DWDM sub-networks from different vendors using different technologies [1]. They vary in number of wavelengths per fiber pair, data rate supported, and/or optical reachability parameters. However, a customer requesting an end-to-end high-speed circuit should not be aware of the underlying heterogeneous sub-networks. It is the carrier's responsibility to optimize circuit routing in its own heterogeneous network to save cost and ensure high network availability.

Traditional point-to-point DWDM sub-networks normally support 2.5Gbps/10Gbps per wavelength. Most recent ROADM (Reconfigurable Optical Add-Drop Multiplexer)-based sub-networks can support 10Gbps/ 40Gbps/100Gbps per wavelength [2,3]. In DWDM networks, the optical signal quality degrades due to physical impairments that accumulate along the optical path. The signal degradation may lead to an unacceptable BER (bit-error rate). Hence, after a certain impairment threshold, the signal needs to be regenerated to regain its original quality. In practice, optical signals are regenerated per wavelength (rather than per fiber) with OEO

(Optical-Electrical-Optical) regenerator. Such limitation on signal path length is called *reachability* [4]. Different vendors apply different technologies to handle the impairments and use different impairment parameters and formulas to determine whether a path is reachable or not. There are no common parameters or formulas to calculate the BER of a path over multiple sub-networks. In fact, those vendor-proprietary reachability parameters/formulas are not publicly available. They are usually built in their own sub-network planning tool. Nevertheless, we noticed that all vendor sub-network planning tools have a common function to determine whether a path within its sub-network is reachable or not. Based on this common function, it is possible to ask each sub-network vendor tool to provide a reachability matrix for its sub-network domain, i.e., a list of all reachable paths within the sub-network. A reachable path is denoted as *express link*. Then we can use the reachability matrices to “glue” those sub-networks together and efficiently route a circuit over multi-vendor DWDM network.

In today's market, most ROADM-based systems support 10Gbps/40Gbps/100Gbps per wavelength. But a large portion of circuits are still requested as lower speeds such as 2.5Gbps/10Gbps. A network carrier should be able to multiplex several low-speed circuits into a high-speed wavelength lightpath in a ROADM network where each low-speed circuit occupies one sub-channel of the high-speed wavelength lightpath. For example, one 10Gbps wavelength path can be de-multiplexed into four 2.5Gbps sub-channels, one 40Gbps wavelength path can be de-multiplexed into four 10Gbps sub-channels, and one 100Gbps wavelength path can support ten 10Gbps sub-channels. A high-speed wavelength lightpath with de-multiplexing capability is named as a *multiplex link*.

In summary, each DWDM sub-network consists of the following three types of links: DWDM links, express links, and multiplex links. Note that, one express link could consist of multiple DWDM links, and one multiplex link could consist of both DWDM links and express links.

In this paper, we propose an architecture solution on efficiently routing optical circuits over heterogeneous DWDM network under multi-vendor environment, including the data flow, generating reachability matrix, building a cost model graph for routing, selecting the appropriate DWDM sub-networks, deciding where to put regenerators, and assigning wavelengths. Accordingly, we built a circuit planning tool to output the detailed path of a new circuit with GUI (graphical

user interface) to simplify the daily operations for network planners using the architecture and solution presented in this paper.

II. HETEROGENEOUS DWDM NETWORK

A. Requirements for Routing High-Speed Circuits

As mentioned above, a large carrier's DWDM network includes multiple DWDM sub-networks, such as traditional point-to-point DWDM sub-networks, early-stage OADM (optical add/drop multiplexing) sub-networks, and modern ROADM sub-networks. On routing an optical circuit, it is difficult for a network planner to manually determine the routing, choose sub-networks, place regenerators and assign wavelength based on current sub-network topologies and available link capacities efficiently. Unfortunately, the planning tool provided by each vendor only works for its own sub-network. There is no tool or solution to do the job effectively over multi-vendor environment. As the carrier DWDM network becomes more complicated with more high-speed sub-networks, the planners are demanding an automatic tool with GUI to visualize the whole network including all sub-networks as well as capacity usage and hot-spot analysis. For a planning request (source, destination, bandwidth, including/excluding nodes), the tool should be able to find, export and visually display one or more cost-efficient route candidates with the selected sub-networks, regenerator placement and wavelength assignment.

B. Express Links

Several DWDM sub-networks from different vendors using different technologies may or may not co-locate at the same locations. Different DWDM sub-networks usually adapt different proprietary fiber parameters or formulas to calculate the reachable paths. To efficiently route circuits cross multiple sub-networks, we need to generate a reachability matrix for each sub-network using the vendor tool i.e., the list of all reachable paths within the sub-network. They are called as express links for the sub-network. One method to generate the express links for each sub-network is illustrated as follows. Assume the vendor planning tool has one function `ReachablePath()` to determine whether a given path is reachable or not, and function `ReachablePath(p)` returns 1 if path p is reachable, 0 otherwise. Given a sub-network $N(V,L)$, parameter k , where V is the set of sub-network nodes, and L is the set of sub-network DWDM links:

1. For any two node pair $(u,v) \in V$, find the k shortest paths p_1, \dots, p_k .
2. For each i from 1 to k , if `ReachablePath(pi)` return 1, report path p_i .
3. All the reported paths are reachable paths.

Note that different parameter k may produce different set of reachable paths. It is easy to see that the bigger the k , the more complete of the reachable paths. After all reachable paths are found, there is no need to increase k anymore.

However, in real network implementation, we find out that k value between 10 and 15 would be good enough.

C. multiplex links

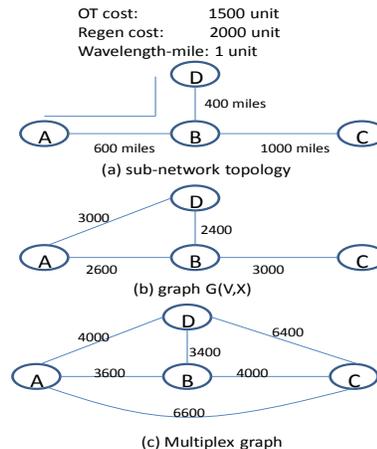


Figure 1: example of multiplex graph

Routing low-bandwidth circuits over high-bandwidth wavelength lightpaths need to use multiplex links. The challenges are to determine where to route each low-bandwidth circuit in the DWDM network and how to multiplex those low-speed circuits optimally to minimize the total network cost. Constrained by current technologies, multiplex links are restricted within each sub-network, i.e., a multiplex link cannot cross more than one sub-network domains. To establish a new multiplex link, a pair of terminal OTs (Optical Transponder) is required at its two end offices. Regenerators are also needed when the multiplex link containing more than one links (DWDM link or express link). Here, we provide a two-step procedure to enumerate all possible multiplex links within each multiplex-capable sub-network.

Step 1: For a sub-network physical topology $N(V,L,E,M)$, where V, L, E, M are the set of nodes, set of DWDM links, set of express links, and set of existing multiplex links of the sub-network respectively, we create a graph $G(V,X)$ whereas the node set V is same as that in the physical topology. Between any node pair, if there is a link in L or an express link in E in the physical topology N , we create one direct edge e in G between the node pair. Its weight $w(e)$ is set as one regenerator cost plus the link's common cost, which is calculated as its distance in mileage multiplied with the unit cost per wavelength-mile.

Step 2: For any node pair in N , if there is no existing multiplex link between them, we create one multiplex link and add it to M by running the shortest path algorithm in $G(V,X)$ with the weights assigned as above. It is easy to verify that the *multiplex cost* to establish the multiplex link between the node pair is the total path weight plus two terminal OT cost minus one regenerator cost. Then the set of multiplex links M are full

mesh links in the sub-network with calculated corresponding multiplex costs.

With the above the two steps, we build a full mesh graph, named as *multiplex graph*. The weight of each edge reflects the cost to establish a multiplex link between its end nodes.

Figure 1 shows a sample multiplex graph construction, based on the simple physical topology with 4 nodes and 3 DWDM links. Figure 1.a is the physical topology with cost parameters, figure 1.b is the constructed graph $G(V,X)$ with edge number as cost units, while figure 1.c is the full mesh multiplex graph with associated multiplex link cost units. In Figure 1.a, we assume the OT cost is 1500 unit, regen cost is 2000 unit, and wavelength-mile cost is 1 unit per wavelength-mile. In graph $G(V,X)$, the edge weight is set as one regen cost plus its common cost, for example, edge BD weight is $2000 + 400 \times 1 = 2400$ units. In figure 1.c, each link stands for one multiplex link and the number on the link is the cost to create the multiplex link, which is calculated as the total path weight from graph $G(V,X)$ plus 2 terminal OT cost minus 1 regen cost. We take multiplex link BD as one example, since the total shortest path weight from $G(V,X)$ between B and D is 2400, the multiplex cost for BD is $2400 + 2 \times 1500 - 2000 = 3400$ units.

III. CIRCUIT PLANNING TOOL METHODOLOGY

D. Architecture of Circuit Planning Tool

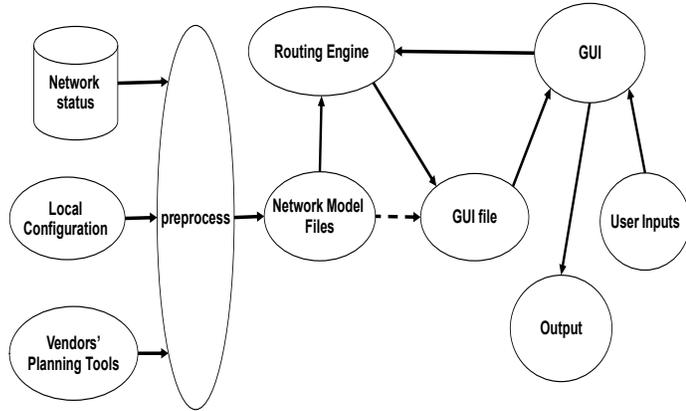


Figure 2: High Level Data Flow

Figure 2 shows the architecture of our circuit planning tool. Network status component collects the information of each DWDM sub-network for links (distance, total capacity, available capacity, wavelength status) and nodes (such as

latitude and longitude). Local configuration component maintains optical transponder costs, regenerator costs, multiplex terminal costs, and multiplex capabilities of each sub-network. It also keep some local configuration constraints, for example, a sub-network may have some special constraints on wavelength assignment, some locations may have space/electricity constraints for regenerator, et al. Vendor's planning tool is used to determine whether a path within its sub-network is reachable or not. The preprocess component integrates the three data sources to create several unified network model files for DWDM nodes, DWDM links, express links, and multiplex links. Those files are used by the GUI component to visualize the network topology and usage information. A user can interact with GUI to specify routing requests, which are forwarded to the routing engine. The GUI will display the routing solution returned by routing engine and the user has a chance to tune the results by changing some parameters. After the user confirms the route, the GUI can export the detail route to other systems for field operation.

E. Routing Engine Flow Chart

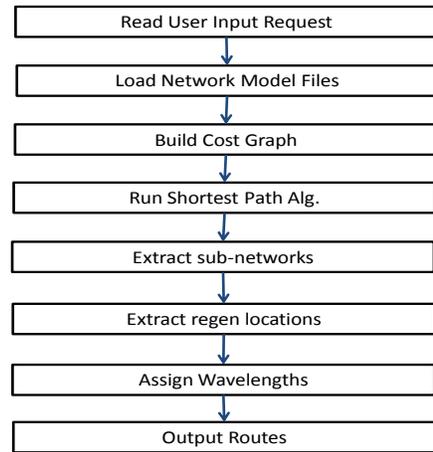


Figure 3: Routing Engine Procedures

Figure 3 shows a total of eight steps within the routing engine module. After getting the routing request forwarded by the GUI, the routing engine loads the network model files generated by preprocess module and filters out some links not meeting user requirement. For example, if a user is requesting a 10Gpbs circuit, those links only supporting 2.5Gpbs are excluded; if user is requesting a 2.5Gpbs circuit, those links supporting only 10Gpbs and 40Gpbs are excluded. Thereafter, the routing engine builds a cost graph model with an appropriate weight assigned on each edge. The shortest path algorithm is applied on the cost graph model to find a shortest path from source to destination. From the solution path, the

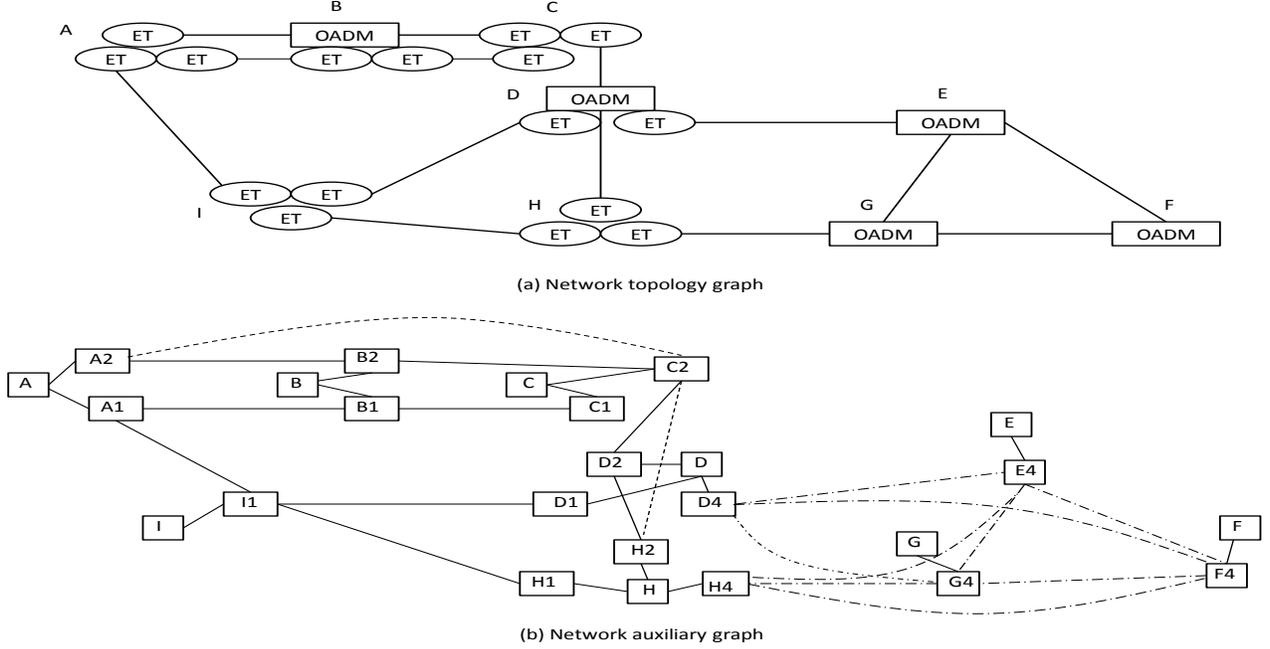


Figure 4: Example of Cost Graph Model

routing engine can extract the sub-networks along the path and the regenerator locations. For each link on the selected sub-network along the solution path, the first fit or other sub-network constrained wavelength assignment policy is used to choose the wavelength. Finally, the output is sent back to GUI for visualization and planner confirmation.

F. Cost Graph Model

One high-speed circuit over multi-vendor DWDM network could route over multiple sub-networks and require several OTs/regenerators to connect them considering both OT/regenerator cost and common cost. Again common cost is model as total mileage multiplying unit cost, denoted as cost per wavelength-mile. Each sub-network has its own unit cost. To find the cost effective route, we introduce a cost graph for a given network and search for the shortest path between source and destination. Denote $S(V,L,E,M)$ for a given network state, where V is the set of the network ROADM locations, L is the set of DWDM links, E is the set of express links (or reachable paths), and M is the set of multiplex links. Let $G(V',E')$ be the corresponding cost graph, where V' is the extended vertex set and E' is the extended edge set. Inside each network ROADM location, different sub-network terminals may co-exist. Then for each ROADM location i in N , we create N_i+1 vertexes in G assuming there are N_i types of sub-network terminating at location i , i.e., one vertex is for the real traffic termination and N_i vertexes for the N_i sub-network types. Then there are total $\sum_i (N_i+1)$ vertexes in G . Next, we create N_i edges for each ROADM location for G : from the traffic termination vertex, we add one edge to each of the corresponding N_i (sub-network type) vertexes with an edge

cost of $(TermOT_cost_i - Regen_cost_i/2)$ for regular type and 0 for multiplex type, where $TermOT_cost_i$ is the cost of terminal OT for the sub-network type i and $Regen_cost_i$ is the cost of regenerator for the sub-network type i . The edge cost is non-negative since half regenerator cost should be less than one terminal OT cost of the same sub-network type. For any link from L and E with sufficient capacity, we first identify the specific sub-network type and its two end ROADM locations. Then we locate the corresponding sub-network type two vertexes and create one edge between them, whose cost is the sum of one regenerator cost plus the link's common cost of this sub-network. Similarly for any link from M with sufficient capacity, we identify the two end ROADM locations and the specific multiplex type, locate the corresponding sub-network type two vertexes and create one edge between them, whose cost is the multiplex cost of the multiplex link. It is easy to verify that a circuit routed between two traffic termination vertexes in G has the same optical transponder cost and common cost as it routed in S .

Figure 4 shows one simple example of network topology graph and its corresponding cost graph. In Figure 4.a, there are totally 9 network office locations, named from A to I, and there are total 3 types of DWDM systems: the first one is point-to-point DWDM systems, A-B, B-C, A-I, I-D, and I-H, supporting 2.5Gbps per wavelength only; the second one is degree-2 OADM systems, A-B-C and C-E-H, supporting both 2.5Gbps and 10Gbps per wavelength without multiplexing capability; the third one is multi-degree OADM systems, H-G-F-E-G, supporting both 10Gbps and 40Gbps per wavelength

with multiplexing capability. For the third multi-degree OADM system, due to optical reachability constraints, we assume that there are only two express links H-G-F and D-E-F, but there are 9 potential multiplex links. For a user request $\langle A, F, 2.5\text{Gbps} \rangle$, we build the cost graph as follows: location A has two sub-network types, type1 and type2, we create three vertexes, A, A1, and A2. Location B has two sub-network types terminating here, so we create three vertexes, B, B1, B2. Location C has two sub-network types and we create three vertexes C, C1, and C2. Although location I has three sub-networks terminating here, they are all the same sub-network type. We only create two vertexes I and I1. Similarly we see that both location D and location H have three sub-network types while location E,F,F only has sub-network type3 terminating here. Although type 3 does not support 2.5Gbps connection per wavelength, it provides multiplex link to support 2.5Gbps circuits. We name the multiplex link type as type4. Figure 4.b is the corresponding cost graph of network Figure 4.a.

Suppose the shortest path from A to F on the cost graph is: $A \rightarrow A2 \rightarrow C2 \rightarrow D2 \rightarrow D \rightarrow D3 \rightarrow F3 \rightarrow F$. The path cost would be $(\text{TermOT_type2} - \text{regen_type2}/2) + (\text{regen_type2}) + (\text{regen_type2}) + (\text{TermOT_type2} - \text{regen_type2}/2) + 0 + \text{multiplexcost_DF} + 0$, which is $2 * \text{TermOT_type2} + \text{regen_type2} + \text{multiplexcost_DF}$. The cost matches physical device requirement for the circuit deployment: one type2 terminal OT at location A, one type2 regenerator at location C, one type2 terminal OT at location D, and one multiplex link between location D and location F over sub-network type3.

Claim: Thus the path with smallest weight corresponding to the least cost route over the network.

Note that in the example above, we only account all the equipment cost including terminal OT and regenerator. If we count the common cost, the above claim would still be true.

V. EXTRACT SUB-NETWORKS, REGENERATOR LOCATION AND WAVELENGTH ASSIGNMENT

After finding the shortest path from the cost graph, we need to find the corresponding physical sub-networks, regenerator locations, and assign wavelengths to the selected links along the route. When creating the cost graph, for each inter-city link, we always find the two vertexes with the same sub-network type on the two end locations. Thus sub-network type change only occurs inside a location. For the shortest path from the cost graph, we can easily identify the sub-network types from the edges corresponding to inter-city links. If two adjacent edges corresponding to the same sub-network type, it means the common location requires one regenerator of the sub-network type. Otherwise two adjacent edges corresponding to two sub-network types, and two terminal OTs would be required at the common location, one terminal OT for one sub-network type. After identifying the sub-network types and regenerator locations, we have identified the inter-city links for the selected path. For each intercity link

along the selected path, we may apply either sub-network constrained wavelength assignment policy (vendor proprietary), first-fit policy, or other wavelength assignment policies with different constraints [5,6,7].

IV. GRAPHICAL USER INTERFACE

We developed a web-based tool to integrate the proposed methodology of routing high speed circuits over heterogeneous networks through a graphic user interface. The tool provides visualization of the heterogeneous DWDM network and the status of its DWDM links (sub-network type, distance, maximum and available wavelengths number, deployment date and other related information). It can show the whole network or any particular set of sub-networks filtered with the sub-network types and/or the supported maximum speeds. It can also predict and highlight those hot-spot links, i.e., DWDM links that will be exhausted by a specified future date based on historical circuit requests and wavelength usage information. After a planner specifies a circuit request with source, destination, bandwidth, acceptable sub-network types, expected deployment time, node inclusion/exclusion list, the tool will output three smallest cost paths and one shortest mileage path for the planner to choose. The planner can even request multiple circuits with same or different source-destination pairs diversely routed from each other in the underlying fiber network. The tool can complete most task computations within several seconds and provide visualization of several candidate paths for interactive navigation. The tool has been deployed since 2009 and is actively used by network planners for their daily circuit planning tasks.

Figure 5 shows a snapshot of a synthetic carrier heterogeneous network. Different sub-networks co-locate at a common office, and different sub-networks may share the same fibre route. The main GUI consists of control panel for routing and legends, network panel with geographical map background, and information panel for nodes, links and routes related information visualization. New features and functions to enhance this tool is a on-going effort, such as new sub-network platform addition, new diverse routing constraints, new regeneration location constraints, new application specific constraints, et al.

VI. CONCLUSION

With new technology innovation and traffic growth, a large carrier's DWDM network has become to a multi-vendor, multi-technology heterogeneous network. It is impossible for a planner to manually route a high-speed circuit or purely depend on vendor's planning tool. In this paper, we presented a systematic solution on efficiently routing a high-speed circuit over such a multi-vendor network and implemented a circuit planning tool to aid planners for daily operation.

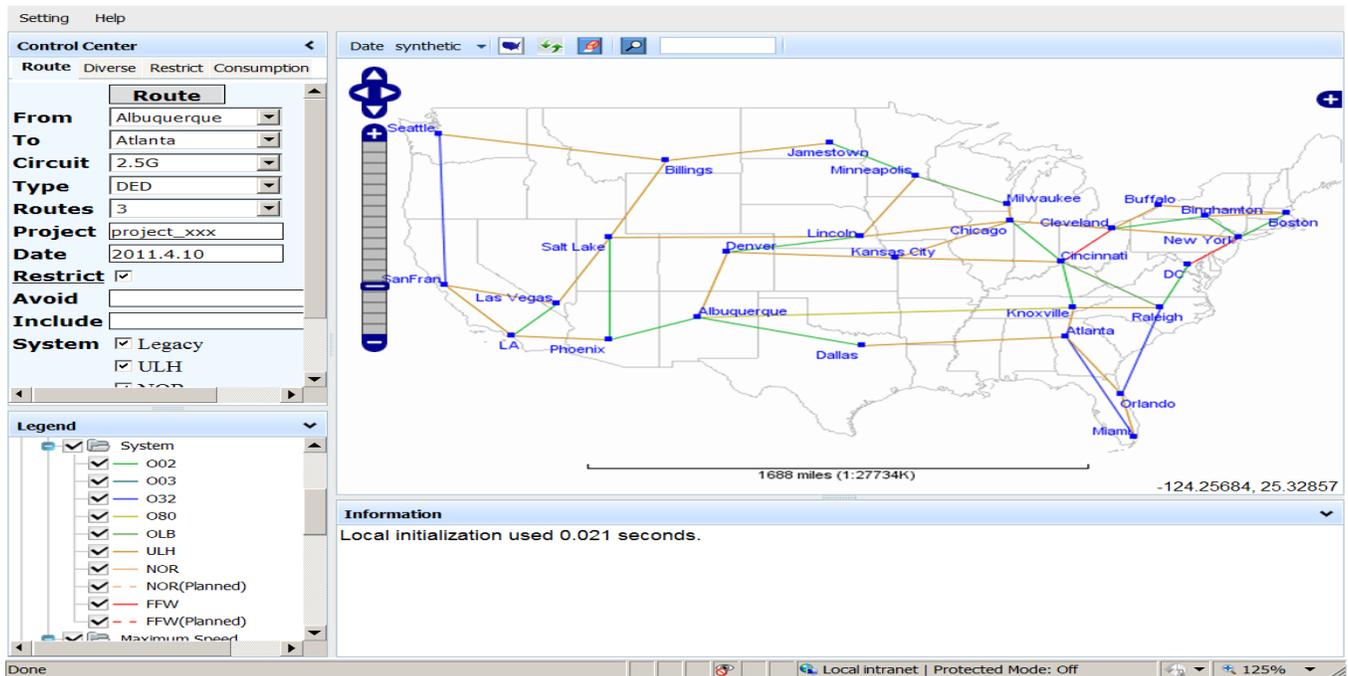


Figure 5: A Snapshot of GUI

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