Line system design for DWDM networks

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Abstract

A line system is a linear sequence of network elements (OADMs) and fibers, all optically transparent. We describe algorithms for partitioning a DWDM mesh network into line systems, given a demand matrix.

Perferred topic area: 1A.

1 Introduction

State-of-the-art dense wavelength division multiplexing (DWDM) allows data transport with very high capacity, measured in terabits per second, and very long reach, thousands of kilometers. One current DWDM technology arranges network elements into line systems, where a line system is a path consisting of alternating network elements and optical fibers. Data can enter and leave a line system at a network element, requiring electrical to optical conversion, but within the line system data remains purely as an optical signal.

The design of such DWDM networks involves algorithmic problems such as grooming [1] and span engineering [2]. The topic of interest here is line system design, that is, the choice of line systems that partition a given mesh network. Figure 1 shows an example of a synthetic backbone network over the continental US and a possible partition into line systems.

We have developed a design tool, Ocube, that designs line systems for Lucent's LambdaXtreme DWDM product family. Ocube has been used to give candidate designs for a number of carrier backbone networks; these designs are used for comparative evaluation of DWDM products. The carrier networks vary in size from a dozen nodes to a few hundred nodes. Fiber usage varies from a fraction of a fiber to three fibers per link.

This paper describes the algorithms used in the Ocube design tool. As might be expected, the underlying algorithmic problem is NP-complete. We describe various exact and efficient algorithms for special cases then describe heuristics used in general.

2 Line system design

We are given a network of available dark fibers, already buried, a list of traffic demands, and a set of optical equipment with price tags. The network is modeled by an undirected graph $G = (V, E)$. Each fiber can carry data on a fixed number of wavelengths, depending upon its type (typically 64 to 128). For simplicity, we treat a single fiber as capable of carrying traffic in both directions (a fiber pair is actually needed).

A demand is a triple (a, z, p), where $a \in V$ and $z \in V$ are the source and destination nodes and p is either "1+0" or "1+1"; the latter requires a pair of edge- and node-disjoint paths between a and z. Each demand represents bandwidth equal to the bandwidth carried by a single wavelength. Demands are symmetric, that is, the demand (a, z, p) specifies one unit from a to z and one from z to a.

A *line system* consists of an *end terminal* (ET), followed by an alternating sequence of fibers and *optical add/drop multiplexers* (OADMs), and ends with a fiber connected to an ET. Notice that an ET has exactly one fiber incident, and an OADM has exactly two fibers incident. A data stream can enter a line system at either an ET or an OADM. To do this it requires an *optical translator* (OT), which converts the data stream to a particular optical wavelength. The data stream can traverse the line system, at this wavelength, to another ET or OADM. It can then leave the line system, where another OT is required. The data stream can traverse many line systems, requiring an OT upon entering and another upon exiting each line system.

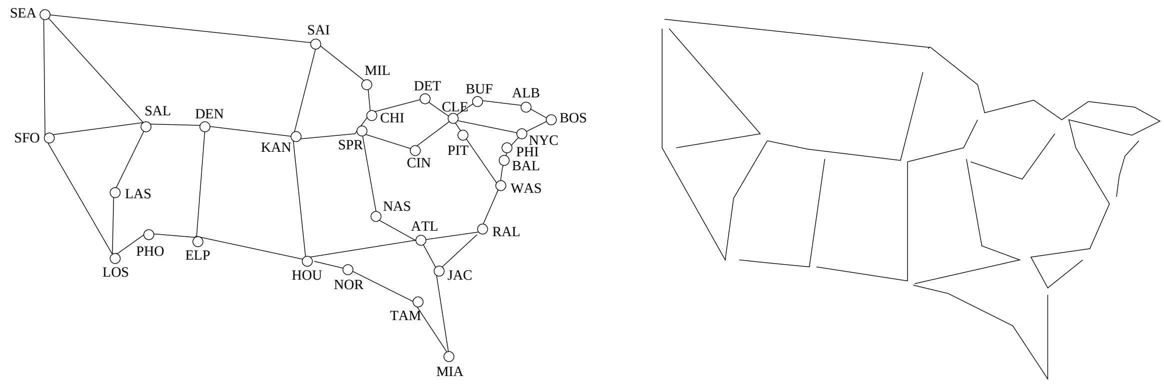

Figure 1: (Left) A synthetic US backbone network. (Right) A partition into line systems.

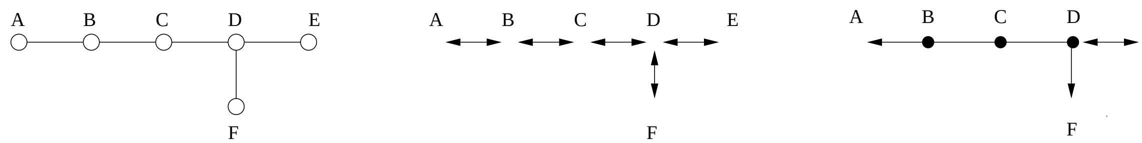

Figure 2: (Left) A dark fiber network. (Middle, Right) Two possible line system designs. Arrows denote ETs and solid circles denote OADMs.

A *line system design* is a partition of the edges of the graph into a set of paths, each path determining a line system. A *routing* determines a path for each demand (or pair of disjoint paths if the demand is 1+1). The *line system design problem with routing* is to choose (1) a line system design and (2) a routing for each demand to minimize total equipment cost.

Figure 2 gives a dark fiber network and two possible line system designs. Both designs require the same number of end terminals and OADMs. For the middle design, a unit demand from A to E requires two OTs (one each at A and E) while a unit demand from A to F requires four OTs (one each at A and F and two at D). If the demand is 2 from A to E and 1 from A to F; the middle design requires the fewest OTs; if the demand is 1 from A to E and 2 from A to F; the right design requires the fewest OTs.

Equipment costs OADM:ET:OT are roughly in the ratio 20:10:1. However, actual costs are quite complex. For example the cost of an ET is a step function of the number of wavelengths that are terminated at the ET. Each jump in cost reflects extra circuit packs added for additional wavelengths carried.

Other constraints complicate the line system design problem. The line system may have a bound both on fiber length and on the number of permissible OADMs. Each optical signal has a *reach* limit, which bounds the fiber distance that can be traveled on a single line system before the optical signal becomes degraded. If the reach limit is exceeded, the optical signal must be regenerated by a pair of OTs.

3 Design heuristics

The line system design problem with routing is easily shown to be NP-hard, even with a very simple model of equipment costs.

We experimented with an integer programming formulation of the problem. Such a formulation is complicated. For example, for each pair of edges incident to a vertex, there is a 0-1 variable that expresses whether that pair of edges is optically connected with an OADM. Linear constraints guarantee that at each vertex, each edge incident to the vertex is connected to at most one OADM. The 0-1 variables are used to model the OT cost of a path satisfying a demand. The global objective function attempts to minimize total equipment cost.

Unfortunately, integer programming is unattractive in this case. First, observed solution times were seriously exponential in the size of the network (e.g. tripling with the addition of a node and link), making the approach infeasible except for tiny networks. Second, it is difficult to model the constraints accurately. For example, equipment costs are step functions, not linear, and bounds on line system length,

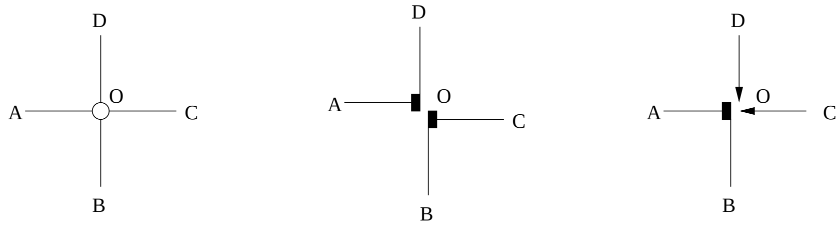

Figure 3: (Left) A deg-4 node O where the through traffic $T(AOB) = 6$, $T(AOC) = 1$, $T(AOD) = 5$, $T(BOC) = 5$, $T(BOD) = 7$ and $T(COD) = 0$. (Middle) MAX THRU places OADMs along *A-O-D* and *B-O-C* and maximizes the total through traffic at O to 10. (Right) MAX REDUCTION may place an OADM along *A-O-B* if this choice reduces the total cost the most.

reach, and OADM count require transitive-closure-like constraints, not easily expressed with linear programming. We discovered that the heuristics described below gave better results. For this design problem, heuristics with an accurate model of the objective function determined cheaper designs than did integer programming with a simplified objective function, while simultaneously reducing computation time.

We first describe some special cases where efficient (i.e. polynomial time) exact algorithms are available.

3.1 Routing with fixed line systems.

For this problem, we assume that the line system design has been fixed. For simplicity, we also ignore fiber capacity. The goal is MIN OT routing, i.e. routing each demand to minimize the number of OTs. We define a new distance function on any pair of adjacent links. If the two links are in the same line system, then the distance is zero. Otherwise, the distance is one. Under this distance function shortest paths are least OT paths. For any demand with 1+0 protection, we can use Dijkstra's algorithm to find a shortest path; for any demand with 1+1 protection, we can use Suurballe's algorithm [4] to find a shortest cycle that contains the source and destination nodes.

Theorem 1 *If OTs have no reach limit,* MIN OT *routing produces optimal routing for any fixed line system design.*

3.2 Designing line systems with fixed routing.

For this problem, we assume that routing has been fixed, and we wish to choose the line system design to minimize the number of OTs. For every pair (u, v) and (v, w) of adjacent links, the *through traffic* $T(u, v, w)$ is the number of unit demands routed u, v, w. If 2 ETs are placed at v, one incident to (v, u) and the other to (v, w) then every unit of through traffic requires 2 OTs at v. On the contrary, if an OADM is placed at v along the direction of u-v-w then no OTs are required for through traffic.

The MAX THRU algorithm chooses, for each node v, a matching of the links incident to v so as to maximize the sum of the through traffic on the matched pairs of links. It then assigns an OADM to each matched pair of links. An ET is placed at any remaining link endpoint. See Figure 3.

Theorem 2 *If line system cycles are allowed, line systems have no length limit, and OTs have no reach limit then* MAX THRU *produces an optimal line system design for the fixed routing.*

Proof: Let $T(v)$ be the total traffic that passes through but does not start or end at v. For a specific line system design, let $M(v)$ be the total traffic through v that passes through an OADM. The number of demands that have to switch from one line system to another at node v is $T(v) - M(v)$. Since $T(v)$ is determined by routing, and MAX THRU maximizes $M(v)$ at each node, no algorithm can outperform MAX THRU. □

The MAX THRU algorithm may well introduce line system cycles, which are not allowed, and may not respect the constraints on line system length and OADM count. It is easy to modify the algorithm to examine each node in turn, choosing an OADM on the basis of through traffic but inserting it only if no constraint is violated (of course, the guarantee of Theorem 2 no longer applies).

An alternate algorithm is MAX REDUCTION. The MAX THRU algorithm does not directly model the

Demands	Optimal ($M)	Our solutions ($M)	%difference
89	101	103	1.98
176	127	131	3.15
264	159	165	3.77

Figure 4: The first column gives the total number of single-wavelength demands; on average each demand traverses about 4.5 links.

Nodes	Links	Demands	Max Thru ($M)	Max Reduction ($M)	%difference
45	61	877	345	315	8.70
52	75	2319	609	578	5.09
52	75	4173	1063	927	12.80

Figure 5: Comparing Max Thru and Max Reduction.

global system cost. Global cost is complicated because of all the side constraints (OT reach, line system length, channel capacity, complex equipment costs). Global cost is however determined once routing and line system design are fixed. Like Max Thru, Max Reduction algorithm assumes a fixed demand routing. OADMs are chosen by examining each node in turn. After examining some nodes, the OADM assignment at those nodes are known. At the next node n, all possible OADM assignments at n are enumerated. For each such assignment, the global network cost is evaluated using the OADM assignments for previously examined nodes and no OADMs at unexamined nodes. The assignment at n that leads to minimum cost is then chosen for n, and the next node examined.

3.3 Combined routing and line system design.

A complete heuristic algorithm, when routing is not known, can be obtained by combining Max Thru (or Max Reduction) and Min OT. An initial routing is found, say using shortest fiber distance. A line system design is found, with Max Thru (or Max Reduction), and then Min OT can be used to reroute, given the line systems. In principle further iteration is possible.

3.4 Lighting fibers on a subset of links.

When a network is lightly loaded, the lit fibers carry traffic much below what the fiber capacity would allow. The cost structure of ETs and OADMs presents a "buy-at-bulk" nature, i.e. as an ET carries more wavelengths the ET cost *per wavelength* is reduced. Hence, one effective way to reduce the total equipment cost in a lightly loaded network is to light fibers only on a subset of the network links.

To choose unlit links, we order the links by the traffic that they carry, the least loaded first. This ordering frees ETs and OADMs that have the highest per wavelength cost. We try each link in turn; if deleting the link reduces total equipment cost, we declare the link dark.

3.5 Wavelength assignment.

Wavelength assignment for one line system is independent of wavelength assignment for any other line system, since a data stream switching from one line system to another must first be converted to an electrical signal. Assigning wavelength to each demand within each line system is equivalent to the classic *interval graph coloring* problem, which can be solved optimally and efficiently (see e.g. [3, 5]). We omit details here.

4 Implementation

We have implemented the heuristics described above using Python. Our implementation also addresses many issues that are not discussed above, e.g. multiple fiber types, multiple fibers per link, incremental designs and hybrid designs with multiple subchannels per wavelength.

It is hard to determine how close to optimality our algorithms are. As mentioned earlier, the design problem is NP-hard even in very special cases. Figure 4 compares our solutions to solutions found by exhaustive enumeration. The network has 24 nodes and 27 links (thus six nodes of degree 3) and some degree of complexity, since it has multiple fiber types with differing capacity.

Figure 5 compares Max Thru and Max Reduction; the latter is consistently better by 5-15%. However, Max Thru has the advantage in running time.

If networks are lightly loaded, the heuristic of choosing lit fibers is particularly effective. It is often the case that chordal links from cycles are good candidates to be unlit. For example, for the synthetic network shown in Figure 1, not lighting links SFO-SAL, DEN-ELP, KAN-HOU and ATL-RAL reduces the total cost by roughly 9%. (Of course, when some links are unlit Ocube finds a different set of line systems from those shown on the right of Figure 1.) For lightly-loaded carrier networks, we have observed savings in the range 7% to 12% by keeping some fibers unlit. As demand increases, this savings usually decreases and eventually disappears.

In addition to providing designs, Ocube has been very useful in quantifying the effects of changes in design rules. For example, OT reach and line system length could perhaps be increased by more expensive OT designs. The plot in Figure 6 demonstrates the dependence of OT count on line system length and OT reach for a sample network and demand set. Clearly such information can help evaluate alternate equipment designs.

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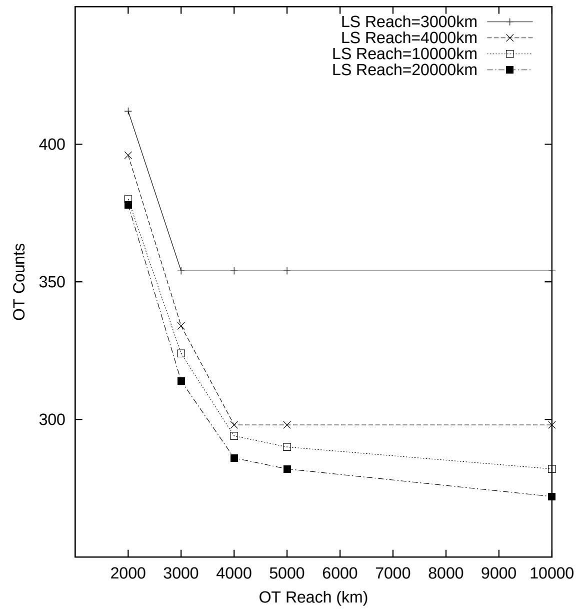

Figure 6: OT counts for varying OT reaches and line system length limits. When the OT reach is longer than the line system limit, OT counts cannot be reduced further no matter how big OT reach is.

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