Maximizing the Transparency Advantage in Optical Networks

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Abstract: We enhance the potential cost savings from optical network transparency by applying *Connected Dominating Sets* and impairment-aware routing, thus reducing the density of OEO nodes substantially below that obtained with more straightforward path improvement heuristics.

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1. Introduction

All-optical transport offers significant advantages to carrier networks, including protocol and format independence and substantial cost savings from reduced numbers of OEO interfaces. However, routing in large-scale transparent networks, which may include many transparent network elements and/or long distances, is problematic because optical signal impairments may accumulate along end-to-end routes. OEO conversion repairs these impairments, but is expensive. Current methods for locating OEO capability operate by iteratively improving pre-computed routes [1]. In this paper, we decouple design from routing to identify significantly more cost-effective OEO placements. Our placement strategy assures that at least one impairment-feasible path exists between *every* pair of nodes in a network. Providing this level of assurance puts us in a regime where call admission and connection set-up can be viewed, once again, as capacity issues. We then apply an impairment-aware routing algorithm that is guaranteed to find the impairment-feasible paths assured by our placements.

This paper focuses on metropolitan-scale networks in which the distance and number of consecutive transparent nodes between OEO nodes in a path must be constrained. Optical signal impairments were modeled analytically with realistic parameters to derive two sets (for OC48 and OC192) of example constraints on distance and consecutive transparent hops. Paths that stay within transparent distance and node limits are considered *impairment-feasible*. These limits provide a surrogate for more detailed error modeling. They capture impairment effects while remaining manageable within the context of design and routing algorithms. We use these constraints to model feasibility in the design problem, which is addressed as a connected dominating set problem. We then embed these same constraints in an impairment-aware routing algorithm. We contrast the results with a more standard approach and show that the number of OEO nodes needed to assure the required level of feasibility is dramatically reduced.

2. OEO Placement Algorithms

We consider two OEO placement strategies. Both try to guarantee that there exists at least one impairment-feasible path between each pair of nodes, while minimizing the number of OEO nodes placed. The difference, however, is that the first generates a set of paths and then tries to place the fewest OEO nodes to make these paths feasible, while the second simply tries to assure that *some* feasible path exists between each pair of nodes. The first strategy is reminiscent of methods proposed in [1], while the second views feasibility as a more general topological property that is independent of any particular set of routes. This latter algorithm places OEO nodes as "stepping stones" to be exploited by impairment-aware routing algorithms.

2.1 Assuring Feasibility for a Given Set of Paths

Our algorithm for selecting OEO nodes to make a *given* set of paths feasible is similar in spirit to methods proposed in [1]. Like those methods it tries to select nodes that are most central, but our algorithm directly measures the impact of each successive choice on feasibility.

Path-Improvement Heuristic: We are given a set of paths that we need to make impairment-feasible by placing OEO nodes. **Initialization.** For each path, determine whether or not it is feasible. For each node that is not an

OEO node compute: the number of feasible paths it is on; the number of infeasible paths it is on; and the number of paths that would become feasible if it were an OEO node. **Main Step.** Select the next OEO node to be the one that would make the most paths feasible, break ties by selecting the node on the most infeasible paths, and if there are still ties select the node that is on the most paths. Update the path and node information to reflect the newly selected OEO node and repeat the main step. **Termination.** The algorithm can stop when all paths become feasible, or if more OEO locations are desired, it can continue until reaching the desired number.

2.2 Assuring Existence of Feasible Paths

We can solve a *connected dominating set (CDS) problem* [2] to identify a set of OEO locations that assure a feasible path between each pair of nodes. A dominating set in a graph is a set of nodes *S* such that every node not in *S* is adjacent to a node in *S*. A connected dominating set is a dominating set *S* that remains connected when all nodes that are not in *S* are removed from the graph. Finding the smallest CDS on a general graph is NP-hard, so we adapt a heuristic described in [2].

The graph in which we identify a CDS is not the original network but a related graph that we construct. The new graph has a node that corresponds to each node in the original network. Two nodes in the new graph are connected if there is a feasible path between them in the original network where all nodes are transparent. (We can identify such paths by solving a sequence of shortest minimum-hop path problems.) The nodes in a CDS on this graph correspond to OEO locations that provide the necessary feasibility in our original network.

To see that there must be a feasible path between each pair of nodes given this OEO placement, note that by definition every node not in the dominating set is adjacent to a node in the dominating set. By construction of our surrogate network, this means that there is a feasible path between them in the original network. Thus, every transparent node can reach some OEO node. Since the CDS is connected, all the OEO nodes can feasibly communicate with each other.

3. Routing Methods

Once the design methodology provides feasible routes, it is the purview of the routing algorithm to find them. We consider two routing algorithms in this study. The first is the Bellman-Ford shortest path algorithm [3]. When applied independently from OEO placement, this algorithm is oblivious to both OEO placement and impairment constraints. In the experiments that follow, the path-improvement heuristic places OEOs using paths generated by shortest-path routing. Thus, the case that combines path-improvement with oblivious shortest-path routing represents a "best-case" scenario for shortest-path routing.

Our second routing method constrains both the distance and the number of nodes along each transparent subpath to provide an impairment-aware routing algorithm. It is implemented as a modification of a standard shortest path algorithm (Bellman-Ford or Dijkstra [3,4]) and can be viewed as finding a shortest path in a network that is expanded to reflect both the distance and the number of transparent nodes between OEO nodes. (Examples of similar time-expanded networks appear in [4].) Our particular expansion explicitly takes into account the restorative effect of OEO conversion. The running time of the impairment-aware routing algorithm depends on the distance limit; therefore, it is not a polynomial-time algorithm, but it appears to be practical for realistic network sizes.

4. Experiments and Results

We conduct experiments on a 200 node network with randomly-placed nodes and "LATA-like" connectivity mimicking that of proprietary real networks. The results obtained for this network are consistent with results for both real and similarly-generated random networks.

We apply both the oblivious-shortest-path and the impairment-aware routing strategies with three different OEO placement strategies. The placement strategies include random placement along with the two strategies in Section 2. We implement these methods to generate a full ordering of the nodes in a list that defines the order in which they would be selected as OEO nodes. This affords us the flexibility to vary the *number* of OEO nodes in computational tests. Section 2.1 describes how to extend the path-improvement heuristic (PIH) to order all nodes. The CDS approach is extended by restarting it after a dominating set is found to identify a new dominating set among the remaining transparent nodes. The extension has the property that any remaining transparent node can reach at least i OEO nodes after the i^{th} round. We apply both routing algorithms with a "minimum-hop" objective criterion, and we apply PIH to the minimum-hop paths identified by oblivious shortest-path routing.

Figures 1 (for OC192) and 2 (for OC48) show the number of impairment-feasible paths found by each of the two routing methods, for each of the three OEO placement methods, as a function of the number of OEOs placed.

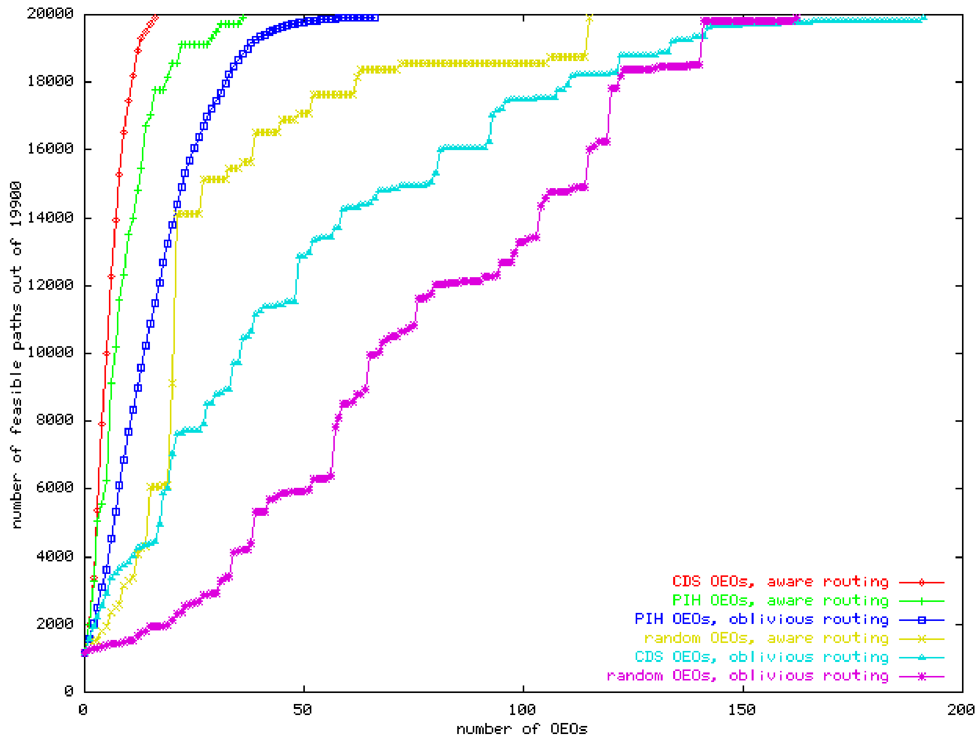

Figure 1. Experimental results for limits of 3 transparent nodes and 80km between OEOs

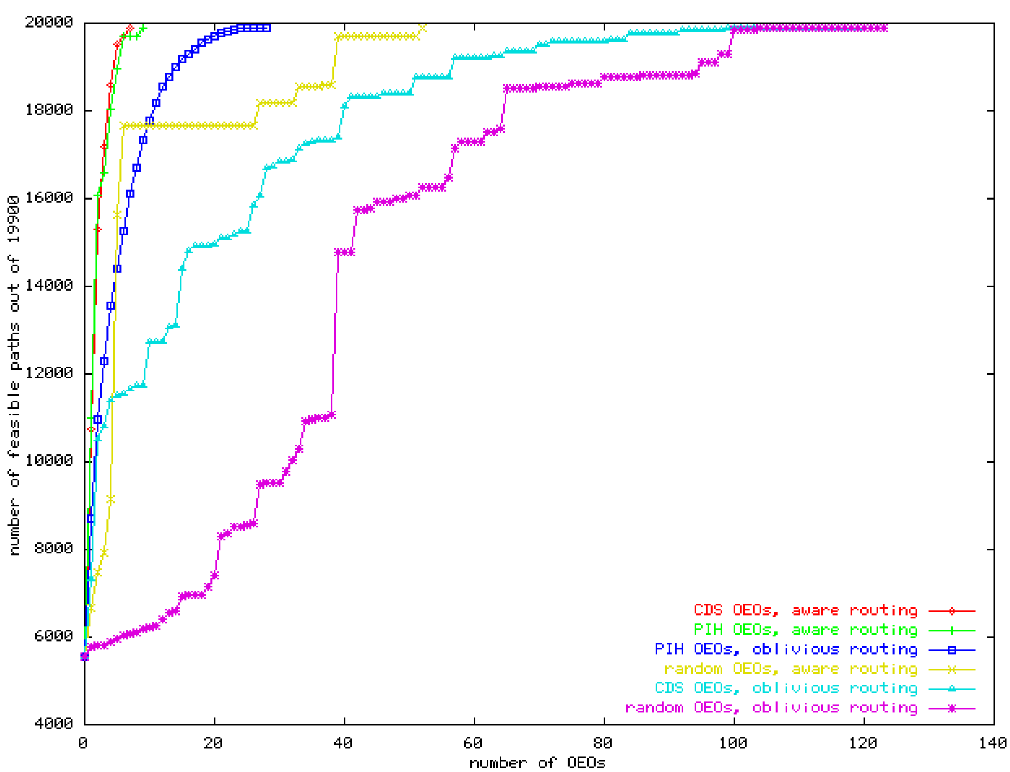

Figure 2. Experimental results for limits of 6 transparent nodes, 170km between OEOs

5. Conclusion

Significant results from the figures are summarized in Table 1. We note that CDS design with impairment-aware routing requires only 16 OEO nodes in the first example and 7 in the second to assure feasible paths, whereas the more standard approach based on PIH with shortest-path routing requires 66 and 28 OEO nodes respectively. We see that impairment-aware routing finds dramatically more feasible paths than oblivious routing for the same number of OEOs from the same placement method. We also find that, under impairment-aware routing, the CDS method needs to place fewer OEOs than the PIH method to provide feasible paths for all pairs of nodes. Our results show that we can assure impairment feasibility between all pairs of nodes using remarkably few OEO nodes.

Table 1. Summary statistics for different combinations of routing and placement methods

	3 transparent nodes and 80 km limits		6 transparent nodes and 170 km limits	
	OEOs needed to provide a feasible path for each pair	Percent of pairs feasible with 16 OEOs	OEOs needed to provide a feasible path for each pair	Percent of pairs feasible with 7 OEOs
CDS & aware routing	16	100%	7	100%
PIH & aware routing	36	89%	9	99%
PIH & oblivious routing	66	58%	28	81%
Random & aware routing	115	30%	52	89%
CDS & oblivious routing	191	22%	119	59%
Random & oblivious routing	162	10%	123	30%

6. References

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