Cost-conscious impairment-aware routing

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Abstract: We present a method for impairment-aware routing in transparent networks that allows constraint dependencies and objectives minimizing regeneration cost. The method is *guaranteed* to identify impairment-feasible paths when they exist and uses transponder resources efficiently.

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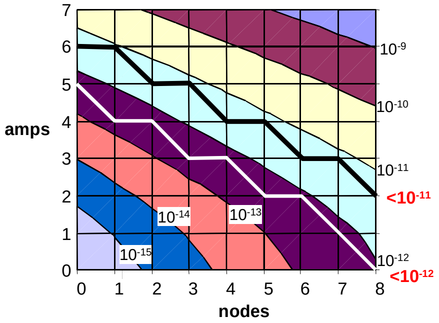
1. Introduction

Routing in large-scale transparent networks is problematic because optical signal impairments may accumulate along end-to-end routes. OEO regeneration repairs such impairments, but is expensive. We describe an impairment-aware routing strategy to identify least-cost impairment-feasible routes. This strategy is *guaranteed* to find an impairment-feasible route for a given request assuming sufficient capacity exists in the network. Moreover, when each OEO-capable node has an associated cost for regeneration, the route identified is the least-cost impairment-feasible route between the designated nodes. By applying appropriate costs, we can minimize the number of OEO regenerations performed, the number of new transponders required, or balance costs associated with using new versus existing transponders.

2. Impairment Models

Methods for routing in networks with transparent elements need models for impairment accumulation to provide regeneration when it is needed. Several authors (e.g. [1],[4],[5]) suggest bounding the number of nodes traversed and/or the distance between OEO regenerations as a means to limit impairment. Such limits are surrogates for more detailed error modeling, capturing main effects while remaining manageable within the context of routing algorithms. The specific constraints to apply depend on the transmission rate and network equipment, and may be derived either analytically or through simulation. We obtain limits using the LinkSIM [3] simulator. Simulation permits the effects of several impairments to be addressed simultaneously, instead of as independent constraints on individual impairments, which allows us to use end-to-end BER as the defining criterion for link performance.



	Allowable Fiber Range (km)	
Nodes	For BER < 10^{-12}	For BER < 10^{-11}
0	552	644
1	460	644
2	460	552
3	368	552
4	368	460
5	276	460
6	276	368
7	184	368

Figure 1: Contour plot of BER for 2.5 Gb/s with table of implied node and distance limits.

To obtain sample distance and node limits we assume a data rate of 2.5 Gb/s and make several simplifying assumptions. We assume that: all link lengths/fibers are identical CSMF (0.25 dB/km, 17 ps/nm/km, 2 dB excess loss per link); all amplifiers (inline and those at transparent nodes) are identical (25 dB gain, no saturation problems, NF=5 dB); and links are deployed in unity gain sections (92 km fiber spans). The current simulation models only the combined effects of attenuation and dispersion, which are dominant effects at 2.5 Gb/s. Results are summarized in Figure 1 by a contour plot of BER as a function of the number of nodes and amplifiers traversed. Superimposed on this plot are staircase functions indicating integer-valued limits on numbers of amplifiers that can be traversed within a given BER. The adjoining table translates these limits (assuming unity gain sections) into constraints on the number of nodes and distance between OEO regenerations. Note that the constraints we apply do not require a single distance and node limit, but rather allow the limits to interact, permitting greater distance with fewer nodes.

3. Least-Cost Impairment-Aware Routing

We consider paths that stay within distance and node limits to be *impairment-feasible*. Given a network with OEO regeneration capability at only prescribed nodes, it is the purview of the routing algorithm to assure impairment feasibility. When OEO-capable nodes have associated costs for performing OEO regeneration, it is also incumbent on the routing algorithm to identify *cost-effective* impairment-feasible routes, by selecting both a path and the specific locations at which to regenerate. To assure impairment feasibility, a routing algorithm must explicitly monitor and constrain impairment metrics along paths and must account for the restorative effect of OEO regenerations. Naïve routing algorithms, which do not explicitly divert to regenerate as needed, can fail to find feasible routes that exist in the network. Even routing methods developed to find impairment-feasible paths, like those described in [4] and [5], can fail to find feasible routes that exist in the network. For instance, the method in [4] is only guaranteed to find an existing feasible path when the metric it constrains is also minimized in the objective. The routing method that we present embeds more general objectives and constraints to limit impairments.

The impairment-aware routing method we propose can be viewed as finding a minimum-cost path in a network that is expanded (either implicitly or explicitly) to reflect the possible impairment states achievable along a path between the given endpoints. To illustrate, consider the case where we constrain both the distance and the number of consecutive transparent nodes between OEOs on a path. The impairment-aware routing algorithm may be viewed as taking place on a graph in which we replace each node v with copies $(v,i,d,\mathbf{in})$ and $(v,i,d,\mathbf{out})$ for each distance d and transparent node count i such that a path of length d with i transparent nodes would be feasible without regeneration. We construct a directed link from $(v,i,d,\mathbf{out})$ to $(w,i,d+l,\mathbf{in})$ if there is a link (v,w) of length l in the original graph. We construct a directed link from $(v,i,d,\mathbf{in})$ to $(v,i+1,d,\mathbf{out})$ if we are permitted to pass through v transparently, and assign it the cost of such a passthrough. We construct a directed link from $(v,i,d,\mathbf{in})$ to $(v,0,0,\mathbf{out})$ if we are permitted to regenerate at v, and assign it the cost of a regeneration. If we are allowed both options, we construct both such links – a path's choice of link corresponds to a choice about regeneration. Directed paths in this graph will remain impairment-feasible. If we trace out a path from an initial node $(s,0,0,\mathbf{in})$, the values i and d correspond to the number of transparent nodes and the distance since the last regeneration. We maintain feasibility by not constructing nodes with infeasible values. The running time of this routing algorithm depends on the distance limit in such a way that the algorithm is not polynomial-time, but it appears 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. We present results from two experiments. The first illustrates the value of impairment-aware routing, and the second illustrates the potential savings from minimizing an objective related to the cost of performing OEO regeneration. Both experiments apply limits that assure $\mathrm{BER} \le 10^{-12}$.

4.1 The Value of Impairment-Awareness in Routing

Since constrained shortest-path problems are not generally polynomially solvable, an alternative approach is to use a k-shortest paths algorithm [2] to generate a sequence of k shortest paths and then determine whether one of these paths is impairment feasible. The k-shortest paths method is oblivious to both impairment accumulation and OEO location, but it generates multiple paths so it is more likely to yield one that is impairment-feasible than a standard single shortest-path method. Each chart in Figure 2 compares impairment-aware routing with k-shortest paths routing (minimizing the number of hops) for a particular OEO location strategy. The right-hand case selects OEO locations by a path-improvement heuristic (PIH) [1] using minimum-hop paths as input. Such a method locates OEOs to reduce impairments along the minimum hop paths provided as input. This case may be viewed as a "best-case scenario" for shortest-path routing because the minimum-hop paths selected by routing also guide OEO placement. The left-hand case places OEOs by a connected dominating set (CDS) method [1] to assure a general feasibility property without regard to specific paths. The vertical difference between the top left line and the other lines represents the number of additional node-pairs that have a feasible path with impairment-aware routing. We see (left) that, when OEO capability is sparsely placed and design is decoupled from routing (as with the CDS method), the difference can be significant. These results suggest that seeking impairment-aware paths from the outset is beneficial in large networks with sparsely-located OEO capability, even when k is relatively large. When design and routing are tightly coupled, as with PIH, k-shortest paths routing performs relatively well, even when k = 3. Thus, the need for impairment-aware routing is related to both the density of OEO capability and the method for locating it.

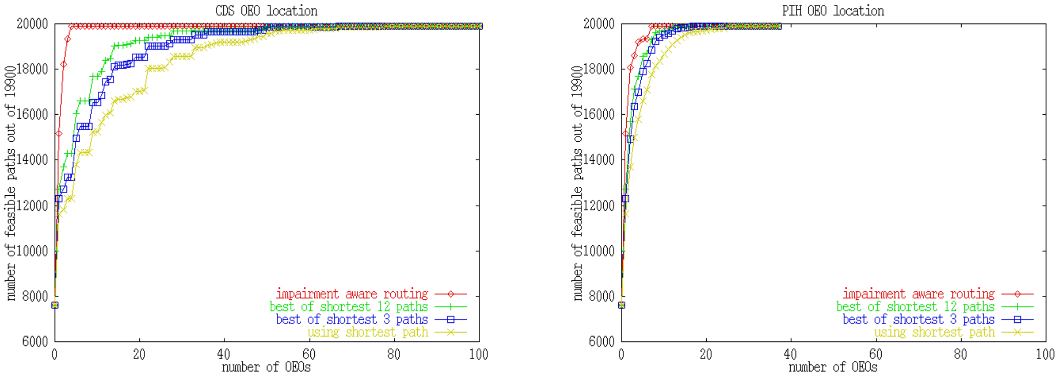


Figure 2: Number of pairs with impairment-feasible paths identified by different routing methods versus number of OEO capable nodes placed by CDS (left) and PIH (right).

4.2 The Value of Cost-Consciousness in Routing

Next, we consider the potential value of minimizing the cost of impairment-aware routing in both a “greenfield” network with no existing transponders and in a planned network with transponders already in place. We perform the following simple experiment to observe the savings from minimum-cost impairment-aware routing. We conduct this experiment on the same 200-node network using PIH to locate OEO capable nodes. To begin, we randomly generate 100 demands and then route each of them by two different methods. The first method is impairment-aware routing directly minimizing the cost of regeneration; the second is impairment-aware routing minimizing hops, followed by minimizing regeneration on this path. Thus, we determine a routing and a placement of transponders in both cases. Figure 3 presents results averaged over 10 trials. The two “greenfield” lines illustrate a small reduction in required transponders by least-cost routing. Next, we remove the demands but leave transponders along the minimum-hop paths in place. The existing transponders may be viewed as an existing designed network. We now generate 100 new demands and route them by the same two methods, adding transponders as needed. In both cases, we assume a higher cost for new transponders than existing ones to minimize the number of new transponders added for each request. The remaining two lines in Figure 3 show the benefit of least-cost routing with existing resources. In the second phase, least-cost routing typically requires addition of fewer than half as many new transponders.

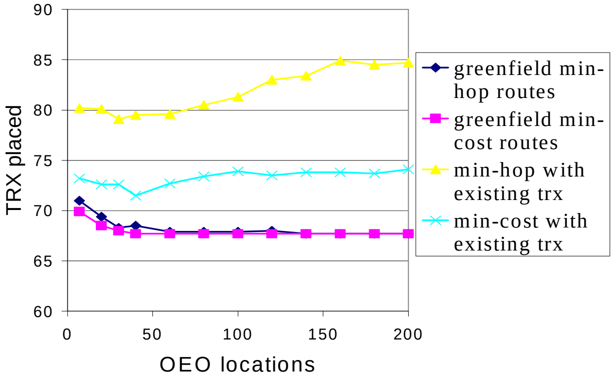


Figure 3: The value of cost-conscious routing in both greenfield and existing networks.

5. Conclusion

We have presented a flexible approach for impairment-aware routing that allows interdependent constraints and objectives that reflect the cost of OEO regeneration. The resulting method *guarantees* identification of impairment-feasible paths when they exist and makes cost-effective use of existing transponders resources, typically using fewer than half as many new transponders as minimum hop routing in a network with existing transponders.

6. References

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