Current Approaches in the Design of Ring-based Optical Networks

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Abstract
We discuss the problem of designing minimum-cost transport networks using path-protection and shared-protection optical rings. A description of the multi-ring network design problem is provided along with a survey of relevant prior work. We then propose three integer programming formulations for the multi-ring network design problem and discuss their comparative features and drawbacks with reference to some preliminary results obtained. We conclude with a discussion of future work in this area.

1 Introduction
Wavelength-division multiplexing (WDM) and optical switching are promising technologies for next generation transport networks in which optical carrier signals are combined, switched and routed in much the same way as digital carrier signals are in SONET networks today. In these optical networks, digital client information in a variety of formats (e.g., SONET, ATM, IP) and data rates will be transported over end-to-end optical channels or lightpaths.

Such optical networks are widely regarded as essential to satisfy the unprecedented growth in demand for transport capacity, largely driven by Internet applications. WDM systems with 40 wavelengths are commercially available and denser multiplexing schemes are in development [1]. When combined with SONET systems operating at 10 Gb/sec., the aggregate data rate of an existing WDM systems can be as high as 400 Gb/sec. — the equivalent of more than 3 million simultaneous calls.

With such a high concentration of traffic on a single fibre, the impact of a cable cut or optical amplifier failure is potentially disastrous. Some form of very fast network restoration is therefore essential. Restoration can be provided at the various client network layers, -indeed, it is essential to recover from node losses within the respective service layer. But for protection against line-related failures, restoration at the optical layer offers universal protection for all client networks [2], some of which have no built-in protection mechanism. It also requires less equipment and fewer actions to effect restoration nearest to the physical layer because the aggregate real-time switching capacity is typically orders of magnitude higher than in client layers.

Two basic approaches for protecting optical networks are under study today. These are the mesh and ring architectures [3,4]. While mesh restorable networks achieve the lowest redundancy in transmission capacity needed for 100% restorability, ring architectures are often preferred in practice because of their simpler and faster switching mechanism (50 -150 msec). Despite their greater capacity requirements, rings can also be more economical than mesh networks, particularly in metropolitan area networks where nodal costs usually dominate over distance-dependent costs for fibre and regenerators. For these reasons, SONET-based rings have already been widely deployed and the same logical architectures are promising and obvious candidates for optical networks.

This paper consequently aims to provide a timely tutorial review the issues involved in the design of networks in which survivable rings are the basic building block, followed by comparative analysis of three alternative theoretical approaches to the multi-ring design problem. In Section 2, we describe the two main survivable ring types. In Section 3 we discuss the multi-ring network design problem and review prior work in this area. In Section 4, we present three integer programming (IP) formulations for the multi-ring network design problem and discuss their advantages and disadvantages in terms of model accuracy and tractability. We conclude with a summary and suggestions for future work in Section 5.

2 Optical Rings
Two types of logical ring have been widely considered for optical ring implementation. These are the path-protection and the shared-protection optical ring. In a path-protection optical ring, the forward and return signals of each lightpath are transmitted in the same direction (e.g., clockwise) around the ring from source to destination on a “working” fibre. At the same time, a copy of each signal is transmitted in the opposite direction (e.g., counter-clockwise) on a protection fibre. In the event of a failure in the normal signal path, the receiving optical add-drop multiplexer (OADM) switches to the protection signal coming from the opposite direction.

A ring may also contain passive or glass-through nodes through which the fibres pass but do not terminate on an OADM. Because the forward and reverse signals
require a single wavelength around the entire ring, the maximum number of wavelengths that can be carried in total on a path-protection optical ring is no more than the number of wavelengths available on each span.

In a 4-fibre shared-protection optical ring, the forward and return signals in a lightpath do not circumnavigate the entire ring; instead they are transmitted over on a bidirectional working fibre pair between the source and destination nodes. Once the forward and return signals reach their end nodes, the wavelengths used to carry these signals may be reused by other lightpaths on the remaining spans of the ring. Therefore, the maximum number of lightpaths that can be carried depends on both the routing of each lightpath and the number of wavelengths available. In the event of a failure, service is restored by looping the lightpaths on the working fibre pair back onto a protection fibre pair and transmitting the signals the long-way around the ring.

A two-fiber shared-protection optical ring, operates in logically the same way except the wavelengths on each fiber are divided into working and protection groups. To eliminate the requirement for wavelength conversion at the nodes for loop-back purposes, the working and protection wavelength groups on each fibre are transposed. If the OADMs in a shared-protection optical ring are not equipped with wavelength converters, lightpaths must avoid the colour clash problem. Further description of path-protection and shared-protection rings can be found in [3].

Lightpaths are also assumed to be full-duplex, i.e. with a forward and return optical signal pair. On each fibre span in a lightpath, an optical channel at a given wavelength is assigned on a dedicated basis to the connection. If wavelength conversion is available at intermediate nodes, different wavelengths may be assigned to each span of a lightpath. Otherwise, wavelength continuity must be maintained along the entire lightpath. In this situation, any two lightpaths occupying the same fibre must be assigned different wavelengths. This has been called the colour clash constraint [5]. This constraint may result in higher blocking and certainly makes lightpath provisioning more difficult. It has been shown, however, that the demand carrying capacity of shared protection rings with and without wavelength converters is virtually the same, when optimally planned [6].

Although terminology is different, it may be useful to network planners to recognize at this point that the path-protection and shared-protection optical rings are identical in virtually every logical aspect to the prior SONET unidirectional path-switched ring (UPSR) and bidirectional line-switched ring (BLSR), which are already under fairly extensive study from an optimization viewpoint. The importance is that, while recognizing the considerable issues unique to the physical layer design of dense WDM transmission systems, the logical structure of the basic combinatorial optimization problem that optical networks present is the same as that in SONET ring networks. Table 1 helps illustrate this logical equivalence.

Table 1: Optical and SONET Networking

<table>
<thead>
<tr>
<th>Optical Networks</th>
<th>SONET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path-protection Optical Ring</td>
<td>Unidirectional Path-Switched Ring</td>
</tr>
<tr>
<td>Shared-Protection Optical Ring</td>
<td>Bidirectional line-switched ring</td>
</tr>
<tr>
<td>Wavelength</td>
<td>Time-Slot or STS-n channel</td>
</tr>
<tr>
<td>Lightpath</td>
<td>Path or digital path</td>
</tr>
<tr>
<td>Wavelength Conversion</td>
<td>Time-Slot Interchange</td>
</tr>
</tbody>
</table>

3 Multi-Ring Network Design

Although the functional operation of a single ring for restoration is simple, the design of fully restorable networks employing multiple rings is an extremely complex optimization problem. This section describes the main aspects of the multi-ring network design problem. At the highest level, the problem inputs include the lightpath demand matrix, the network topology, the ring type(s) under consideration and their associated cost model(s) and the design constraints. The solution is a set rings (specifying type, capacity, assignment of demands and routing between rings so as to satisfy all end-to-end lightpath requirements at minimum total cost.

Usually, the demand matrix is derived from forecast traffic requirements of client transport networks (e.g., SONET, ATM) and higher-layer services (e.g., voice, video, data). Individual service demands are aggregated, after any hubbing and grooming stages, to generate a required number of lightpaths between each logical node pair in the optical network layer. This yields the demand matrix for the optical layer design. Demands may be forecasted for several periods and the planning problem then involves finding the optimal sequence of deployment decisions. This is known as a multi-period planning environment. Here, we assume a single-period planning environment in which all decisions are made at once, independent of any future time periods.

Another input in any transport network design problem is the underlying network topology, i.e route map or fibre map. Here we assume that the topology is already given for the network based on the existing fibre infrastructure (e.g., fibre cables, cable ducts, right-of-ways). Occasionally, however, the network planner may want to
examine the impact of adding or deleting fibre spans from the network topology. Topology optimization is a relatively untouched but increasingly important aspect of research on which some preliminary results are presented in a companion paper [7].

Although considerable earlier research on ring network optimization considered either uncapacitated or uniform capacity rings [8, 9, 10] of only one logical type, network planners now need to consider several candidate ring technologies in heterogeneous designs. By a ring technology, we mean one combination of logical ring type (e.g., path-protection vs. shared-protection) and a specific discrete modular line capacity (e.g., number of wavelengths supported) on spans of the ring. For instance, in a SONET context, OC-192 2-fiber BLSR is a specific ring technology. Also for simplicity, in some prior work the cost of a ring has been modelled as fully-allocated unit costs although. With the very large modular capacities represented by dense WDM systems, however, it is now quite important for model accuracy to avoid this linearization and portray the true as fixed and variable costs in the problem formulation. This is highly desired to reflect the large step-wise increases in total cost associated with equipment placement due to the very coarse-grain modularity of optical rings. Computationally this also underlines the importance for true integer- (as opposed to faster running linear-) programming solution techniques.

The most basic constraint to be respected in the design optimization is that of capacitiation; the number of optical paths assigned to any ring cannot exceed its wavelength capacity. (Note that unlike flows in ATM or packet layer networks, which can be fractional, capacitiation of spans and lightpaths quantities in the optical network is strictly integer.) Lightpath routing may also be constrained as to the nodes at which lightpaths can transit from one ring to another enroute from source to destination. For example, it may be desirable for operations, maintenance and administration reasons, to limit inter-ring transitions to nodes equipped with optical crossconnect switches (OXC). This is especially important if wavelength converters are required for provisioning flexibility (e.g., due to the high cost of wavelength converters they will tend to provided only at key hub locations [2].) The optimal hub location problem may thus be of greater economic importance for optical networks than for their SONET counterparts, where TSI could be afforded in the ring nodes themselves.

For each ring in the design, the network planner must specify its logical type, capacity, topological layout (i.e., the nodes and fibre spans in the ring) and active and glass-through node locations, in addition to all add-drop (wavelength transponder) interfaces. This includes determination of an assignment of demands to rings, direction of routing in each ring, and the location at which demands transit from one ring to another when more than one ring is traversed from origin to destination. Even for relatively small problems involving few ring candidates (a combination of ring technology on a specific cycle of the network graph), the number of ring and routing combinations is astronomically large. And the number of ring candidates is itself exponential with the number of nodes in the network.

### 3.1 Related Work

Aside from a few specific case studies of optical ring-based networking per-se, most of the relevant literature for optical ring network optimization is found in the form of mathematical formulations for the SONET multi-ring network design problem. An overview of those methods now follows. A comprehensive survey is available in [11].

A now-popular approach is to route the demands over the network topology first and then select a set of rings that covers all of the spans that have been assigned to at least one lightpath. This is called span coverage. Most such methods route the demands using a shortest-path algorithm and select rings using either a heuristic algorithm [8, 12, 13] or integer programming [9]. With the exception of [8], however, they do not account for the discrete multi-modal capacity of actual ring systems or the location of glass-through nodes.

Another basic approach, and the basis of some widely used manual planning tools, is to select a set of rings first and then find a routing that satisfies all demands. When demands cannot be served, another ring is placed. Several heuristics have been proposed using this approach [1,14,10,16]. In [14, 16] the nodes to be included in each ring are specified in advance. In [1,10] the nodes in a ring are chosen based the mutual demand or community of interest. In contrast, [15] assumes that an initial design is provided and uses a local neighbourhood design modification search to make successive improvements.

### 4 New Design Formulations

The methods we propose now are based on integer programming (IP) so they have the prospect of certain claims to optimality, within the logical problem model. They differ from the work in [9] by modelling aspects such as modularity, inter-ring routing costs, and glass-through location in detail. On the other hand, computational constraints may prohibit finding strictly optimal solutions for large problems using these formulations. Nonetheless, solved with relaxed tolerances on optimality, they can provide very good, feasible, designs of significant real-world size even when not provably optimal.

The level of accuracy required in an optimization
model also depends on its purpose, and the accuracy of the input data available. For preliminary comparison of alternatives with simplifying assumptions may be sufficient and make it feasible to obtain timely basic results. During network deployment, additional model accuracy may be required for making detailed decisions about routing and equipment location choices. Thus, a range of optimization models can be of use. With this in mind, we are not seeking a single “master formulation”. Rather we are studying three basic formulations (implemented in AMPL, solving with CPLEX) with various advantages.

The physical graph topology and point-to-point demand matrix are given. We accept an implicit assumption that, on shared protection rings, wavelength converters are available at all OADMs, so there are no colour clash constraints to be explicitly satisfied. Separate findings [6] show that a fixed-wavelength assignment problem can always be solved separately to yield loading efficiencies that are essentially equivalent to that achieved if wavelength conversion (or TSI) is available at each node. So there is very little overall degradation of model accuracy, but the computational benefit is great. Given a set of eligible ring technologies and corresponding costs, the objective of each formulation is to find a set of survivable rings that fully serves all demands with minimum the total cost.

4.1 Notation

Sets:
- \( J \): set of ring candidates.
- \( I \): set of routes.
- \( K \): set of demands.
- \( I(k) \): subset of routes available for demand \( k \).
- \( I(s) \): subset of routes that intersect span \( s \).
- \( J(i) \): subset of ring candidates that intersect route \( i \).
- \( J(s) \): subset of ring candidates that cover span \( s \).
- \( S(i) \): subset of spans in route \( i \).
- \( S(j) \): subset of spans in ring candidate \( j \).

Design Parameters:
- \( \alpha_{jk} \): equals one if demand \( k \) is carried by ring \( j \) and zero otherwise (section 4.4 only).
- \( b_{ij} \): unit OADM and OXC interface cost associated with carrying route \( i \) on ring \( j \).
- \( c_{j} \): fixed cost of ring \( j \).
- \( d_{k} \): size (quantity) of demand bundle \( k \).
- \( e_{i} \): unit OXC interface cost at the end nodes of route \( i \).
- \( m_{j} \): wavelength capacity of ring candidate \( j \).
- \( w_{s} \): number of demands crossing span \( s \).

Variables:
- \( X_{j} \): integer number of ring candidate \( j \) to instantiate.
- \( G_{ij} \): quantity of demand on route \( i \) carried by ring candidate \( j \).
- \( F_{i} \): quantity of demand carried on route \( i \).

4.2 Span Coverage

In this formulation, we assume that the demands have already been routed over the network topology and the objective is to find the min-cost subset of shared protection rings that cover the loaded spans. Here the set of ring candidates \( J \) may be formed by enumerating all possible combinations of ring capacity and topological layout, or some subset thereof. In practice, the number of ring candidates can be limited by imposing a hop-limit, i.e. the maximum number of nodes in the ring. In this formulation, the fixed cost, \( c_{j} \), of ring candidate \( j \) includes the cost of fibre and OADM common equipment but excludes the cost of optical add-drop port cards. The formulation for this Span Coverage IP (SCIP) is given below.

**SCIP**

Minimize:

\[
\sum_{j \in J} c_{j} \cdot X_{j} \tag{1}
\]

Subject to:

\[
\sum_{j \in I(s)} m_{j} \cdot X_{j} \geq w_{s}, \quad \forall s \in S \tag{2}
\]

\[
X_{j} \geq 0, \text{ integer,} \quad \forall j \in J \tag{3}
\]

The objective function (1) is to minimize the total facility cost over all rings. Constraint set (2) ensures that the aggregate span capacity of all rings that intersect each span \( s \) is greater than or equal to the working load assigned to that span. Note that this formulation implicitly assumes that there are no constraints on inter-ring transitions and that all nodes are equipped with OADMs. In addition, the formulation is only suitable for shared-protection optical rings because the capacity of a path-protection optical ring is shared amongst all its spans and, therefore, cannot be modelled on a per-span basis, as in constraint set (2).

Another drawback of the span coverage approach is that the resultant design cost may be heavily dependent on the pre-determined demand routing pattern. There are two reasons for this. First, small changes in the routing pattern can trigger a step-wise increase in the design cost when ring system capacity is exceeded and a new ring is triggered or when very lightly loaded spans arise, which must strictly then be covered. Secondly, there may not be a top-
ologically efficient way to cover all of the loaded spans in the network graph. In other words, the topology may not support a ring set that closely matches the span usage and capacity requirements of the routing pattern. Lee et al. [7] show that design costs can vary by up to 28% in this class of design simply by choosing different routing patterns. This formulation has been used extensively in [7] for characterizing the performance of various span elimination heuristics. The results of that work show a very strong correlation (0.93) between the IP solutions and those obtained by the detailed heuristic algorithm (RingBuilder) described in [8]. Typical runs times are on the order of thirty seconds for networks with up to 300 candidate rings. These results are for a Sun UltraSparc HPC-450 with four processors, each running at 250 MHz.

4.3 Fixed Charge and Routing

This next formulation simultaneously determines the optimal demand routing and ring set. Here cost is modelled by both fixed ring costs and variable routing costs. Like the previous formulation, we assume that the set of ring candidates \( J \) consists of various combinations of ring capacity and topological layout. In addition, we assume that a set of demand routes is generated by finding some subset of paths between the source and destination nodes for each demand. In practice, it is usually necessary to limit the number of routes per demand for tractability. The formulation for this Fixed Charge and Routing IP (FCRIP) is given below.

**FCRIP**

\[
\begin{align*}
\text{Minimize:} & \quad \sum_{j \in J} c_j \cdot X_j + \sum_{i \in I} \sum_{j \in J(i)} h_{ij} \cdot G_{ij} + \sum_{i \in I} e_i \cdot F_i \\
\text{Subject to:} & \quad \sum_{j \in J(s)} F_j = d_k, \quad \forall k \in K \\
& \quad \sum_{j \in J(s)} G_{ij} \geq F_i, \quad \forall i \in I, \forall s \in S(i) \\
& \quad \sum_{i \in I(s)} G_{ij} \leq m_j \cdot X_j, \quad \forall j \in J, \forall s \in S(j) \\
X_j & \geq 0, \text{ integer, } \quad \forall j \in J \\
F_i & \geq 0, \text{ integer, } \quad \forall i \in I \\
G_{ij} & \geq 0, \text{ integer, } \quad \forall i \in I, \forall j \in J(i)
\end{align*}
\]

The objective (4) is to minimize the sum of the fixed ring costs and the incremental intra- and inter-ring routing costs. Constraint (5) ensures that for each demand bundle \( k \), the sum of the demand carried by all available routes equals the total demand \( d_k \). Constraint (6) ensures that on each span \( s \) of route \( i \), the sum of demand carried by the rings that intersect span \( s \) is equal to the total demand carried over route \( i \). Constraint (7) states that the total demand carried on each span \( s \) of ring candidate \( j \) does not exceed the total capacity of all copies of ring candidate \( j \).

The main advantage of this formulation is that it jointly solves for the ring set and the routing pattern in a way that does not implicitly assume full span coverage, i.e. it solves that span elimination problem as well. In other words, it inherently determines the optimal routing pattern that minimizes the cost of the ring set. Although the above formulation is for shared protection optical rings, it can be easily extended to include path protection rings.

As in the previous formulation, the above formulation implicitly assumes that there is an OADM at each node of the ring candidate and there are no restrictions on the locations at which inter-ring transitions take place. The major disadvantage of this formulation is the large number of integer variables required for even moderately sized problems. It has, however, been used to find feasible, but not provably optimal, solutions for networks with up to 28 nodes and 48 spans.

4.4 Foundation Design

Up to this point, we have defined a ring candidate in terms of its type, topological layout and wavelength capacity only and have formulated the design problem to select a subset of these rings that serves all demands. In this last formulation, we extend our definition of a ring candidate to include a specification of the active and passive node locations and the subset of demands carried by the ring. Clearly, the number of all such candidates, even in relatively small networks, would be enormous. Therefore, the basic idea here is to restrict attention to a subset of *elite* candidates that have been frequently selected by other designs methods and are known to have high figures of merit (e.g., capacity utilization). In this situation, the problem is to select, from this collection of elite candidates, a subset of rings that handles or covers each demand at least once. The formulation for this variant of the Foundation Design IP (FDIP), is as follows:

**FDIP**

\[
\begin{align*}
\text{Minimize:} & \quad \sum_{j \in J} c_j \cdot X_j \\
\text{Subject to:} & \quad \sum_{j \in J} \alpha_{jk} \cdot X_j > 1, \quad \forall k \in K \\
X_j & \in \{0,1\}, \quad \forall j \in J
\end{align*}
\]

The objective function (12) is to minimize the total design cost of the rings. Here the cost \( c_j \) is the actual cost
of ring candidate $j$ as specified by the location of active and glass-through nodes and the subset of demands carried by the ring. Constraint set (13) ensures that each demand is handled by at least one ring. Strictly speaking, this will not guarantee that all demands are served end-to-end but it is believed that the set of rings that are chosen will constitute a solid foundation upon which a complete design may be constructed and that the existing RingBuilder system is ideally suited to identify the vocabulary of elite ring candidates. At the time of writing, no experimental results were available for this formulation.

5 Summary and Conclusion

We have discussed three current approaches, based on formal methods, for the multi-ring design problem. A summary of their respective features and advantages is given in Table 2.

Table 2: Comparative Summary of Three IP-based Approaches to Multi-Ring Network Design

<table>
<thead>
<tr>
<th>Model Attribute</th>
<th>Span Coverage</th>
<th>Fixed Cost &amp; Routing</th>
<th>Foundation Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass-through</td>
<td>N</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>Multi-modularity</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Span Elimination</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Inter-ring transitions</td>
<td>N</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>Ring Types</td>
<td>BLSR</td>
<td>BLSR/UPSR</td>
<td>BLSR/UPSR</td>
</tr>
<tr>
<td>Relative Run Times</td>
<td>Fast</td>
<td>Slow</td>
<td>Moderate</td>
</tr>
<tr>
<td>Design Completeness</td>
<td>Complete</td>
<td>Complete</td>
<td>Incomplete</td>
</tr>
<tr>
<td>Pre-processing</td>
<td>Minimal</td>
<td>Moderate</td>
<td>Greatest</td>
</tr>
</tbody>
</table>

Preliminary results indicate that these approaches can provide useful solutions to a difficult optimization problem. One aspect of this problem that has not been addressed by these formulations is the optimal location of wavelength converters in ring-based optical networks. Other challenges for future work will involve the inclusion of dual ring interconnect, topology optimization and probabilistic demand matrices.

6 References


