TOPICS IN OPTICAL COMMUNICATIONS

Translucent Optical Networks: The Way Forward

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ABSTRACT

The transmission reach of signals in optical transmission systems is limited. To go beyond these transparent reach limits, signal regeneration is necessary to re-amplify, reshape, and retime the optical signals. Translucent optical networks are a type of optical transport network specifically devised to address such a concern by allowing for sparse but strategic signal regeneration in the network. Translucent optical networks seek a graceful balance between network design cost and service provisioning performance, and can achieve performance comparable to that of an all-electronic switching network, but requiring far fewer signal regenerators. Despite massive progress, there are many outstanding issues regarding the implementation of translucent networks planning and operation. This article reviews a range of translucent optical networks and discusses various research issues, particularly involving network planning, lightpath routing and wavelength assignment, and network survivability. We also suggest other potential research topics such as traffic grooming, fault detection, and multicasting for translucent networks.

INTRODUCTION

Optical transport is evolving from traditional *opaque* networks that use all-electronic switching techniques toward all-optical *transparent* networks. A significant factor that mitigates against the introduction of all-optical networking is the fact that most optical technologies are analog rather than digital. Many factors may degrade optical signal quality in long-reach optical transmission systems to make the data unrecognizable at the receiver. Contributing factors include optical noise, chromatic dispersion, PMD, nonlinear effects, and crosstalk. Thus, there is a maximum transparent reach limit for signals within optical transmission systems. To go beyond the limit, signal regeneration is mandatory to re-amplify, reshape, and retime the optical signals. 3R regeneration provides all three functions, and 2R regeneration provides the first two. Regeneration is helpful to improve signal quality such that a lightpath can travel farther before it reaches its destination or needs another regeneration. Regeneration can, in principle, be accomplished purely in the optical domain; however, regeneration in the electronic domain, which converts an optical signal into electronic format and then uses the electronic signal to modulate an optical laser, is currently the most economic and reliable technique.

Optical translucent networks use a set of sparsely but strategically placed 2R and/or 3R regenerators for the purpose of signal regeneration [1]. Rather than purely electronic or purely optical, a translucent optical network is a compromise between all-electronic switching and all-optical switching, which seeks a graceful balance between network design cost and service provisioning performance. Translucent networks show the following major advantages. First, translucent networks allow a group of regenerators at each OXC node to be available to all wavelengths incident to the node and used as required. This sharing of regenerators significantly improves regenerator usage. Second, the inherent wavelength conversion capability of regenerators can be used to effectively alleviate wavelength collision when routing lightpaths, thereby saving the cost of wavelength converters and improving wavelength resource utilization. Third, it is unlikely that optical cross-connect (OXC) nodes will be deployed universally in future optical transport networks. Rather, many switching nodes will be electronic. Thus, we can benefit from the inherent signal regeneration capability of these electronic switches. Extensive recent studies indicate that even if only a few opaque nodes or regenerators are employed, a translucent network can effectively achieve elegant service provisioning performance close to that of a fully opaque network, but much better than that of a fully transparent network [2–5]. Translucent networks thus promise good economics and efficiency of regenerator utilization.

In this article we present a survey of recent research advances in planning and operation of translucent networks. Our aim is to provide a better understanding of current research issues in this emerging field and propose solutions to them. The rest of this article is organized as follows. First, different types of translucent networks are classified and defined. A detailed investigation of planning and lightpath routing for translucent networks is then performed. Subsequently, other research topics pertaining to translucent networks are also suggested. The

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article concludes with final remarks.

TRANSLUCENT OPTICAL NETWORKS

We can broadly classify translucent optical networks into three categories, namely

- Translucent networks made up of transparent islands [2, 6]
- Translucent networks with sparsely placed opaque nodes [3, 4]
- Translucent networks made up of translucent nodes [6]

A translucent network can be made up of several subdomains (termed *islands*) of optical transparency [2, 6]. Here, "optical transparency" means that all nodes in an island are transparent; no nodes in the island have regeneration capability. Regeneration OXC nodes are located only on the island boundary. Therefore, within each island, lightpaths sourced from a node can transparently reach any other node without any signal regeneration; whereas between different islands, it is necessary for the lightpaths to pass island boundaries and traverse regeneration OXC nodes on the boundaries. Figure 1 illustrates a translucent network made up of three transparent islands, in which nodes 4, 7, 8, and 9 are boundary regeneration nodes to relay lightpaths crossing neighboring transparent islands.

A translucent optical network can be more general than one with regeneration nodes only at island boundaries. We may also strategically distribute regeneration capability around an entire network. Instead of being dedicated to routing lightpaths only in and out of transparent islands, switches that have an electronic regeneration function can be shared by all lightpaths in the network as a whole. One such a type of implementation is based on sparse placement of opaque switches [3, 4]. Here, one deploys a relatively small number of strategically chosen opaque (i.e., electronic) nodes, at which wavelength conversion and regeneration is possible. All other nodes are lower-cost optically transparent OXCs. Figure 2 depicts an example of such a type of translucent network, where nodes 1 and 3 are opaque, whereas the rest of the nodes are transparent. Opaque nodes can regenerate optical signals and convert wavelengths electronically, while transparent ones have the optical switching function only.

Another distributed regeneration approach is to deploy hybrid optical switches (termed *translucent* switches) at some or all of the nodes in an optical network [5]. Each of these switches contains an optical switching core and an electronic switching core [including a bank of regenerating OEO transponders (typically 2R) and an electronic cross-connect] as depicted in Fig. 3. Each lightpath through a translucent node can be switched either all-optically (via the optical module) or through the electronic core module, which regenerates its payload and assigns it a new wavelength as desired (if available). The decision between optical or electronic switching is based on the signal quality (e.g., BER) of the lightpath, i.e., whether regeneration is required before further transmission.

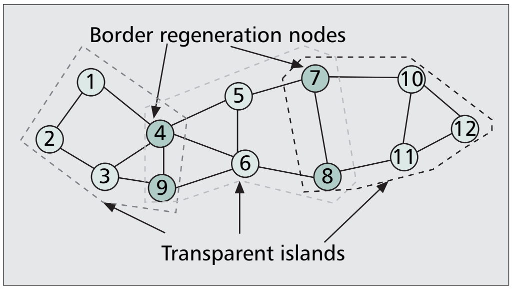


Figure 1. *Example of a translucent network with multiple transparent islands.*

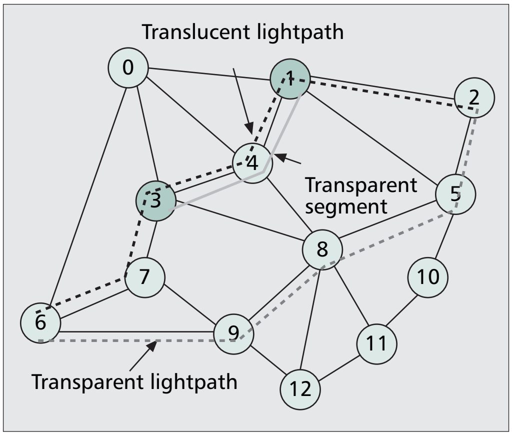


Figure 2. *Example of a translucent network with sparsely placed opaque nodes (adapted from [4]).*

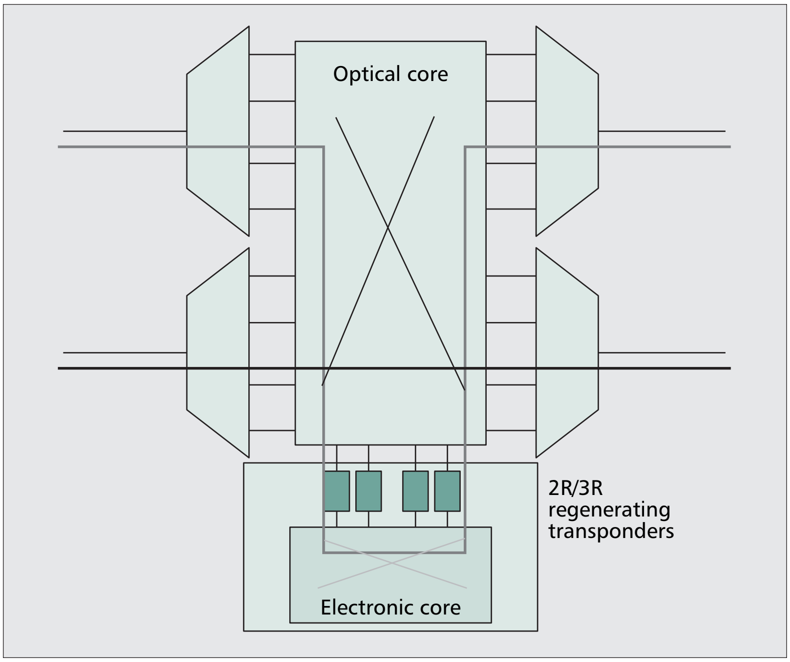
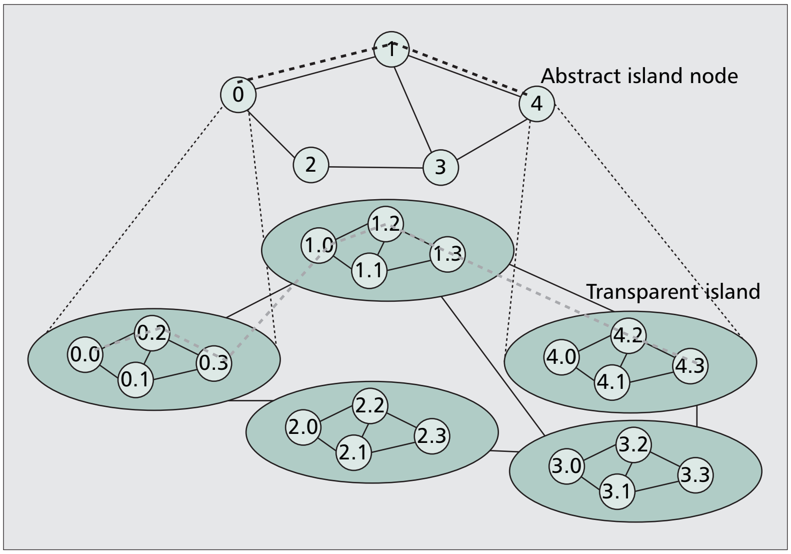


Figure 3. *Architecture of a translucent OXC node.*

Associated with the concept of translucent network, there are two types of lightpaths: translucent and transparent [3, 4]. A lightpath is called translucent if there are some opaque or regeneration nodes en route for signal regeneration (and wavelength conversion); a lightpath is called transparent if there are no opaque or regeneration nodes en route. We also refer to the lightpath segment between two neighboring



■ **Figure 4.** *Routing in a translucent network with multiple transparent islands.*

opaque or regeneration nodes a transparent segment. In Fig. 1, for example, all lightpaths crossing transparent islands are translucent in that they must traverse regeneration nodes on the island boundaries. On each lightpath, the section between two neighboring island boundary nodes is transparent, as no regeneration nodes are traversed when the lightpath crosses a transparent island. In Fig. 2 lightpath (2-5-8-9-6) is transparent because all nodes en route are transparent, while lightpath (2-1-4-3-7-6) is translucent because nodes 1 and 3 are opaque. The translucent lightpath is made up of three successive transparent segments, including segments (2-1), (1-4-3), and (3-7-6).

TRANSLUCENT NETWORK PLANNING AND CONNECTION ROUTING

Numerous issues and problems need to be addressed when planning and operating translucent networks. They include:
- Transparent island division
- Opaque node placement
- 2R/3R regenerator allocation
- Routing and wavelength assignment

The first three issues are related to translucent network planning and specific to each type of translucent network, and the fourth issue is common to the operation of all types of translucent networks. Today's generalized multiprotocol label switching (GMPLS)-based control and operation techniques have been fledged enough to easily handle most control functionalities such as establishing a lightpath and releasing a lightpath in translucent networks. Thus, in this article our focus is on how to efficiently choose translucent lightpaths based on an updated network state database.

TRANSLUCENT NETWORK WITH TRANSPARENT ISLANDS

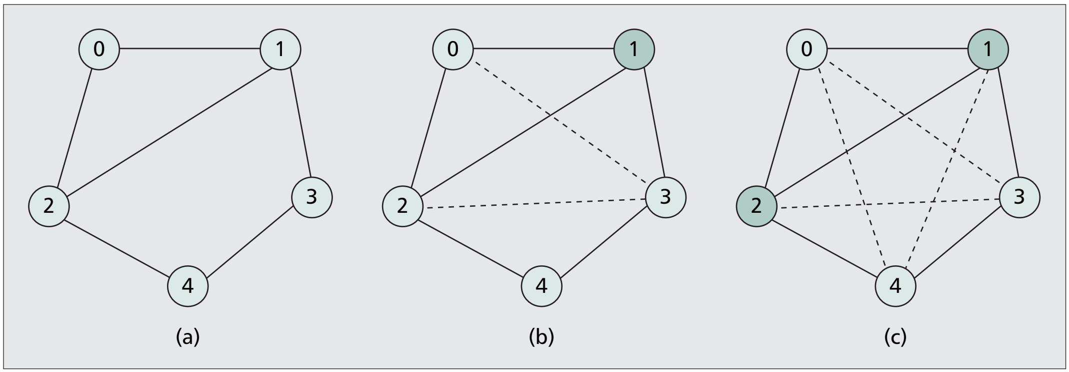
In a multi-island translucent network, one important question is how to efficiently and economically partition a large-scale optical network into several nonoverlapping transparent islands [2, 6]. This is of importance because the smaller the number of transparent islands, the fewer opaque nodes required, and thereby the total network design cost will be less.

Given inputs include:
- A large-scale optical network topology
- A parameter of maximum transparent reach limit (i.e., the maximum distance a lightpath can traverse before regeneration is required); the objective of the transparent island division problem is to partition a large network into the fewest nonoverlapping portions so that in each portion the constraint of maximum transparent reach is always satisfied

Although to the best of our knowledge there are no literature reports, it can be proved that this is an NP-complete *K*-cluster problem. Thus, efficient heuristics are useful. Karasan and Arisoylu [2] addressed the transparent domain partition by employing an ILP model and a heuristic to continuously merge graph faces to clusters (i.e., transparent islands) to minimize the number of total divided transparent islands. More research is needed in this direction.

For a multi-island translucent network, we also need to devise how to efficiently establish lightpath connections that may exist within a single island or traverse multiple transparent islands. It is straightforward to route lightpath services between a pair of nodes within the same transparent island. The shortest path routing algorithm or other more advanced algorithms traditionally developed for lightpath routing and wavelength assignments in a transparent network can be used. However, for a node pair belonging to different islands, because a lightpath between them spans multiple transparent domains, a hierarchical routing strategy can be proposed to efficiently choose routes across multiple domains. The hierarchical strategy models the translucent network in two layers, with the top one including all abstract island nodes and the bottom one containing extended information of each abstract node. Based on such a model, lightpath routing and wavelength assignment is implemented in two steps from the top layer to the bottom layer. Specifically, in the top layer we first find a route that transits the minimum number of transparent islands, and then in each transit abstract island node we search for a transparent segment between its two boundary nodes. Consequently, the found lightpath contains multiple transparent segments with 2R or 3R regeneration on each traversed island boundary node.

Figure 4 illustrates an example of how to find a route and assign wavelengths based on the hierarchical routing strategy. Specifically, each island is first modeled as an abstract node in the top layer. For instance, island 0 is abstracted as node 0. For each abstract node, more detailed network topological information is displayed in the bottom layer. Abstract node 0 contains four OXC switch nodes from 0.0 to 0.4. To associate an abstract node with a real switch node, the node index in the bottom layer is a combined one. The first number indexes an island that a switch node belongs to and the second indexes the switch node in the island. Based on such a two-layer



■ **Figure 5.** *Example to illustrate the HNF algorithm: two opaque nodes yield full translucent reachability (adapted from [4]).*

To efficiently place opaque nodes in a translucent network, a simple strategy based on a criterion termed transitional weight can be applied. That is, by counting the times lightpaths transit a node based on shortest path routing, a node is assigned a larger transitional weight if more lightpaths transit the node.

architecture, if for example there is a request to establish a connection between nodes 0.0 and 4.3, a crossing-island route (0-1-4) is first computed as shown in the top layer. Then within each island, corresponding transparent segments are routed. For example, in domain 1, a segment between 1.0 and 1.3 is routed via node 1.2. All these segments are interconnected to form a long translucent lightpath as illustrated in the bottom layer.

The above hierarchical routing strategy provides a generic proposal on how to route a lightpath in a multi-island translucent network environment. Further research is needed to explore more detailed issues. For example, a division of transparent islands may generate multiple islands in different sizes. Under this circumstance, when searching for a route traversing multiple transparent islands, the size of island should be taken into account to select small islands first. Interested readers may refer to [7] for more information on how to hierarchically route a lightpath in a multi-domain transport network.

TRANSLUCENT NETWORK WITH SPARSELY PLACED OPAQUE NODES

Translucent networks with sparsely placed opaque nodes contain two types of OXC nodes, i.e., opaque and transparent nodes [3]. For this type of network, we need to study issues of opaque node placement and lightpath routing and wavelength assignments with both signal regeneration and wavelength conversion taken into account on opaque nodes.

To efficiently place opaque nodes in a translucent network, a simple strategy based on a criterion termed "transitional weight" can be applied [3]. That is, by counting the times that lightpaths transit a node based on shortest path routing, a node is assigned a larger transitional weight if more lightpaths transit the node. A larger transitional weight represents a higher chance that wavelength conversion capability and signal regeneration capability may be required on this node. Given a pre-planned budget or some parameters, the total number of opaque nodes to deploy in an optical network may be constrained in advance. The nodes to deploy as opaque switches can be determined based on their individual transitional weights by the order from the largest to the smallest.

Alternatively, one may have no idea on how many opaque nodes to deploy in an optical network. To save overall network design cost, minimizing the total number of opaque nodes in a network, which ensures all the node pairs can always reach one another via a direct lightpath (either, a transparent or translucent lightpath) under a certain maximum transparent reach limit, can be another objective for the opaque node placement problem. Similar to the previous *K-cluster* transparent island division problem, this problem is essentially an NP-complete *K-center* problem. Therefore, efficient heuristics are valuable to solve the problem.

The simplest heuristic can be again based on *transitional weights* to incrementally add opaque nodes to those with higher transitional weights until there are sufficient opaque nodes in the network to assure the constraint of maximum transparent reach limit. Other more advanced heuristic such as Hub Node First (HNF) algorithm [4] can also be proposed to minimize the number of required opaque nodes. Figure 5 illustrates an example of the HNF algorithm, which allocates opaque nodes by giving higher priority to nodes with higher nodal degrees within a logical mesh graph. Here the logical mesh graph is constructed by connecting each node pair, whose two end nodes can reach each other via a transparent or translucent lightpath. Specifically, assume a one-hop transparent reach and a simple physical network topology as shown in Fig. 5a. Subject to the one-hop maximal transparency reach, an initial logical mesh graph can be constructed, identical to the physical topology as shown in Fig. 5a. Based on the nodal degrees in the logical graph, we see that nodes 1 and 2 have the same nodal degree. We therefore randomly select one of them, e.g., node 1, to place an opaque switch and update the logical graph to connect any two nodes in the neighboring node list of node 1 (as these two nodes can reach each other via direct translucent lightpath relayed at node 1). The newly added edges are shown by dotted lines in Fig. 5b. The resultant logical graph shows that it is not fully connected yet, so we need to add more opaque nodes. Node 2 has a higher priority than node 3, because the former has a higher nodal degree in the original network as shown in Fig. 5a, although nodes 2 and 3 both have the same nodal degree in the logical graph, so we select

For the problem of lightpath routing and wavelength assignments, it is possible to simply apply shortest path or fixed alternate path routing algorithms to search for translucent lightpaths between a node pair. However, these simpler algorithms are generally less efficient by their nature.

node 2 to place an opaque switch and update the nodal degree for each node in a similar way. Now we find that the logical mesh graph becomes fully connected, so the algorithm is terminated with two opaque nodes placed at nodes 1 and 2.

An optical network with sparsely placed opaque nodes is analogous to an optical network with partial wavelength conversion [3]. A wavelength-plane-based algorithm, which is extended from the work in [8], can be applied for lightpath routing and wavelength assignments. Due to the similarity of the algorithm to the traditional Dijkstra's algorithm in the fundamental searching principle, the algorithm was also termed 2D-Dijkstra's algorithm [3]. It is called "2D" because the basic shortest path searching steps are applied in both topological and wavelength domains. The detail on 2D-Dijkstra's algorithm constrained by a maximum transparent reach limit can be found in [3]. Specifically, besides the examination of wavelength resources, a constraint on maximum transparent reach limit is monitored when searching for a lightpath. The algorithm accumulates the length of transparent segment before an electronic switch node is reached, and all-optical wavelength conversion (if there is any) at intermediate transparent OXC nodes using analog optical wavelength converters (not OEO wavelength conversion with regeneration) is modeled as an extension to transparent segment length, as signal degradation due to all-optical wavelength conversion can be approximately equivalent to degradation caused by a certain transmission distance in an amplified optical fiber system [3]. The algorithm terminates if there is a lack of regeneration nodes on lightpaths or not enough network resources available to establish a new connection. Of course, for the problem of lightpath routing and wavelength assignments, it is possible to simply apply shortest-path or fixed alternate path routing algorithms to search for translucent lightpaths between a node pair. However, these simpler algorithms are generally less efficient by their nature as they separate the searching processes in the topological domain from the wavelength domain.

Translucent Network with Translucent OXC Nodes

We now consider networks consisting of a group of translucent nodes (Fig. 3). This type of translucent network exhibits the most uniform signal regeneration distribution. Signal regenerator allocation is a critical issue. A range of heuristic solutions have been proposed to solve the problem when there is a limited number of 3R regenerators that is permitted to be distributed in the network. Yang and Ramamurthy [5] proposed heuristics such as "nodal degree first," "centered node first," etc. to allocate regenerators, specifically for the network cases with topological information only and more information on traffic distribution. In addition, similar to the opaque node placement, a simple regenerator allocation strategy can be proposed based on the transitional weight of each OXC node. Specifically, the strategy allocates more regenerators to nodes with higher probabilities of regeneration demand. Given a transitional weight on each node and a total number of regenerators R that are planned to allocate in a network,

$$R_k = \left\lfloor (w_k \cdot R) \Big/ \sum_{k \in N} w_k \right\rfloor$$

regenerators are allocated on node k. The equation sums up all the transitional weights on the nodes, and then allocates regenerators to each of the nodes in proportion to their relative weights.

Other allocation objectives can aim to minimize the number of required 3R regenerators such that all node pairs can always reach each other via a direct lightpath (either a transparent or translucent lightpath) under a certain maximum transparent reach limit. Again, this constrained optimization problem is an NP-complete *K-center* problem. ILP models were developed in to minimize the total number of fibers and regenerators respectively for the cases of regenerator sharing per node, per link, and per path. In addition, one may again apply the same strategy as for the previous opaque node placement to allocate regenerators. One can allocate regenerators simply based on transitional weights, or extend the HNF algorithm to perform an allocation. Of course, the feasibility of other allocation approaches can be further proposed.

For lightpath routing and wavelength assignments, algorithms such as fragmentation, traceback, and hybrid weighted shortest path first were proposed in [5]. However, more advanced algorithms such as 2D-Dijkstra's algorithm [3] that jointly considers both topologic and wavelength information can be used as well. To implement 2D-Dijkstra's algorithm, a supergraph with multiple wavelength planes is constructed and inter-plane wavelength conversion links are interconnected between planes on each translucent node if there is at least one signal regenerator free at the node. Nonetheless, different from 2D-Dijkstra's algorithm for a translucent with opaque nodes, 2D-Dijkstra's algorithm here is required to monitor the number of regenerators remaining on each translucent node. Because there are a limited number of signal regenerators, if a translucent node is exhaustive of the regenerators, its inter-wavelength-plane links should be dropped.

Other Research Topics

Besides the above planning and operational issues, several other important research topics, relevant to translucent networks, need to be explored:

- Protection and restoration of translucent networks
- Traffic grooming on sparsely placed opaque nodes or translucent nodes
- Network performance monitoring and fault detection on sparsely placed opaque nodes
- Multicasting on sparsely placed opaque nodes

As in other transport networks, network protection and restoration is critical to a translucent network [2, 4]. To enable survivability, an extra constraint should be ensured. That is, between any node pair, besides a working route, a link-disjoint protection route is required that satisfies the constraint of maximum transparent reach limit. In a multi-island translucent network, due to the additional constraint from the protection route, a larger number of transparent islands can be expected than in the case that simply considers working route only. More research is expected to devise efficient transparent island division algorithms subject to the network survivability constraint. For a translucent network with sparsely placed opaque nodes, it is again a *K*-center problem to place a minimum number of opaque nodes that guarantee both working and protection routes to satisfy the constraint of maximum transparent limit. Due to the additional constraint from the protection route, a larger number of opaque nodes can be required compared to the case that simply considers working route only. For a translucent network made up of translucent nodes, the regenerator allocation given the network survivability constraint is also more complex than the case without survivability. A possible extension can be made based on the previous transitional weight-based algorithm. Finally, for all the translucent network cases, in addition to a working lightpath, the process of routing and wavelength assignment should also ensure a protection lightpath to satisfy the constraint of maximum transparent reach limit.

In a translucent network with sparsely placed opaque nodes or translucent nodes, it is easy in principle to groom low-bit-rate electronic tributaries onto a high-bit-rate wavelength channel on opaque and translucent nodes. Previous investigations have indicated that an optical network with sparse traffic grooming capability can achieve performance close to that of a network with full range of traffic grooming capability on each node [9]. Thus, a translucent network with sparsely placed opaque nodes or translucent nodes can inherently take advantage of this at no or very low cost. To date, little research has been done in this field to take advantage of potential traffic grooming capability of sparsely placed opaque nodes or translucent nodes.

Channel monitoring and fault detection is a critically important function in all-optical networks. In each opaque node in a translucent network, optical channels incident to the node are converted into electronic payloads, thereby providing a convenient and reliable way to accurately monitor channel signal quality, for example, bit error rate (BER), without the need for optical performance monitoring (OPM). It also facilitates fault detection on each transparent segment between two neighboring opaque nodes on a lightpath. An interesting research question is: how many opaque nodes are required, and how many lightpaths should be statically pre-established in an optical network so that a combined detection of loss of several lightpath signals on opaque nodes can uniquely identify the location of a network failure or largely reduce the set of doubted failure locations?

Finally, the growing popularity of multicast services such as IPTV and video on demand (VoD) means that the function of multicasting will play a more and more important role in future transport networks. Ease of multicasting is an important advantage of opaque nodes. Compared to signal multicasting in all-optical OXC nodes [10], which may suffer from high power loss due to signal splitting for multicasting purposes, multicasting on an opaque node is extremely convenient due to the maturity of electronic node architectures and the ease of duplicating signals in the electronic domain. It has been shown that an optical network with sparsely placed multicasting-enabled all-optical OXC nodes can achieve performance close to that of a network with all multicasting-enabled OXC nodes [10]. We therefore expect that a translucent network with sparsely placed opaque nodes can achieve similar performance. Thus, more interesting research in this field could consider how to take advantage of an opaque node's multicasting capability and devise an economic multicasting infrastructure. In light of the fine granularity of IP packets and the mature multicast techniques already available in the IP layer, we envision that it would be an efficient solution for multicasting to combine the multicast techniques in both the IP and optical layers. Specifically, the optical layer creates a coarse multicasting tree infrastructure, and the IP layer makes a graceful tree selection to fulfill each user's multicast request.

In light of the fine granularity of IP packets and the mature multicasting techniques already available in the IP layer, we envision that it would be an efficient solution for multicasting to combine the multicasting techniques in both the IP and optical layers.

CONCLUSIONS

This article has addressed key issues and problems in translucent optical network planning and operation. These problems involve:
- Transparent island division
- Opaque node placement
- 2R/3R regenerator allocation
- Lightpath routing and wavelengths

The first three problems are related to network planning: how to plan the most economical translucent networks while not breaking the constraint of maximum transparent reach limit. All these constrained optimization problems are NP-complete. Rather than optimal solutions, efficient heuristics are of value to search for suboptimal solutions. Although various solutions have been proposed, we think that there are still many challenging issues yet to be overcome and investigated to plan an efficient and economic translucent network. The problem of lightpath routing and wavelength assignments is also of importance to translucent networks operation. Although interesting strategies such as hierarchical routing and 2D-Dijkstra's routing algorithms can bring efficient solutions to lightpath connection establishment, more research effort is expected to produce more efficient and simpler algorithms. Network protection and restoration is also critical to translucent networks. The network survivability introduces the second constraint of maximum transparent reach limit on each protection lightpath. Consequently, this poses more challenges on the network planning and operation. Further research is therefore required to explore the planning and operational principles in this field. Finally, benefiting from inherent capabilities possessed by opaque and translucent nodes, other interesting research topics such as sparse traffic grooming, sparse multicasting, and sparse fault detection can also be looked into. In summary, for translucent optical networks, many open research issues still remain. We hope this article will spark new research interest in this field.

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