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Optimal regenerator placement in translucent optical networks

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ABSTRACT

The distance an optical signal can travel, before its quality degrades to a level that requires *3R-regeneration*, is called the *optical reach*. In a *translucent optical network*, if an optical signal has to be communicated over a distance that exceeds the optical reach, the signal is regenerated at selected nodes of the network, so that the signal quality never degrades to an unacceptable level. Given a value of the optical reach, the goal of the *Regenerator Placement Problem* (RPP), in networks handling ad-hoc demands for lightpaths, is to find the minimum number of nodes capable of 3R regeneration necessary in the network and their positions, so that every pair of nodes (u, v) can establish a lightpath (either transparent or translucent) from u to v. In this paper we have presented two Integer Linear Program (ILP) formulations that can optimally solve the RPP problem for practical-sized networks within a reasonable amount of time. The first formulation works for networks having 35 nodes or less. The second formulation works for larger networks as well (we have reported results with up to 140 nodes). We have used a branch-and-cut approach to implement the second formulation, where we have intercepted the optimization process with control callbacks from the CPLEX callable library to introduce new constraints, as needed.

1. Introduction

In an *all-optical* network, *optical-bypass* is used to carry all traffic entirely in the optical domain so that, if there is a lightpath from a source $\mathcal{S}$ to a destination $\mathcal{D}$, no Optical–Electrical–Optical (OEO) conversion is needed at any intermediate node in the path from $\mathcal{S}$ to $\mathcal{D}$. All-optical networks are also referred to as *transparent* networks, in contrast to *opaque* networks that use all-electronic switching techniques [1–3]. The quality of transmission (QoT) of an optical signal propagating through a network degrades, due to physical layer impairments, such as *optical noise*, *chromatic and polarization mode dispersion*, *four wave mixing*, *cross-phase modulation* and *cross-talk* [1,4]. This leads to an increase in the *Bit Error Rate* (BER) of the signal and the corresponding lightpath becomes infeasible for communication, if the BER value crosses a certain threshold. As a result, in a wide-area backbone optical network, spanning a large geographical area, all end-to-end connections cannot always be established in the optical domain [1,4].

Physical layer impairment aware route and wavelength assignment (PLI-RWA) deals with designing optical networks, taking into account these degradations. When the quality of an optical signal becomes unacceptable, it is necessary to *reamplify*, *reshape* and *retime* the optical signal. These three processes cleanup and rectify the optical signals, and are often jointly called *3R regeneration* [1,5]. The notion of *translucent* networks, introduced by

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Ramamurthy et al. in [3,6,7], has features of both transparent and opaque networks. In a *translucent network*, at least one optical signal is regenerated at one or more regeneration points (typically a selected subset of the nodes of the network has the capacity to carry out 3R-regeneration [1]), so that the signal may be communicated over long distances. Henceforth, in this paper, we will call a node which has the capacity to carry out 3R regeneration as *a regenerator node*. Even though regeneration can be accomplished completely in the optical domain, regeneration in the electronic domain (i.e., using OEO conversion) is still the most economical and reliable technique [8]. When OEO conversion takes place, carrier wavelength conversion is available for free [5,9], so that, if a lightpath from $\mathcal{S}$ to $\mathcal{D}$ undergoes OEO conversion at some node $\mathcal{P}$, the carrier wavelength of the incoming lightpath to $\mathcal{P}$ may be different from the carrier wavelength of the outgoing lightpath from $\mathcal{P}$.

Physical layer impairments (PLI) can be classified into two categories – linear impairments and nonlinear impairments [5,10,11] (some researchers have categorized them somewhat differently as Class 1 and Class 2 impairments [12,13]). Linear impairments are independent of the signal power and affect each of the wavelengths (optical channels) individually, whereas nonlinear impairments affect not only each optical channel individually but they also cause disturbance and interference between them [5]. *Optical reach* [2,14] (also called *transparent reach* [1,5] and *transmission reach* [8]) is the maximum distance an optical signal can travel before 3R-regeneration is needed. Optical reach is a popular metric [2,8] to determine when 3R regeneration is needed and usually ranges from 2000 to 4000 km [4].[1]

A lightpath that involves one or more regenerators is often called a *translucent lightpath* [1]. Each translucent lightpath is a concatenation of two or more transparent (i.e., all-optical) lightpaths, where one transparent lightpath is from the source of the communication to a regenerator node, one is from a regenerator node to the destination for the communication and the remaining transparent lightpath(s), if any, is (are) from a regenerator node to another regenerator node. An example of a long haul network with distances between the nodes in km is shown in Fig. 1. If the optical reach is 2000 km, an optical signal from node *A* cannot reach node *D* without 3R-regeneration, so that a lightpath from *A* to *D* must be a translucent lightpath. It may be easily verified that a translucent lightpath from *A* to *D* using the route $A \rightarrow B \rightarrow C \rightarrow D$ involving a 3R-regeneration either at *B* or *C* is a valid solution.

Following [5,8,16], when carrying out network planning, we classify the requests for communication as follows:

(a) some requests for communication are relatively permanent and are called *permanent lightpath demands* (PLD) (or static demands);
(b) some requests have a lifetime (i.e., a start time when the lightpath is set up and an end time when the lightpath is taken down). These are called *dynamic lightpath demands* (DLD) and may be further subcategorized as follows:
  (i) the start time and the lifetime of the request may be known in advance. Such requests are called, *scheduled lightpath demands* (SLD),
  (ii) neither the start time nor the duration of such a request is known in advance. Such requests are called *ad-hoc lightpath demands* (ALD).

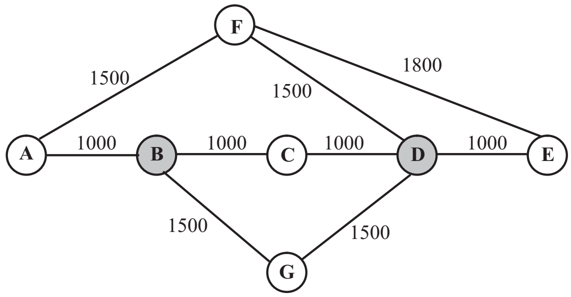

Fig. 1. Long haul optical network with distances between the nodes in km.

Route and wavelength assignment where all requests are PLDs (DLDs) are called *static*, also *offline* [5,9,10] (*dynamic*, also *on-line* [5,9,10]) PLI-RWA. In a translucent network, the PLI-RWA problem will be inevitably coupled with regeneration placement problem [5,8–10] in which the network designers are trying to plan and design, for a given network topology, a translucent network with an optimal number of regeneration sites. Static PLI-RWA in a translucent network requires users to specify beforehand all pairs $\{\mathcal{S}, \mathcal{D}\}$, such that a lightpath (translucent or transparent) will be set up from $\mathcal{S}$ to $\mathcal{D}$. In networks that handle ALD, the concepts of islands of transparency [17] and sparse regeneration [2,3,14] have been studied extensively.

In a network that handles ad-hoc lightpath demands, using sparse regeneration, there are two types of problems that have to be handled:

*Problem*1 (to be handled during the network design phase): Given a network topology, select a minimum number of nodes to be regenerator nodes, so that each node can communicate with any other node in the network, using either a transparent lightpath or a translucent lightpath. This is called the *Regenerator Placement Problem* (RPP) [2,6,9,14].

*Problem*2 (to be handled when the network is in operation): In response to a new request for communication, say from node $\mathcal{S}$ to node $\mathcal{D}$, set up, if possible, a lightpath (transparent or translucent) from $\mathcal{S}$ to node $\mathcal{D}$, taking into account all existing lightpaths in the network. This is called the *Routing with Regenerator Problem* (RRP). Given a network topology with selected nodes identified as regenerator nodes, and a number of lightpaths already in existence, the objective of RRP is to optimally route the new lightpath from

[1] In [15] it was stated that an optimal value of the optical reach ranges between 2500 km and 3500 km.