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Heuristic and optimal techniques for light-trail assignment in optical ring WDM networks

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Abstract

In this paper we address the problem of constrained optimization (ILP formulation) and propose a set of heuristic algorithms for assigning light-trails [1–4,7,10] to WDM ring networks to facilitate IP centric dynamic communication at the optical layer. A light-trail is a generalization of a lightpath such that multiple nodes can take part in communication along the path without the need for optical switching. A light-trail represents an opportunistic medium in which multiple spatially distributed sub-lambda flows can be groomed despite without the need for optical switching. A light-trail is analogous to an optical bus such that multiple connections between source–destination pairs can be provisioned under the constraint that no two connections have overlapping time-intervals. This enables traffic grooming at the optical layer. In this paper we first describe a constrained optimization procedure for assigning light-trails in WDM ring networks. We then show five heuristic algorithms that solve the light-trail assignment problem in polynomial time. The heuristic algorithms are based on dynamic (unknown traffic) and static (known traffic) approaches. A simulation study compares the performance of ILP and heuristic algorithms.

Keywords: Light-trail; WDM ring networks; Traffic grooming; Dynamic provisioning

1. Introduction

Fiber optic communication provides a befitting transport mechanism for the near exponential surge of data traffic. The present mode of fiber optic networking is based on lightpaths or optical circuits that are end-to-end all-optical paths residing on a single wavelength. However as we move from circuit switched to IP centric communication [9,8] due to the emergence of IP as a universally accepted protocol, the full granularity – that of an entire wavelength provided by a lightpath is not an efficient means for bandwidth provisioning. The result is that networks using lightpath communication and wavelength routing are over-provisioned leading to expensive network element deployment and not being able to provide the dynamic guarantees of bandwidth provisioning as required by IP centric communication. Light-trails [1–5,10] on the other hand offer a low cost pragmatic alternative by providing dynamic provisioning as compared to rigid lightpath communication. *A light-trail is a generalization of a lightpath such that multiple nodes along the trail can take part in communication without the need for optical switching [5,10]*. Thus, a light-trail can cater to sub-lambda flows in an efficient manner. The principle of a light-trail is similar to that of an optical bus whereby multiple nodes along the bus can communicate to their downstream nodes (broadcast medium), under the constraint that no two nodes transmit at the same time. To enable non-time overlapping transmissions we make use of an out-of-band control channel that arbitrates communication amongst nodes in a light-trail. A light-trail by it self is semi-permanent, defined by its two extreme nodes – a convener node and an end node (Fig. 1). The light-trail can be further understood as an optical bus exemplified by a wavelength, switched between the convener and the end

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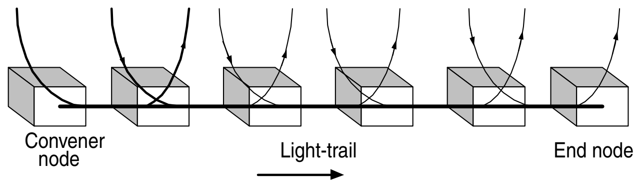

Fig. 1. The concept of multi-point lightpath or simply, a light-trail.

nodes and shown in Fig. 1. Though the setting up procedure of light-trails does involve optical switching, the procedure to set up 'connections' between nodes within the light-trail does not involve any kind of optical switch configuration. Connections in a light-trail can be of dynamic nature and the out-of-band control protocol does the task of connection management. This means that the out-of-band protocol arbitrates communication and resolves conflicts in the light-trail. The protocol shown in [1] also has the added responsibility of light-trail management in addition to the dynamic connection management, whereby it sets up the light-trails, tears them down as well as dimensions (grows/contracts) the set of light-trails as per requirement. The hardware and protocol for light-trails are shown in [1–5,10] for ring and mesh nodes.

1.1. Need for a heuristic algorithm for light-trail assignment in ring networks

A *Need for optimization*: light-trails present a mechanism that enables dynamic provisioning, optical grooming and optical multicasting. Spatially diverse sub-wavelength flows from multiple nodes are groomed in the wavelength bus (light-trail) by arbitrating the bandwidth in the light-trail to accommodate each flow. A light-trail represents an opportunistic medium for multiple nodes to share wavelength bandwidth. While the out-of-band control channel is fundamental in bandwidth arbitration in the light-trail, it also manifests itself in another important way: the control channel also sets up, tears down and dimensions light-trails in the network. This double abstraction of the control plane in light-trail networks – at the connection (intra-light-trail) level, and at the network-wide light-trail level is fundamental to enable the network to support traffic growth. While setting up and tearing down connections is dynamic (due to absence of optical switching), the setting up and tearing down of light-trails is significantly time-consuming. It was shown in [15] that the time required to set up connections is of the order of 10 μs, while the time to set up light-trails was three orders of magnitude higher at 2.4 ms. To preserve the dynamic provisioning property of light-trails, it is desired to minimize the probability of setting up a light-trail for a new traffic request. Alternatively it is desired to create a topology of light-trails mapped to nodes and wavelengths across the network, such that traffic is readily routed across these light-trails. The problem of grooming spatial sub-wavelength flows into light-trails while considering the temporal aspects of traffic leads to a constrained optimization problem. *The fundamental question is how to set up the static light-trails in the best possible manner?* In order to do this, we have to minimize the resources (wavelengths) used, minimize the provisioning time, and maximize the possibility that a new bandwidth request will find an available light-trail, thus reducing the probability of needing to create an extra light-trail. A factor that has to be taken into account is that light-trail communication is constrained by the bus property, i.e., by the fact that upstream nodes have a higher priority for establishing connections as compared to downstream nodes. The bus property leads to a situation where, if a node is in the process of transmitting data over a connection, and an upstream node desires to use the light-trail, the node has to interrupt and halt its transmission allowing the upstream node to transmit. As a result, the queuing delay on nodes in a light-trail will depend on their position within the trail. As most broadband applications have stringent latency requirements, the queueing delay is a function of the node's position with respect to the convener of the light-trails. The goal of the optimization process is to create a system where we assign optimal light-trails across a network graph such that the traffic latency incurred in provisioning connections or new light-trails is within the bounds required by the traffic demands.

In this paper, we will first develop a linear program for optimally assigning light-trails taking into account the temporal aspects of traffic. The constrained optimization will attempt to maximize the wavelength utilization in each light-trail. Subsequently we will build heuristic algorithms for assigning light-trails thereby reducing the apparent complexity of the linear program. Our optimization is significantly different from earlier light-trail optimization approaches shown in [2] and [6]. While [2] is a simple optimization of allocating light-trails to a given traffic matrix, [6] shows how to allocate light-trails based on hop distances. However, this approach is similar to the routing and wavelength assignment (RWA) problem for lightpaths and does not consider the temporal (stochastic) aspect or the sub-wavelength characteristics of light-trail flows. Our approach is a mid-way between the approaches of [2] and [6] whereby we consider factors like light-trail fairness and optimum size both part of our optimization. We first normalize each source–destination flow by taking the average rate of the flow, the latency of the service represented by the flow and the ratio of the flow to the light-trail (wavelength) bandwidth. Then by considering the entire set of possible light-trails, we allocate flows from source–destination pairs by creating an optimum sub-set of chosen light-trails. The resultant optimum set of chosen light-trails is the output of our constrained optimization problem. We constrain our optimum set of light-trails to have maximum utilization in each light-trail. This ensures that the total number of light-trails selected (and hence wavelengths) is minimized. The light-trail assignment problem is analogous to the bin packing problem [2,6] with a slight modification, of aligning the flows within each light-trail (bin) under the constraint that a light-trail is a unidirectional bus and has limited