Computer Networks 103 (2016) 181–195

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

# Heuristic algorithms for efficient allocation of multicast-capable nodes in sparse-splitting optical networks☆

Costas K. Constantinou[a,*], Georgios Ellinas[a,b]

[a] KIOS Research Center for Intelligent Systems and Networks, University of Cyprus, Nicosia 1678, Cyprus
[b] Department of Electrical and Computer Engineering, University of Cyprus, Nicosia 1678, Cyprus

ARTICLE INFO

*Article history:*
Received 30 July 2014
Revised 8 October 2015
Accepted 29 February 2016
Available online 8 April 2016

*Keywords:*
Optical networks
Sparse splitting
Multicast
Multicast-capable node allocation

ABSTRACT

Optical splitters are utilized in optical nodes for splitting the received signal into multiple copies, in order to efficiently provide multicast capabilities in optical networks. In practice, only a fraction of the network nodes are equipped with optical splitters. These nodes are called multicast-capable (MC) and the remaining nodes are called Multicast Incapable (MI). In some networks, if the MI nodes are destinations of the multicast request, they can drop a small fraction of the incoming signal's power locally and transmit the rest to the next node. This ability is called Drop-and-Continue (DaC) and the relevant networks are called DaC networks. In the absence of the DaC capabilities, the network is called Drop-or-Continue (DoC). The current paper deals with both aforementioned categories of networks, and proposes three heuristic algorithms for the efficient allocation of a limited number of MC nodes in the network, so as to achieve a low average cost of the light-trees that are calculated for routing the multicast requests. It is shown through simulations that the proposed techniques significantly outperform the relevant conventional splitter placement techniques. This work also investigates the impact of networks having DaC rather than DoC capabilities, as well as the impact of the percentage of MC nodes on the network performance, providing guidance for the efficient design of optical networks with sparse multicasting capabilities.



## 1. Introduction

Optical networks have evolved steadily over the last two decades from wavelength division multiplexed (WDM) point-to-point systems at the physical layer providing transport capabilities through optical fibers, to ring, and subsequently mesh topologies with intelligent switching elements (reconfigurable optical add-drop multiplexers (ROADMs), optical cross-connects (OXCs), etc.) that can now provide provisioning of wavelength and sub-rate connections, fault accommodation, as well as several other control functionalities at the physical (optical) layer. With the successful commercialization of WDM, and several key technology advancements of optical component technologies (such as optical amplifiers, lasers, filters, and optical switches amongst others) within the optical networking space, the standardized optical transport network (OTN) nowadays provides for carrier-grade operations, administration, and maintenance (OAM) for managed wavelength services, as well as fault accommodation for high service availability [1].

☆ This work was supported by the Cyprus Research Promotion Foundation's Framework Programme for Research, Technological Development and Innovation 2009 (DESMI 2009–2010), co-funded by the Republic of Cyprus and the European Regional Development Fund, and specifically under Grant TPE/EPIKOI/0311(BIE)/11.

* Corresponding author. Tel.: +35722893450.
*E-mail addresses:* constantinou.k.costas@ucy.ac.cy (C.K. Constantinou), gellinas@ucy.ac.cy (G. Ellinas).

http://dx.doi.org/10.1016/j.comnet.2016.02.028
1389-1286/

Next-generation optical networks are expected to support traffic that will be heterogeneous in nature with both unicast, as well as multicast applications. Even though most connections carried over an optical mesh network are still currently unicast connections (e.g., high-bandwidth point-to-point connections for enterprise customers) new traffic requirements and applications are driving the evolution of the network architectures, requiring multicast capabilities to deliver high-bandwidth content. For example, recent bandwidth-intensive applications that are driving the use of optical multicasting include telepresence, grid computing, telemedicine, software and video distribution for residential customers, movie broadcasts, interactive distance learning and video training, and distributed games amongst others.

Multicasting refers to the simultaneous transmission of information from a single source to several destinations. Optical multicast requests are established via the provisioning of trees (called *light-trees* in optical networks), that are created utilizing optical splitters at the network nodes [2,3]. Thus, in order to support these multicast connections, the utilization of multicast-capable nodes (nodes where optical splitting can take place), strategically placed at certain node locations during the network design phase, is of great interest, as it will provide efficient multicast connectivity while keeping the network cost low (by not utilizing MC nodes throughout the entire network). This results in a *sparse-splitting* network [2,3], where some of the network nodes are multicast-capable, while the rest are multicast-incapable (MI) (nodes that do not have optical splitting capabilities). These MI nodes can also be distinguished as *Drop-and-Continue* (DaC) or *Drop-or-Continue* (DoC) nodes. A DaC node can transmit the optical signal to the following node in its path *and* can also drop it locally as well, while a DoC node can either transmit the optical signal to the following node in its path *or* drop it locally. Since both networks architectures are viable possibilities [4,5], the current paper deals with both DaC and DoC networks. The analysis of both cases can subsequently be utilized by network engineers and designers to ascertain both architectures when deciding what technologies and architectures to deploy in their networks.

As the problem of where to optimally place the MC nodes in the network (MC node allocation) is an NP-complete problem [6], polynomial-time heuristics that give approximate solutions are used in practice. This is precisely the focus of this work. In the current paper three heuristics are proposed for efficient MC node allocation, that can be applied for both DoC and DaC networks. Their performance evaluation, through simulations on the well-known USNET and NSFNET networks as well as on larger, randomly created networks, has shown that they achieve an important decrease of the average cost of the derived multicast trees compared to the conventional placement methods. Furthermore, this work also investigates the impact of networks having DaC rather than DoC capabilities, as well as the impact of the percentage of MC nodes on the network performance, providing guidance for the efficient design of optical networks with sparse multicasting capabilities.

The remaining of the paper is organized as follows: The problem formulation is given in Section 2, as well as the notation and definitions that are used throughout the paper. The existing work on MC node allocation is presented in Section 3. Section 4 presents the proposed techniques for cost-efficient allocation of MC nodes, while their performance evaluation is presented in Section 5. Finally, in Section 6, the conclusions of the paper are presented, as well as directions for future work.

## 2. Problem formulation, notation, definitions

Throughout the paper, the following notation and definitions are utilized.

- The network is modeled as a directed graph $G = (V, A)$, where $V$ ($|V| = n$) and $A$ ($|A| = m$) are the sets consisting of the network nodes (representing the optical switching nodes) and arcs (representing the optical fibers), respectively.
- The notation $[i, j]$ stands for the arc originating from node $i$ and ending at node $j$.
- A cost $c_{ij}$ is assigned to each arc $[i, j]$.
- The network directed graph is considered to be symmetric: for every arc $[i, j]$ in $A$, the corresponding opposite arc (i.e., $[j, i]$) also belongs to $A$, with $c_{ij} = c_{ji}$ (as each network link consists of two fibers with opposite orientation).
- Each fiber carries $W$ wavelengths, denoted by $\lambda_1, \ldots \lambda_W$.
- The set consisting of the MC nodes of the network is denoted by $MC_{set}$, and $|MC_{set}| = p$.
- The multicast session is denoted by $S = \{s, d_1, d_2, \ldots, d_k\} = \{s, D\}$, where $s$ is the source node and $D = \{d_1, d_2, \ldots, d_k\}$ is the destination set consisting of $k$ destinations.
- The light-tree (or simply, tree) for routing a requested multicast session is denoted by $T = (V_T, A_T)$, where $V_T$ and $A_T$ are the sets consisting of the light-tree nodes and arcs, respectively.
- A *branch node* of a tree is defined as a node on the tree that has out-degree at least equal to 2.
- The paths on the tree that originate from a branch node are the *branches* of it.

As it will be shown in Section 4 below, the proposed MC node allocation methods are based on the calculation of light-trees. The derivation of the latter is performed under the following assumptions:

- Each network node has full wavelength conversion capability (utilized mainly to limit the strain on the wavelength resources and overcome wavelength contention issues when setting up a large number of multicast connections). There are currently a number of techniques for wavelength conversion based on a number of technologies such as nonlinear optical gating based on fiber loop, cross-phase modulation, cross-gain modulation, four-wave mixing based on semiconductor optical amplifiers, etc., with some of them being simple, and cost-effective, with minimum power requirements (such as injection induced wavelength conversion of a single-mode laser).