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Impairment-aware multicast session provisioning in metro optical networks

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ABSTRACT

This work investigates the problem of designing, engineering, and evaluating metropolitan area transparent optical networks for the provisioning of multicast sessions. Apart from finding the minimum-cost tree and using metrics on the physical performance of the system, namely the *Q*-factor, this work investigates different node architecture designs including architectures with active and passive splitters and architectures with different receiver and transmitter designs. Different network engineering approaches are also utilized and are used to ascertain whether a multicast connection should be admitted to the network. "Tree balancing techniques" are used for routing the multicast sessions, aiming at maximizing the multicast connections that can be admitted to the network.

1. Introduction

Advances in optical wavelength division multiplexing (WDM) networking have made bandwidth-intensive applications widely popular. Clearly, most connections carried over an optical mesh network have been high-bandwidth point-to-point (PtP) connections. However, a number of recent new customer applications have driven the need to support multicast connections, potentially over optical mesh networks. These applications, requiring point-to-multipoint (PtMP) connections from a source node to several destination nodes in the network include video distribution for residential customers, video conferencing between telepresence-equipped rooms for global enterprise customers, video training and e-learning, grid-computing applications, telemedicine applications, etc.

Multicasting provides an easy means to deliver messages to multiple destinations without requiring too much message replication. Next-generation networks must have the capability and build-in intelligence to support all types of traffic (unicast, multicast, and groupcast) and all kinds of applications. All-optical multicasting (the assumption in this work is that the network is completely transparent without OEO conversions and thus it has no regeneration points) has been investigated in the research community since the early days of optical networking [1–8], but has only recently received considerable attention from the service providers, mainly because now many applications exist that can utilize the multicasting feature. In these networks, optical splitters can be used to split the incoming signal to multiple output ports, thus enabling a source node to establish connections with multiple destinations by creating a "light-tree".

There exist several routing heuristics for finding the light-trees; however, for the majority of them there is no consideration on the physical layer constraints. In this work, we

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present "tree-balancing" routing techniques aimed at maximizing the multicast connections which can be admitted to the network. These techniques, that also take into consideration the physical layer impairments (PLIs), are shown to improve the overall blocking probability compared to previous tree routing techniques found in the literature. To investigate whether a multicast connection should be admitted to the network, apart from finding the minimum cost tree, a *Q*-budgeting approach is used as a metric of the physical performance of the system [9]. Furthermore, the availability of transmitters and receivers is also investigated for the establishment of the multicast connection. The assumption in this work is that a multicast call is accepted into the network only if a working tree can be found that satisfies the physical layer constraints (acceptable BER at all the destinations of the multicast session) and it also has available network resources (available transmitter/receiver and wavelength).

This paper extends on the work presented in [11]. Specifically, in [11], several "tree-balancing" techniques that consider the PLIs were initially introduced. However, in that work, no specific multicast-capable node architecture or engineering was assumed; rather, the multicast-capable node architecture was treated as a "black-box". This work goes one step further, by examining several node architectures and engineering designs utilizing active or passive splitters and different types of transmitters and receivers including every possible combination between fixed and tunable transceivers. A small number of these were first presented in [14] but the work here is greatly expanded and more in-depth. Specifically, several transceiver designs are for the first time discussed and evaluated (fixed TXs/tunable RXs, tunable TXs/fixed RXs) and the presentation of the node architectures and network engineering cases is presented in detail. Furthermore, this work expands on the multicast routing algorithms examined, as a number of new and existing algorithms are developed and compared for every node architecture/network engineering presented.

The novelty of the work stems from the fact that in the literature most of the work that includes PLIs deals only with unicast connections, whereas this work investigates multicast connections, presenting a complete solution of node architecture design, network engineering, as well as multicast routing algorithms for the case when the PLIs are also considered. Furthermore, it is shown that the proposed algorithms, that take the physical layer constraints into consideration, outperform the rest of the tree routing techniques that either consider only the power budget or route the multicast connections irrespective of the physical layer constraints. This work clearly shows that different engineering of the physical layer produces different multicast group blocking, a strong indicator that a more refined interaction between physical and logical layer is needed for efficient multicast connection provisioning.

In Section 2 the physical layer system model used to account for the physical layer impairments is presented. This is followed by the description of different node architecture designs in Section 3 and of various multicast tree routing heuristic algorithms in Section 4. Provisioning approaches for the multicast connections for the impairment-aware case are described in Section 5 and performance results for these schemes for all the routing techniques are shown in Section 6. The paper ends with some concluding remarks in Section 7.

2. Physical layer system modeling

The Bit Error Rate (BER) of the system is the main performance indicator in a fiber-optic digital communication system. However, as the BER is a difficult parameter to numerically evaluate, the required system *Q*-factor for a target BER is derived instead using Eq. (1) [9,10].

$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{e^{\frac{-Q}{2}}}{Q\sqrt{2\pi}} \tag{1}$$

The value of the *Q*-factor can be calculated using Eq. (2) [9–11] and compared to the required performance,

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \tag{2}$$

where I_0 and I_1 represent the received current levels for symbols 0 and 1 respectively and σ_i is shown in Eq. (3) [9–11] as the sum of the variances of the thermal noise, shot noise, various components of beat noise, and relative intensity noise (RIN) (σ_0 and σ_1 denote the sum of the variances for the various noise components for symbols 0 and 1 respectively).

$$\sigma_i^2 = \sigma_{\mathrm{th}}^2 + \sigma_{\mathrm{shot}-i}^2 + \sigma_{\mathrm{ASE-ASE}}^2 + \sigma_{s-\mathrm{ASE}-i}^2 + \tag{3}$$

$$\sigma_{\mathrm{RIN}-i}^2 + \sigma_{\mathrm{ASE-shot}}^2$$

This approach assumes a baseline system with various receiver noise terms as well as Amplified Spontaneous Emission (ASE) noise. To include other common physical layer impairments such as crosstalk, fiber nonlinearities, distortion due to optical filter concatenation, and Polarization Mode Dispersion (PMD) amongst others, a simple *Q*-budgeting approach is used as described in [9]. The approach starts from the *Q*-value for the baseline system and budgets *Q*-penalties for the various physical layer impairments that are present. The *Q*-penalty (Q_{dB}) associated with each physical layer impairment in a system is commonly expressed in dB and in this work the following definition is used: $Q_{\mathrm{dB}} = 10 \times log(Q_{\mathrm{linear}})$. The *Q*-penalty is calculated as the Q_{dB} without the impairment in place minus the Q_{dB} with the impairment present. This approach enables a network designer to calculate the impact of physical layer effects, such as non-linearities, polarization effects, optical crosstalk, as well as aging and safety margins, in the design of an optical network.

The values used for this budgeting approach are shown in detail in [11]. The reader should note that when calculating the dB value for fiber nonlinearities (such as cross-phase modulation and four wave mixing), a worst-case value is assumed that covers the cases of varying number of channels on each path based on the work in [9] that included detailed time-domain simulations for the nonlinear effects. It must also be pointed out that amplifier gain control is assumed [12] and that no polarization dependent gain/loss (PDG/PDL) or amplifier ripple are present, thus precluding power instabilities.

The formulation used for the calculation of the variances of the different noise components (thermal, shot, various components of beat noise, and RIN noise) can be found in