Node Architecture Design and Network Engineering Impact on Optical Multicasting Based on Physical Layer Constraints

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Abstract: Different node design architectures and node engineering approaches are considered for fully-transparent metropolitan area optical networks for the provisioning of multicast sessions. A number of multicast routing approaches are considered that take into account the physical layer constraints. The goal of this work is to minimize the overall blocking probability in the network, while ensuring that the provisioned multicast connections meet a prescribed bit error rate.

1. Introduction

High-bandwidth multicast applications are becoming widely popular, further driving the requirement for next generation optical networks to support all types of traffic (unicast, multicast, groupcast) and all kinds of applications. Even though there is a large body of work on optical multicasting, this area is receiving renewed attention from the service providers, as the number of multicasting applications is constantly increasing. In these networks optical splitters can be used in network nodes to split the incoming signal to multiple outputs, thus enabling the establishment of connections with multiple destinations [1]. In transparent optical networks, a light-tree is created to serve a multicast request, which is a set of lightpaths from the source to all the destination nodes [2].

Recent work on the problem of routing and wavelength assignment (RWA) for provisioning multicast connections in transparent optical networks have included the inclusion of physical impairments to investigate whether a multicast connection should be admitted to the network, apart from finding the minimum cost tree. In our previous work a Q-budgeting approach is used as a metric of the physical performance of the system as described in [3]. In [4] the detailed design of the node architecture and the engineering of the nodes are presented, in order to study the impact of physical impairments on the provisioning of the connections. In this article, we expand on that work by investigating the node design and considering nodes with active or passive splitters, and nodes with various transmitter/receiver designs.

2. Physical Layer System Modeling

Modeling of the physical layer is based on the physical path Q factor that is subsequently used to calculate the Bit Error Rate (BER) of the system, a parameter that is difficult to evaluate upfront [3,5]. 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 PMD among others, a simple Q-budgeting approach is used as described in [3]. We start from the Q-value for the baseline system and budget Q-penalties for the various physical layer impairments present. Thus, this approach enables a network designer to calculate the impact of physical layer effects, such as non-linear effects, polarization effects, optical crosstalk, etc., in the design of an optical network without the computationally complex time-domain approach, thus enabling simulation repetitions that are needed for system engineering.

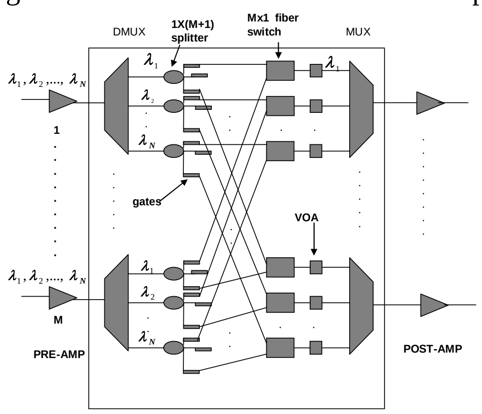
The Q penalty Q_{dB} associated with each physical layer impairment in a system is expressed in dB and is calculated as the Q_{dB} without the impairment in place minus the Q_{dB} with the impairment present. After the Q factor is evaluated, the BER can then be calculated [5]. In this work, a Q threshold is set for a specified BER and the decision to provision a given multicast connection relies on whether we are above or below the set threshold [6].

3. Node Architectures and Node Engineering Designs

In this section we present different node architectures and different node engineering designs and examine the physical performance of the network using the Q-budgeting approach. We investigate architectures that utilize passive optical splitters at the nodes versus architectures that utilize active splitters, as well as architectures with various transmitter/receiver designs (all possible transmitter/receiver architecture design combinations). Different node engineering designs are also considered for the different architecture options.

3.1 Architectures with Passive vs. Active Splitters

Figure 1 shows an example of the network node design, utilizing passive optical splitters, initially ignoring the transmitter/receiver design. In order to determine the Q-value for each multicast call, a baseline system Q-value is first calculated based on the signal and noise terms, assuming 10 Gbps bit rate, a pre-amplified photodiode, and 32 wavelengths spaced at 100 GHz. Insertion loss is calculated based on the worst case scenario, considering passive or active splitters, and the amplifier gain is set for the worst case scenario. Variable optical attenuators (VOAs) are present in this architecture and in an actual system they would be used to control the effects of Polarization Depended Gain/Loss (PDG/PDL) as well as to attenuate the input power to the post-amplifiers. Controllable Semiconductor Optical Amplifiers (SOAs) are also introduced as gates to block the power at outputs where the signal is not destined for. All gates are controlled together in an intelligent manner to avoid clashing at the same output port and/or same wavelength of the switch. In the case of active splitters, no gates are required, since the splitters are assumed to split the power only as many times as is needed for the signal to be forwarded to the destined outputs.



NOISE FIGURE OF EDFAS

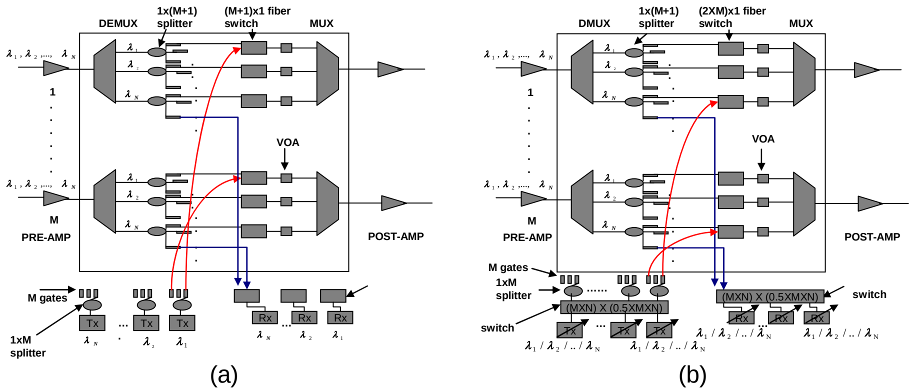
$Gain\ in\ dB$	NF
$G < 13$	7
$13 < G < 15$	6.7
$15 < G < 17$	6.5
$17 < G < 20$	6
$G > 20$	5.5

Figure 1: Generic node architecture.

For the active vs. passive splitter comparison, +3dBm power was launched into system with pre-amplifiers set to an output power of 6dBm and post-amplifiers set to an output power of 3dBm which results in improvement of the overall node noise figure. Mux/demux insertion losses are assumed to be 3dB, and switch, gate, and VOA losses are set to 0.6, 0.6, and 0.5dB respectively, with the fiber attenuation set at 0.3dB/Km. Noise figures (NFs) for the EDFAs are based on realistic device specifications and are shown in Figure 1. At the destination nodes, PIN photodiodes are used and the pre-amplifier gain is assumed to depend on the degree of that node, with a maximum output power of -4dBm and a noise figure of 4.5dB.

3.2 Architectures with Different Transmitter/Receiver Designs

A number of different node architecture designs were also considered for different types of transmitters/receivers. In this case passive splitting is assumed throughout and the node engineering is modified to account for the various new architectures. The node architectures examined include nodes with fixed Txs/Rxs, tunable Txs/fixed Rxs, fixed Txs/tunable Rxs, and tunable Txs/Rxs. For all the cases considered, the number of transmitters/receivers for each source/destination node is assumed to be equal to the number of wavelengths. Figure 2 shows an example of the case of fixed transmitters/receivers (Figure 2(a)) and tunable transmitters/receivers (Figure 2(b)). Figure 2 also shows the different component losses inside the node, including the losses for the switches added at the receivers. The assumption in this work is that these switches can add/drop 50% of the total number of wavelengths in the network. The size of the switches is proportional to the number of wavelengths and the fan-out of the source node. For all these architectures mentioned above, signal launched power into the fiber is now set to 5dBm, and each node's EDFA is assigned a realistic noise figure depending on its gain (NF numbers are shown in Figure 1), with the gain of each pre-amplifier compensating the loss of each preceding fiber span.. The gain of each post-amplifier compensates for the actual node loss and is engineered based on the worst case insertion loss through the node. Again, the noise figure of the PIN receiver's pre-amplifier is assigned a value of 4.5dB with a gain that is adjusted so as to bring signal power at -4dBm.



COMPONENT LOSSES IN THE NODE

Component	*Losses in dB*
MUX/DMUX	3
Splitter	$10 * log(Fanout)$
Gate	0.6
VOA	0.5
Switch	1

MEMS LOSSES

Size	*Losses in dB*
$X \leq 25$	1
$25 < X \geq 36$	1.5
$36 < X \geq 56$	2.2
$56 < X \geq 68$	3
$68 < X \geq 80$	3.7
$80 < X \geq 100$	4.5
$X > 100$	5

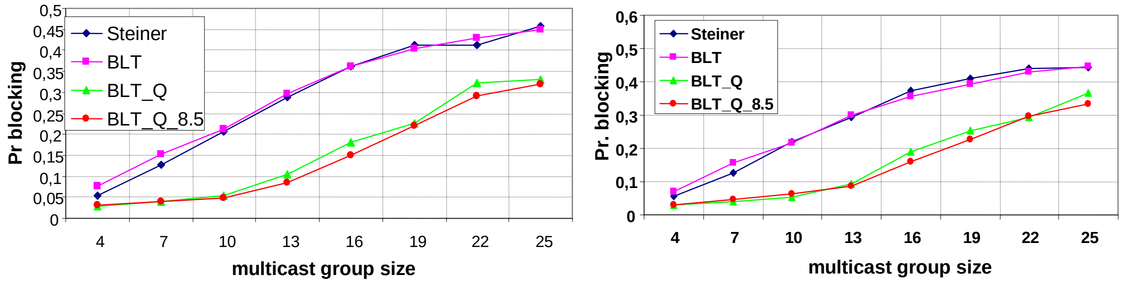
Figure 2: Node engineering for (a) fixed Tx/Rx, (b) tunable Tx/Rx.

4. Performance Results

In our performance analysis, for each multicast connection request, the algorithm first solves the multicast routing problem and then assigns a wavelength for that tree (first-fit wavelength assignment algorithm). Multicast requests are blocked if there is no available wavelength for the entire tree. A multicast connection is admitted in the network if: (a) a route and wavelength assignment can be found, (b) the Q-factor for each path on the tree is above the predetermined threshold, and (c) there are available Txs and Rxs for that connection. If the physical impairments constraints are not met, a new wavelength assignment is implemented and the heuristic is repeated until no new wavelength assignments are possible. In that case, the call is blocked. Five multicast routing algorithms are used in this work, namely the Steiner tree heuristic (minimum cost tree based on shortest path calculations) [7], the balanced light-tree (BLT) heuristic [8] algorithm that only takes power budget constraints into consideration, the BLT_Q and $BLT_{Qthreshold}$ heuristics as described in [3,4] that take the Q factor into consideration as well, and the shortest path tree (SPT) heuristic that finds the multicast tree by merging all unicast shortest path connections from source to all destinations.

For our simulation model we used a metro/regional network consisting of 50 nodes and 196 links. This network has an average node degree of 3.92 and an average distance between the links of 60 Km. Multicast connection requests arrive at each node dynamically, and follow a Poisson process with exponentially distributed holding times with a unit mean, generating a network load of 100 Erlangs. The simulation model generated 5,000 requests for each multicast group size and 8 multicast group sizes were considered (in the worst case half of the network nodes are considered as destinations). The Q threshold used in this work is 8.5dB, which corresponds to a BER of 10^{-12}.

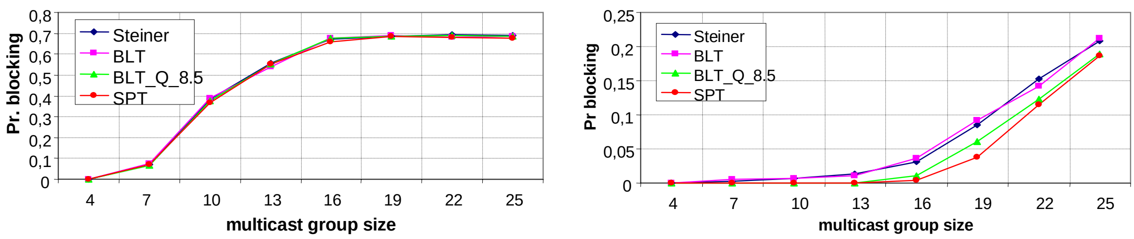
As shown in Figure 3, simulation results indicate that the $BLT_{Qthreshold}$ and SPT heuristics perform the best for both passive and active splitting cases, and that there is no particular advantage of using active instead of passive splitters, at least for the worst case scenario. This is due to the fact that VOAs are used to attenuate the total power to a predetermined value that is calculated based on the worst case scenario. Results were slightly better for active splitters because at the destination nodes the signal is dropped to the Rx before facing VOA attenuation, thus resulting in an improvement on the Q-factor.



(a) (b)

Figure 3: Blocking Probability versus multicast group size for node engineering with (a) active splitters and (b) passive splitters

Figures 4(a) and 4(b) show the simulation results for the blocking probability versus the multicast group size when a number of multicast algorithms are used assuming node engineering with passive splitters for the case of fixed transmitters/receivers and tunable transmitters/receivers respectively. Clearly, blocking probability is greatly reduced in the case of tunable Txs/Rxs, since in this case there is more flexibility in the network to assign wavelengths to the multicast connections. The results for the tunable Tx/Rx case also show that the SPT and $BLT_{Qthreshold}$ algorithms perform the best as in both cases the blocking due to Q is limited compared to the other routing algorithms.



(a) (b)

Figure 4: Blocking Probability vs. multicast group size for node engineering with (a) fixed Txs/Rxs, (b) tunable Txs/Rxs.

It is clear from this work that different node architectures and engineering designs produce different multicast group blocking, a strong indicator that a better interaction between physical and logical layers is needed for multicast connection provisioning. Our current work focuses on further accounting and determining the impact of PDG and PDL on the algorithms and the system performance.

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