Hierarchical Optical Switching: A Node-Level Analysis

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Abstract

We consider hybrid optical devices consisting of a waveband (transparent optical) and a wavelength (opaque OEO) switch. Such hybrid devices are suitable for supporting hierarchical optical paths (wavelength and waveband paths). We study the node-level cost-performance tradeoffs using both analytical models and simulations. The results demonstrate a significant cost reduction that could be achieved for a moderately small reduction of throughput.

Introduction

The continuing increase of Internet traffic keeps the pressure on the backbone telecommunication networks that have to provide more and more capacity satisfying the growing bandwidth demands. Optical networking technology has become a key to accommodating the rapidly increasing IP traffic. Emerging optical networks are expected to support the increasing network load by employing both advanced transmission (wavelength multiplexing division (WDM)) and switching (optical switches and cross-connects) technologies [1]. Both types of technologies pose various challenges that need to be addressed.

In the traditional IP networks, costs considerations and scalability concerns stimulated development of hierarchical mechanisms designed to provide various levels of traffic aggregation supported by evolving DiffServ [2] and MPLS standards [3]. In case of the optical networking, the same factors translate into creation of optical wavebands comprising of multiple wavelengths. In such architectures, the optical nodes can have multiple switching granularities, such as wavelengths and wavebands [4], [5], [6]. The potential cost benefits of waveband aggregation was demonstrated in [7], [8]. The cost advantage is based on the fact that a waveband can be switched by the optical node as a single unit, thus reducing the number of expensive OEO ports required for processing individual wavelengths. The optical paths thus form a hierarchy in which a higher-layer path (waveband) consists of several lower layer paths (wavelengths).

The path hierarchy reduces node costs because a waveband path occupies only two (input and output) ports of an optical switch in a node. The hierarchical optical node functionality is realized by hybrid optical devices consisting of a waveband (transparent optical) and a wavelength (opaque OEO) switch. In this paper, we analyze the effect of several parameters (number of wavelengths in a waveband, size of OEO switch etc.) on the performance of hierarchical optical node. We study the node-level cost-performance tradeoffs using both analytical models and simulations.

The rest of the paper is organized in the following way. In Section 1, we describe the architecture of hierarchical optical node and cost factors. In Section 2, we address some of the factors affecting the performance of hierarchical optical nodes. In Section 3, the cost and performance factors, described in the previous two sections, are analyzed jointly and the cost-performance tradeoffs are discussed. Finally, in Section 4, we outline some of the study items to be addressed in our future work.

1. Hierarchical Optical Node: Architecture and Costs

In a hierarchical optical network, wavelength paths are aggregated into a waveband path at one node and disaggregated at another node. The nodes participating in aggregation/disaggregation require both a waveband (transparent optical) and a wavelength (opaque OEO) switch. We call this node a “hierarchical optical node”. In a hierarchical node, a wavelength path input to a wavelength switch can be directly routed to a neighbor node, or aggregated into a waveband path and then routed to a neighbor node via a waveband switch.

The detailed architecture of hierarchical optical node is shown in Figure 1. The node has \( P_t \) input and output fibers; in this paper, we analyze the case of \( P_t = 25 \). Each fiber carries \( W \) wavelengths; we assume \( W = 160 \). The wavelengths in each input fiber are aggregated (using either interleavers or filters) in \( K \) wavebands consisting of \( G \) wavelengths (the values of \( G \) analyzed in this paper are from 2 to 40), where \( K = W/G \). The optical processing of wavebands is done at \( K \) waveband
switches (denoted as WBS 1, 2,..., K in Figure 1). A waveband \( i \) at any fiber is connected to a corresponding WBS \( i \). Hence, the WBS \( i \) optically switches only wavebands with index \( i \) from input to output fibers. The optical processing of wavebands may not be possible. A contention for the same output fiber among different wavebands cannot be resolved in the waveband part of the device (in waveband switch). The waveband switch also cannot process a waveband if different wavelengths in it have to be switched into different output fibers. For these and other related tasks (such as adding a wavelength into a waveband), one or more wavebands have to be dropped to the OEO part of the device (wavelength switch). The OEO is equipped with PM multiplexers and demultiplexers, each of them capable to process a waveband consisting of \( G \) wavelengths.

The cost of the hierarchical optical node is comprised of the costs of its individual components: transponders, transparent optical switches (waveband switches), opaque OEO switch, interleavers (filters) and multiplexers (demultiplexers). These costs can be expressed in the following way (using the appropriate units \( A \)). Depending on the bit rate, the transponder cost \( C_T \) can be equal to \( A \), 2.5\( A \) or 7\( A \). The cost \( C_I \) of interleaver is \( A \), the cost \( C_D \) of demultiplexer is \( 2A \). The cost of wavelength switch is \( C_{WS} = \sqrt{(GP_M)} \), and the cost of waveband switch is

\[
C_{WB} = \begin{cases} 4y & \text{if } P_M \leq 7 \\ 16y & \text{if } 8 \leq P_M \leq 39 \\ 64y & \text{if } 40 \leq P_M \end{cases}
\]

where \( y = 2.5A \). The cost of hierarchical optical node is computed by the formula

\[
C_{HON} = \begin{cases} P_C + (160/G)C_{WB} + P_l(GC_T + C_D) + C_{WS} & \text{if } G = 40 \\ 2P_C + (160/G)C_{WB} + P_l(GC_T + 2C_D) + C_{WS} & \text{if } G < 40 \end{cases}
\]

The difference between the cases \( G=40 \) and \( G<40 \) is due to the fact that different devices (interleavers for \( G=40 \) and filters for \( G<40 \)) are used for creation of wavebands. In the remaining part of the paper, we compare the performance and cost of the hierarchical optical node with those of 3rd generation wavelength switch, whose cost is computed by the formula

\[
C_{WS} = 100y + 4000C_T
\]

In this formula, we use the same input parameters, \( P_l=25 \) and \( W=160 \), as in the case of hierarchical optical node.

2. Performance of Hierarchical Optical Node

Hierarchical switching and routing introduces its own performance issues. First, individual wavelengths are aggregated into wavebands, which causes aggregation overhead (defined and analyzed later in this section). The waveband is then routed across the network until, at some point, it encounters waveband contention. At this node, the waveband is forwarded through the OEO switch, which changes its aggregated “color”. When some of the wavelengths in the waveband reach their destination, the whole waveband has to be forwarded to the OEO switch again so that the corresponding wavelengths could be dropped. In this paper, we analyze two of these three factors (aggregation overhead and waveband contention).

Consider a single hierarchical optical node (we assume here \( W=160 \), \( P_l=25 \), \( P_M=16 \) serving the arriving traffic. We assume that the traffic load is \( \rho \), which means that probability of a wavelength being used is \( \rho \). There are several factors limiting maximum load \( \rho \) that a hierarchical optical node can handle.

The waveband aggregation overhead occurs when wavelengths are packed into groups of size \( G \). Let us assume that \( \rho = 1 \) and the incoming traffic is uniformly bounded to output ports (Figure 2). In other words, 6.4
wavelengths (which is 160/25) from each input port are destined to each output port (fiber). In case of $G=1$, every wavelength is routed to a destined port so that the switched traffic is 100% of the incoming traffic. Increasing the number of wavelengths in a group to 2 will decrease the switch throughput but not as much as in the case of $G=4$ and $G=8$ when the throughput drops to 80%. In these scenarios each group of 6.4 wavelengths from input ports requires 8 wavelengths at an output port, which is a 20% overhead. The throughput drops to 20% when $G=32$. Note that the total number of switch ports is reduced from 4000 (for $G=1$) to 125 (for $G=32$), but the lower switch cost provides lower throughput. In conclusion, from the analysis of only one node and simple traffic model we conclude that the value $G=8$ is a reasonable tradeoff.

Now we relax the assumption on deterministic and uniform traffic distribution and assume that each incoming wavelength has the same probability of being directed to any of the outgoing fibers. As illustrated in Figure 3, if wavelengths directed to different output fibers are grouped together in wavebands, the total number of wavelengths in these wavebands will typically exceed the number of actual switched wavelengths. We define the ratio of the number of required wavelengths to the total number of wavelengths ($W$) as aggregation overhead.

![Figure 3: Waveband aggregation overhead.](image)

We can analyze the behavior of waveband overhead by using the following simple probabilistic model. Suppose that $W_p$ wavelengths are randomly distributed into $P_i$ output fibers. Each output fiber can get $i$ wavelengths with probability $p$, where

$$P_i = \binom{W}{i} \left( \frac{\rho}{P_i} \right)^i \left( 1 - \frac{\rho}{P_i} \right)^{W-i}.$$

If $x$ wavelengths have to be switched to the same fiber, it will require $\left\lceil \frac{x}{G} \right\rceil$ wavebands. The average number of required wavelengths is

$$\sum_{i=1}^{\left\lceil \frac{x}{G} \right\rceil} p_i \left\lfloor \frac{i}{G} \right\rfloor G.$$

We can also assume that on average $G/2$ wavelengths are wasted when wavebands (each consisting of $G$ wavelengths) are switched to outgoing fibers. Since there could be $\min(P_i, W/G)$ of such groups at each incoming fiber, about $(G/2)\min(P_i, W/G)$ of $W$ wavelengths is an overhead at each fiber. So the maximum throughput satisfies the equation

$$W_p + (G/2)P_i = W.$$

Therefore, the maximum throughput satisfies the approximate relation

$$\rho = 1 - \frac{G}{2}(P_i/W).$$

![Figure 4: Aggregation overhead vs. waveband size.](image)

Figure 4 illustrates the behavior of the wavelength ratio for various loading conditions and $G=4,8,16$ (results were obtained by simulations). The beginning parts of the curves approximately match the formula $(G/2)\min(W,G,P_i)$. The level aggregation threshold determines the largest throughput that could be obtained in this model. As expected, larger values of $G$ lead to smaller throughput values: 65%, 20% and 5% for $G=4,8$ and 16, respectively.

![Figure 5: Wavebands and contention resolution.](image)
Waveband overhead can be reduced by configuring wavebands of different sizes [9], but this topic is outside the scope of this paper.

Another factor affecting the performance of hierarchical optical nodes is contention of wavebands. Assuming that each incoming waveband has the same probability of being directed as a whole (in other words, none of the wavelengths of the group deviates from the path of the group) to any of the outgoing fibers (Figure 5), we can evaluate the number of contentions among wavebands. Each such contention requires using OEO ports for its resolution (here we ignore the second order effects of being unable to convert one waveband into another).

We can analyze the behavior of waveband contentions by using the following simple probabilistic model. Consider \( N \) output fibers, each receiving a waveband of the same aggregated color with probability \( \frac{p}{N} \) (here we assume uniform distribution). Since there are \( N \) wavebands in total, a fiber can receive \( i \) wavebands with probability

\[
P_i = \binom{N}{i} \left( \frac{p}{N} \right)^i \left( 1 - \frac{p}{N} \right)^{N-i}.
\]

Only one of these \( i \) wavebands can be processed, so the average number of contentions expected by a slot is equal to \( C = p_1^2 + 2p_2^3 + 3p_3^4 + \ldots + (N-1)p_N \). The characteristic function of this distribution has the form

\[
\varphi(z) = \sum_{i=0}^{N} p_i z^i = (1 - p/N + zp/N)^N.
\]

Since \( \varphi'(1) = p_1 + 2p_2 + 3p_3 + \ldots + Np_N \) and \( p_0 = p_1 = p_2 = \ldots = p_N = 1 \). The value of \( C \) can be calculated as

\[
C = \varphi'(1) - (1 - p_N).
\]

Since \( \varphi'(1) = p \), it follows

\[
C = \rho - (1 - (1 - p/N)^N) = \rho - 1 + e^{-p}.
\]

Note that the \( P_i \) output fibers will generate \( CP_i \) contentions. Since there are \( G/W \) aggregated colors and \( P_M \) ports in OEO to serve them, on average, \( (G/W)P_M \) of these contentions could be resolved, which brings the number of unresolved contentions to

\[
C' = \max\{CP_i - (G/W)P_M, 0\}.
\]

To compute the throughput of the waveband component of the hierarchical optical node, we set \( P_M = 0 \). Then the throughput is \( \rho - C' = \rho - C \), which is equal to \( 1 - e^{-\rho} \).

The maximum throughput is thus equal to

\[
T = 1 - e^{-1} = 0.64.
\]

For general case, the throughput is

\[
T = \rho - \max(\rho - 1 + e^{-\rho} - (G/W)(P_M/P_i), 0).
\]

The maximum throughput is when we substitute \( p = 1 \):

\[
T = 1 - \max(e^{-1} - (G/W)P_M, 0) \leq 63\%.
\]

Figure 6 illustrates the behavior of the average number of contentions for various loading conditions and \( G = 4, 8, 16 \) (results were obtained by simulations). As expected, larger values of \( G \) lead to larger throughput values (here we assume that the number of contentions is limited by \( P_M = 16 \)): the throughput is 10%, 20% and 30% for \( G = 4, 8, \) and 16, respectively.

3. Cost-Performance Tradeoff

We analyzed the cost-performance tradeoffs of hierarchical optical nodes using the results of two previous sections. We used the cost functions from Section 2 to compare the costs of an OEO device with a comparable hierarchical optical device (Figure 7). We used the composition of the waveband overhead and number of contentions (computed in Section 2) to evaluate the throughput of hierarchical optical node.

![Figure 6: Required OEO size (number of transponders) versus waveband size.](image)

![Figure 7: Cost-performance tradeoff.](image)
We considered three values of transponder costs ($A$, $2.5A$ and $7A$) and 25 input/output fibers. We analyzed the cost ratio (which we defined as the ratio of cost of wavelength switch to the cost of hierarchical optical node and throughput, using the throughput of hierarchical optical node for several representative values of $G$ and $P_m$. The results are shown in Figure 8.

As waveband size $G$ increases from 2 to 40, the average throughput of the hierarchical optical node first increases and then rapidly decreases. This behavior indicates the existence of optimal waveband size (close to $G=6$). As the size of wavelength switch increases, the throughput increases slightly, but the dependency on $P_m$ is relatively small compared with the dependency on $G$. The combination of parameters $G=6$ and $P_m=16$ provides for 25 input/output fibers approximately half of the throughput (41%) of wavelength switch with significant reduction of cost (3 to 14 times, depending on the cost $C_T$ of transponders). This cost-performance analysis demonstrates the value that could be delivered to the network utilizing hierarchical optical nodes.

![Figure 8: Throughput and cost ratios of wavelength switch and hierarchical optical node.](image)

4. Conclusion

We considered hybrid optical devices consisting of a waveband (transparent optical) and a wavelength (opaque OEO) switch. We studied the node-level cost-performance tradeoffs using both analytical models and simulations. The results demonstrate a significant cost reduction that could be achieved for a moderately small reduction of throughput. In our future work, we plan to address other factors affecting the performance. In particular, we plan to address wavelength divergence, routing and scheduling algorithms and non-uniform wavebands.

References


