Performance Evaluation for Optical Networks with OTDM Add-Drop functionality

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ABSTRACT

The solution of Routing and Wavelength Assignment (RWA) problem allows to overlay a logical topology, comprising logical connections and routers, on a physical topology, comprising optical fibers and optical crossconnects, using either Lightpaths or Super-Lightpaths which use a simple bit level Time Division Multiplexing. In this paper we introduce an Add-Drop function which allow to reuse the Super-Lightpath sub-channels. Being the mathematical problem computationally intractable we have used heuristic methods which show that the number of wavelengths required to overlay the same logical topology on the same physical topology is reduced up to 27% using the Add-Drop function.

Keywords: Optical Time Division Multiplexing, Add-Drop, SuperLightpath, Performance Evaluation.

1. INTRODUCTION

Wavelength Routed (WR) optical networks represent the most interesting solution for the constant increase in bandwidth demand, due to the growth of both real-time services and number of connected users. WR networks allow for the exploitation of the huge fiber bandwidth, which is divided into many non overlapping channels, each one represented by a different wavelength. In WR networks each logical connection between a source node and a destination node is realized through a Lightpath that is a semi-permanent optical channel composed by the union of consecutive optical fibers from the source node to the destination node. In this paper we assume to be in a network where no wavelength converters are available, so a Lightpath is characterized by employment of a single wavelength: in this way packets transmitted by source node transparently cross intermediate nodes, without changing wavelength, until they arrive to destination node, where they are converted to electronic domain.

An evolution of Lightpath solution is possible thanks to Optical Time Division Multiplexing (OTDM) performed directly in the optical domain. In particular each channel, represented by its wavelength, is partitioned into a fixed number of sub-channels, each one represented by a specific time slot in the OTDM frame. Currently wavelength channels at 40 Gb/s are commercially available and, by means of OTDM, 100 Gb/s and 160 Gb/s have been experimentally demonstrated also in long distances (1000 km), conversely a strong control of fibre impairments is necessary for higher bit rate, that permits for an instance OTDM at 640 Gb/s on medium distances (about hundreds of kilometers [1]. In this way the huge lightpath bandwidth, which is too much large for a single logical connection, is splitted and can be used by more logical connections. In particular it is possible to construct a Super-Lightpath which is able to carry all connections from a single source node to D different destinations using a single wavelength: each connection uses one or more sub-channels and each destination is able to extract sub-channels directed to itself and to route the Super-Lightpath until the last destination is reached.

To establish a session in OTDM/WR networks, it is needed to determine the route, the wavelength and the time slot to be used. This problem is known as Super-RWA (Routing and Wavelength Assignment) problem and it has been analyzed in [2]. The results of Super-RWA problem is to define the Super-Lightpaths, in particular their routes and so the order in which the destinations are reached, and for each Super-Lightpath to assign a wavelength so that different Super-Lightpaths having at least one optical fiber in common use different wavelengths. The Super-RWA problem is NP-hard and so it can be solved only through heuristics.

In this paper we propose the use of Super-Lightpath with Add-Drop function: in this case is still used a OTDM scheme domain and a clustering of the connections from a source node toward D destinations, but now each destination node, after the data reception from a sub-channel, can reuse that sub-channel to transmit its own data directed to one of the Super-Lightpath destinations. This is possible thanks to deployment of Add-Drop multiplexers (ADM) in optical domain [3]. With this solution it is possible the sub-channels reuse allowing to overcome an inefficiency of simple Super-Lightpath approach: a sub-channel, after the data receiving in its own destination node, continues with unnecessary data toward the final destination of the Super-Lightpath.

The paper is organized into four section. In section 2 the new scenario of Super-Lightpaths with Add-Drop function is presented and an example showing advantages of this solution is proposed. In section 3 the new Super-RWA problem is described and a solution is proposed. In section 4 numerical results are shown and finally in the last section conclusions are discussed.
2. ROUTING AND WAVELENGTH ASSIGNMENT

In a WR network the RWA problem consists in overlaying a logical topology, composed by IP routers and logical connections, over a physical topology, made of optical cross-connects (OXCs) and optical fibers. In this section we will highlight that using a OTDM scheme with Add-Drop functions, and so Super-Lightpaths with Add-Drop, it is possible to reduce wavelengths needed to solve RWA problem with respect to Lightpath case and also with respect to Super-Lightpath case. To better explain this aspect we analyze an example in which are used the logical topology and the physical topology reported in Figure 1(a) and 1(b) respectively.

![Figure 1](image)

**Figure 1.** The logical topology (a) is mapped on the physical topology (b) according to three different solutions: Lightpath (c), Super-Lightpath (d) and Super-Lightpath with Add-Drop.

In Figure 1(a) a logical topology composed by three IP routers and three directed logical connections is reported; for the sake of simplicity only one-way connections have been considered. The physical topology, proposed in Figure 1(b), is composed by five optical fibers and five OXCs; it is clear from Figures 1(a) and 1(b) that only three OXCs, A B and C, have also a logical function. We propose three different solutions of the RWA problem: in Figure 1(c) Lightpath solution, in figure 1(d) Super-Lightpath solution and in Figure 1(e) Super-Lightpath with Add-Drop solution.

As shown in Figure 1(c) if Lightpath solution is used three different Lightpaths are needed to solve the RWA problem: a Lightpath from A to C using the wavelength $\lambda_1$, a second one from A to B using $\lambda_1$ also, because it has no optical fibers in common with first one, and a last one from B to C using $\lambda_2$, because it has an optical fiber in common with the first one. When an OTDM scheme is used only two Super-Lightpaths are needed, as reported in Figure 1(d). The first one, which uses $\lambda_1$ and connects A to C passing on B, implements the link from A to B, through a sub-channel extracted by node B, and the link from A to C, through a different sub-channel on the same wavelength. The second one implements the logical link between B and C using $\lambda_2$.

Our solution is proposed in Figure 1(e) where using both OTDM scheme and Add-Drop functions the three logical connections are realized through a single Super-Lightpath connecting A, B and C. The Super-Lightpath is divided into two sub-channels: one representing logical link from A to C, which is transparently routed from A to C where it is converted to electronic domain, and the other one implementing the logical connections from A to B and from B to C. In this last case node B extracts the sub-channel information from A to itself and use this sub-channel to transfer data from itself to C. Of course to adopt this solution, B has to support Add-Drop functionality.

In Figure 1 we have examined a simple network with only three logical nodes and five physical nodes, but for real network with a greater connectivity degree, the detection of paths it is harder. In particular the RWA problem can be generally formulated as follows, where the parameter $D$ represents the number of destinations reached by each Super-Lightpath (if $D = 1$ the Super-Lightpaths become simple Lightpaths):

**GIVEN**

1) A physical topology, comprising nodes connected by optical fibres.
2) A logical topology, comprising nodes connected by logical links.

**FIND**

For each source node:
1) The set of $D$ destinations that, using OTDM, are multiplexed in a Super-Lightpath.
2) The order in which those destination must be reached by the Super-Lightpath.

For each Super-Lightpath:
1) A route from the source node to all D destinations in the Super-Lightpath.
2) A wavelength color such that two Super-Lightpaths using the same optical fiber have two different colors.

**SUCH THAT**

The total number of required wavelengths is minimized.

We call this problem RWA if we use $D = 1$, Super-RWA (SRWA) if we use $D \neq 1$, Super-RWA Add-Drop modified (SRWA-AD) if we use the Add-Drop function after the Super-Lightpath building. For real networks with a moderate number of nodes the mathematical problem is numerically intractable then to solve the RWA, SRWA and SRWA-AD problems we used two heuristics from literature [2]:
- **Super-Shortest Path First Fit (SPFF):** very simple algorithm that starting from a source node builds a Super-Lightpath selecting from the current node the closest one among the destination nodes still not used, until $D$
destinations are reached. The wavelength assignment is done looking for the first available wavelength on the resulting path.
• **Super-Maximum Fill (MF):** more complex algorithm, it first selects a wavelength and then tries to route all the possible Super-Lightpaths on such a wavelength.

### 3. SUPER-RWA ADD-DROP MODIFIED ALGORITHM

In this section we introduce an algorithm to solve the Super-RWA Add-Drop modified problem. The algorithm employs one of the two heuristics (SPFF and MF) to construct a Super-Lightpath and then choose how to reuse sub-channels to maximize carried logical connections and hence to minimize the number of wavelengths needed.

To give a more detailed description of the algorithm we introduce some notations. Let $D$ be the number of destinations of each Super-Lightpath, and $Di$ the $i^{th}$ destination. Let $Gi$ the $i^{th}$ sub-channel and $G$ be the Add-Drop degree ($1 \leq G \leq (D - 1)$), in other words $G$ is the number of sub-channels available for the reuse. If $G = 1$ we can reuse only the first sub-channel, after that the first destination has been reached, if $G = 2$ we can reuse as before the first sub-channel and also the second one, after that the second destination has been reached, . . . , if $G = D - 1$ we can reuse all sub-channels except for the last one (logically the next to last sub-channel is reusable only for the communication between the next to last and the last Super-Lightpath destination). Our Add-Drop algorithm can be formulated as follows:

**Algorithm 1 Add-Drop algorithm**

1. Construct a Super-Lightpath with $D$ destinations using SPFF or MF algorithm
2. $g = 1$
3. $j = g, k = j$
4. $k = k + 1$
5. if (There is a logical connection between $Dj$ and $Dk$) then
6. Sub-channel $Sg$ is used
7. if $[(k = D) \text{AND} (g = G)]$ then
8. STOP {Last destination reached and no more sub-channels}
9. else
10. if ($k \neq D$) then
11. $j = k$, GO TO 4 {Last destination not reached}
12. else
13. if $[(k = D) \text{AND} (g < G)]$ then
14. $g = g + 1, j = j + 1$, GO TO 4 {Last destination reached but other sub-channels to be reused}
15. end if
16. end if
17. end if
18. else {There is not a logical connection between $Dj$ and $Dk$}
19. if ($k \neq D$) then
20. GO TO 4 {Next destinations are considered}
21. else
22. if ($g = G$) then
23. STOP {Last destination reached and no more sub-channels}
24. else
25. $g = g + 1$, GO TO 3 {Last destination reached but other sub-channels to be reused}
26. end if
27. end if
28. end if

### 4. EXPERIMENTAL RESULTS

In this section we present experimental results obtained solving the RWA, the SRWA and the SRWA-AD problems when the physical topology is represented by the U.S. Long-Distance Network [4] comprising 28 nodes and 45 links. Three different connectivity degrees $p$ ($p = 8, p = 12, p = 16$) have been considered and for each connectivity degree we have randomly generated 50 logical topologies. Then we have solved the RWA, the SRWA and the SRWA Add-Drop modified problems for each logical topology using both heuristics SPFF and MF and we have reported the results in the three Tables above, one for each connectivity degree. In the first column of each Table the first value represents the number of Super-Lightpath destinations, the second one represents the Add-Drop degree. In the other columns we have reported for each heuristic the average numbers of wavelength required to solve the problem and the percentage gain with respect to SRWA case, defined as:
\[ \eta(D/j) = 100 \frac{w(D/0) - w(D/j)}{w(D/0)} \]  

Table 1. Effectiveness evaluation of the Super-Lightpath solution with Add-Drop for U.S. Long Distance Network with \( p = 8 \) and \( D = 1, 4, 8 \).

<table>
<thead>
<tr>
<th>( D - G )</th>
<th>( w ) SPFF</th>
<th>( \eta )</th>
<th>( w ) MF</th>
<th>( \eta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-0</td>
<td>36.13</td>
<td>-</td>
<td>25.05</td>
<td>-</td>
</tr>
<tr>
<td>4-0</td>
<td>15.55</td>
<td>-</td>
<td>15.55</td>
<td>-</td>
</tr>
<tr>
<td>4-1</td>
<td>15.95</td>
<td>8.86%</td>
<td>11.95</td>
<td>4.78%</td>
</tr>
<tr>
<td>4-2</td>
<td>15.55</td>
<td>11.14%</td>
<td>11.7</td>
<td>6.77%</td>
</tr>
<tr>
<td>4-3</td>
<td>15.55</td>
<td>11.14%</td>
<td>11.6</td>
<td>7.57%</td>
</tr>
<tr>
<td>6-0</td>
<td>17.65</td>
<td>-</td>
<td>12.55</td>
<td>-</td>
</tr>
<tr>
<td>6-1</td>
<td>15.4</td>
<td>12.75%</td>
<td>10.95</td>
<td>8.37%</td>
</tr>
<tr>
<td>6-2</td>
<td>15</td>
<td>15.01%</td>
<td>10.75</td>
<td>10.04%</td>
</tr>
<tr>
<td>6-3</td>
<td>14.65</td>
<td>17%</td>
<td>10.35</td>
<td>13.39%</td>
</tr>
<tr>
<td>6-4</td>
<td>14.55</td>
<td>17.56%</td>
<td>10.3</td>
<td>13.81%</td>
</tr>
<tr>
<td>6-5</td>
<td>14.55</td>
<td>17.56%</td>
<td>10.3</td>
<td>13.81%</td>
</tr>
</tbody>
</table>

Table 3. Effectiveness evaluation of the Super-Lightpath solution with Add-Drop for U.S. Long Distance Network with \( p = 16 \) and \( D = 1, 4, 8 \).

<table>
<thead>
<tr>
<th>( D - G )</th>
<th>( w ) SPFF</th>
<th>( \eta )</th>
<th>( w ) MF</th>
<th>( \eta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-0</td>
<td>46.55</td>
<td>-</td>
<td>32.94</td>
<td>-</td>
</tr>
<tr>
<td>4-0</td>
<td>19.93</td>
<td>-</td>
<td>14.88</td>
<td>-</td>
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<td>4-1</td>
<td>18.55</td>
<td>6.88%</td>
<td>14.12</td>
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<tr>
<td>4-2</td>
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<td>8.18%</td>
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<td>7.11%</td>
</tr>
<tr>
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<td>18.22</td>
<td>8.55%</td>
<td>13.82</td>
<td>7.11%</td>
</tr>
<tr>
<td>8-0</td>
<td>21.48</td>
<td>-</td>
<td>13.76</td>
<td>-</td>
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<tr>
<td>8-2</td>
<td>16.89</td>
<td>21.38%</td>
<td>11.94</td>
<td>13.25%</td>
</tr>
<tr>
<td>8-3</td>
<td>16.22</td>
<td>24.48%</td>
<td>11.29</td>
<td>17.95%</td>
</tr>
<tr>
<td>8-4</td>
<td>15.89</td>
<td>26.03%</td>
<td>11.06</td>
<td>19.66%</td>
</tr>
<tr>
<td>8-5</td>
<td>15.67</td>
<td>27.07%</td>
<td>11</td>
<td>20.08%</td>
</tr>
<tr>
<td>8-6</td>
<td>15.67</td>
<td>27.07%</td>
<td>11</td>
<td>20.08%</td>
</tr>
<tr>
<td>8-7</td>
<td>15.67</td>
<td>27.07%</td>
<td>11</td>
<td>20.08%</td>
</tr>
</tbody>
</table>

Results show that the Add-Drop solution performs better and allows for saving up to 27% of wavelength needed with respect to Super-Lightpath case. Moreover all results confirm that the S-SPFF algorithm is outperformed by the S-MF and show that the percentage gains are increasing monotonic functions with saturation thresholds.

5. CONCLUSIONS

In this paper we have extended the Super-Lightpath concept to the one of Super-Lightpath with Add-Drop. Subchannels reuse make it possible to carry, on the same Super-Lightpath, communications between the internal nodes of Super-Lightpath. Numerical results show a gain up to 27% in the number of wavelengths required to solve the Super-RWA when using Super-Lightpath with Add-Drop.

The feasibility of the Add-Drop approach depends on the relative cost of optical transmitters and receivers and of high-speed multiplexers and demultiplexers. These costs are today rapidly changing due of the rapid evolution of electrical and optical technology. In our solution we must consider a lot of parameters and it is very questionable to estimate the gain considering on one hand the reduced number of wavelengths, on the other the greater complexity of installed optical components.

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REFERENCES