Traffic grooming, routing, and wavelength assignment in WDM transport networks with sparse grooming resources

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Abstract

While a single fiber strand in wavelength division multiplexing (WDM) has over a terabit-per-second bandwidth and a wavelength channel has over a gigabit-per-second transmission speed, the network may still be required to support traffic requests at rates that are lower than the full wavelength capacity. To avoid assigning an entire lightpath to a small request, many researchers have looked at adding traffic grooming to the routing and wavelength assignment (RWA) problem. In this work, we consider the RWA problem with traffic grooming (GRWA) for mesh networks under static and dynamic lightpath connection requests. The GRWA problem is NP-Complete since it is a generalization of the RWA problem which is known to be NP-Complete. We propose an integer linear programming (ILP) model that accurately depicts the GRWA problem. Because it is very hard to find a solution for large networks using ILP, we solve the GRWA problem by proposing two novel heuristics. The strength of the proposed heuristics stems from their simplicity, efficiency, and applicability to large-scale networks. Our simulation results demonstrate that deploying traffic grooming resources on the edge of optical networks is more cost effective and results in a similar blocking performance to that obtained when distributing the grooming resources throughout the optical network domain.

Keywords: WDM optical networks; RWA; Wavelength assignment; Traffic grooming

1. Introduction

Optical fibers can carry multiple data streams by assigning each to a different wavelength. This approach is known as wavelength division multiplexing (WDM). Currently, WDM is classified as: (1) coarse WDM (CWDM) with ≈40 wavelengths per fiber and (2) dense WDM (DWDM) with ≈160 wavelengths per fiber. Each wavelength can be viewed as a channel that provides an optical connection between two nodes. Such a channel is called a lightpath or a connection. Once a set of lightpaths has been determined, each lightpath needs to be routed and assigned a wavelength. This is referred to as a routing and wavelength assignment (RWA) problem [1].

RWA was proven to be insufficient to ensure the most efficient utilization of network resources [2]. In order to overcome the deficiencies associated with RWA, telecommunication carriers start adopting a technique that consists of efficiently grooming the low speed traffic streams into high capacity channels. This technique is referred to the RWA problem with grooming (GRWA).

The traffic grooming problem in WDM mesh networks has been considered by several researchers [2,3,10–15]. In [2], the authors propose several node architectures for supporting traffic grooming in WDM mesh networks. They formulate the static traffic grooming problem for single-hop and multi-hop networks as an ILP problem and present two heuristic algorithms to compare the performance with that of the ILP. In [3], the authors consider the traffic grooming problem with the objective of minimizing the number of transponders in WDM mesh network. The problem is first formulated as an ILP problem. Because it is very hard to find a solution for large networks, the
authors reduce the size of the ILP problem by proposing a decomposition method that divides the traffic grooming problem (GRWA) into two smaller problems: the traffic grooming and routing problem (GR), and the wavelength assignment problem (WA). The GR problem is formulated as an ILP problem, while heuristic algorithms are proposed to solve the WA problem. Despite of using the decomposition technique, the ILP formulation still cannot be directly applied to large networks. Moreover, this approach requires all traffic requests to be known in advance, which cannot be satisfied in dynamic grooming.

Contrarily to the aforementioned research work, where the authors consider only static traffic, the authors in [4] addressed the issue of using fixed-alternate routing during the dynamic traffic grooming. The objective is to satisfy as many connections as possible in the network, leading to a high network throughput and low network blocking probability. An online algorithm, namely, fixed-order grooming (FOG) is proposed. The FOG algorithm can be used for both single-hop traffic grooming and multi-hop traffic grooming.

As WDM networks are migrating from ring to mesh topologies, it is very important to solve the traffic-grooming problem in a mesh network with sparse resources. In a sparse grooming network, some nodes may have some grooming capabilities while others may not have any (traffic must stay on a distinct wavelength when flowing through these nodes). This problem was addressed in [5,10], where the authors presented an ILP formulation and a heuristic approach to solve the grooming node placement problem in sparse grooming networks under static and dynamic traffic conditions. Contrarily to our study, this work does not support networks with sparse wavelength conversion resources. It is assumed that all the nodes in the optical network either have grooming capabilities or not, while in our work, we impose constraints on the grooming capabilities in terms of the number of transceivers used for originating and terminating optical lightpaths.

Most previous research on traffic grooming in WDM mesh networks assumes that the traffic grooming resources are distributed throughout the optical network domain. Unfortunately, this may not be practical or cost-effective. In this work, we conduct extensive simulation experiments to demonstrate that it is more cost effective to place traffic grooming resources on the edge of optical networks rather than distribute them throughout the optical network domain. Furthermore, our simulation results show that edge grooming resources in similar blocking performance to that obtained when deploying traffic grooming resources throughout the optical network.

In addition, because of the high cost of all-optical wavelength conversion resources, our approach allows wavelength conversion to take place at nodes with traffic grooming capabilities, thus, utilizing optical transponder capabilities to perform traffic grooming and wavelength conversion without having to deploy distinct wavelength conversion resources. This eliminates the wavelength continuity constraint and thus, significantly improves the blocking probability.

The rest of the paper is presented in the following order. Section 2, formally introduces the traffic-grooming problem (GRWA) and presents an integer linear programming (ILP) formulation of the problem. Next, in Section 3 we present our most-contiguous heuristic to solve the GRWA problem in networks with sparse resources under static and dynamic traffic patterns. In Section 4 we introduce a genetic approach to solve the GRWA problem in optical networks with collocated traffic grooming and wavelength conversion resources. Detailed performance comparisons are provided in Section 5. Finally, Section 5.2 concludes this study and provides ideas for future extensions.

2. ILP formulation of the GRWA Problem in WDM networks with sparse resources

We formulate the static GRWA problem in optical networks with sparse traffic grooming and wavelength conversion resources as an integer linear programming (ILP) problem. Our formulation considers two possible objective functions: (1) minimize the total number of hops used by all incoming lightpath requests, and (2) minimize the total cost of traffic grooming and wavelength conversion equipment.

2.1. Problem statement

Our formulation relies on the following assumptions:

1. The network is a general mesh topology with directed fiber connections. A pair of fiber links (i.e., one in each direction) is needed to connect a pair of nodes.
2. Network switches may or may not have support for traffic grooming.
3. Traffic grooming capability of each node is limited to the number of traffic grooming devices (resources) installed on that node.
4. Traffic grooming devices can perform wavelength conversion but the cost of a traffic grooming device is more than that of a wavelength conversion device since traffic grooming devices are capable of achieving more complex functionality (i.e., multiplexing and de-multiplexing connections). Thus, traffic grooming or wavelength conversion devices should be deployed in nodes based on whether traffic grooming is needed or not.
5. Lightpaths do not contain loops. We use the K-shortest paths algorithm to enumerate the K-shortest and loop-free paths between two nodes.

Our formulation requires the optical network graph and the lightpath connection requests to be provided as input. The graph of the network is given as a set of edges and vertices \((G = (V, E))\). The requested connections are given by a matrix for each desired connection size, with each element...
specifying the number of connections (of that size) for that source-destination pair. If desired, one or more vertices may be forced not to have any traffic grooming equipment.

2.2. Resource utilization formulation

Assume:

- \( lm \) and \( mn \): Start-end node pairs for a physical fiber link. In addition, we enforce \( l \neq m \neq n \) at all times.
- \( s,d \): Source and destination nodes, respectively, of a requested connection.
- \( i,j \): In general the row and column indices of a matrix.
- \( w \): A particular wavelength.
- \( c \): A particular connection size.
- \( P \): Number of all possible lightpaths between source and destination nodes.

Given:

- \( C_{\text{max}} \): Capacity of one wavelength on one fiber.
- \( C = [1;3;12; \ldots ; C_{\text{max}}] \): Capacities of connection sizes.
- \( L \): Number of links.
- \( W \): Number of wavelengths per fiber.
- \( N \): Number of nodes.
- \( N_{sd} \): Number of source-destination pairs.
- \( D = [d_i] \): Vector of length \( P \), where \( d_i \) is the number of links used by path \( i \).
- \( \phi = [\phi_m] \): Vector of length \( N \), where
  \[ \phi_m = \begin{cases} 1 & \text{if node } i \text{ has no grooming devices} \\ 0 & \text{otherwise} \end{cases} \]
- \( A = [a_{ij}] \): Requested connections matrix of size \( N_{sd} \times |C| \), where
  \[ a_{ij} = \begin{cases} n & \text{if } n \text{ conns. of size } c_j \in \text{ Care req.} \\ 0 & \text{otherwise} \end{cases} \]
- \( A = [a_{ij}] \): The \( P \times N_{sd} \) lightpath-connection incidence matrix, where
  \[ a_{ij} = \begin{cases} 1 & \text{if lightpath } i \text{ is between sd pair } j \\ 0 & \text{if lightpath } i \text{ is not between sd pair } j \end{cases} \]
- \( G^w = [g^w_{ij}] \): A set of \( W \) \( P \times L \) lightpath-link incidence matrices, where
  \[ g^w_{ij} = \begin{cases} 1 & \text{if lightpath } i \text{ uses wavelength } w \text{ on link } j \\ 0 & \text{if lightpath } i \text{ does not use wavelength } w \text{ on link } j \end{cases} \]

Variables

- \( X = [x_{ij}] \): The path variable matrix with size \( P \times |C| \), where
  \[ x_{ij} = \begin{cases} n & \text{if lightpath } i \text{ has } n \text{ conns. of size } c_j \\ 0 & \text{if lightpath } i \text{ has no conns. of size } c_j \end{cases} \]
- \( S = [s_i] \): Vector of length \( P \), where
  \[ s_i = \sum x_{ij} \]
- \( y^m_{mn} \): Indicator variable for route and wavelength assignment of traffic introduced on the nodes. Given a node \( m \) and routing wavelength \( wd \) we have for each link.
  \[ y^m_{mn} = \begin{cases} 0 & \text{if no lp starts at } m \text{ and uses } wd \text{ on } mn \\ 1 & \text{if an lp starts at } m \text{ and uses } wd \text{ on } mn \end{cases} \]
- \( y^m_{lm} \): Indicator variable for route and wavelength assignment of traffic on the nodes. Given an incoming wavelength \( ws \) and outgoing wavelength \( wd \), node \( m \), and incoming link \( lm \), we have for each outgoing link \( mn \):
  \[ y^m_{mn} = \begin{cases} 0 & \text{if no lp uses } ws \text{ on } lm \text{ and } wd \text{ on } mn \\ 1 & \text{if lp uses } ws \text{ on } lm \text{ and } wd \text{ on } mn \end{cases} \]

Optimize Minimize the total number of hops used by all the routed connections.

Minimize \( S.D \) (1)

Subject to

\[ A^T X A \geq A \] (2)

\[ \sum_{1 < j < i \in |C|} c_i \cdot a_{ij} \cdot c_j (G^w) \leq C_{\text{max}} \quad \forall \, k, w \] (3)

\[ S \cdot (col_{lm} (G^w) \cdot col_{mn} (G^w)) = y_{lmn} \] (4)

\[ y^m_{lmn} \leq y_{lmn} \] (5)

\[ C_{\text{max}} y^m_{lmn} \geq y_{lmn} \] (6)

\[ S \cdot (col_{mn} (G^w) - \sum_{l \in |C|} \psi_{lmn} w = \gamma_{lmn} \] (7)

\[ \phi_m \sum_{mn, wd} y^m_{mn} \leq 1 \quad \forall \, lm, ws \] (8)

\[ \phi_m \left( y^m_{lmn} + \sum_{ln, wd} y^m_{ln} \right) \leq 1 \quad \forall \, mn, wd \] (9)

Explanation of equations. We desire to minimize the number of hops used by all the nodes in the network. We start by enumerating all the possible lightpaths, and then, impose our desired conditions on the selected lightpaths. The objective function to minimize is (1). Inequality (2) requires the number of routed connections for a given source destination pair to be greater than or equal to the number of requested connections for that pair. Inequality (3) requires the sum of the sizes of the connections on any channel to not exceed the channel capacity. We use (4) to substitute for the expression on the left hand side in the next inequalities. Inequalities (5) and (6) are used to make the \( y \) variables boolean and exist for each fixed set of \( ws, wd, lm, n \). Inequality (7) gives variables that express how many connections were added at a given node and sent out on a given channel and exists for
each fixed set of $wd, m, n$. Nodes without grooming devices cannot demultiplex connections (8) or multiplex connections (9). Wavelength conversion on nodes without grooming devices is precluded by the enumeration of the lightpaths.

2.3. Network cost formulation

In order to formulate a cost based objective function, we assume that the main cost for the traffic grooming enabled switches comes from adding connections, dropping connections, and wavelength conversion. The cost for grooming is $\alpha$ times the number of groomed connections and $\beta$ times the number of wavelength conversions. The statement of the cost based ILP requires all of the utilization specification presented in the previous section except for $D$ and the optimization function. Here we re-define $D$ and provide a new optimization function.

Optimize Minimize the total cost of the grooming and wavelength conversion equipment. We assume that $\alpha < \beta$ to reflect typical equipment costs.

- $D = [d_i]$: Vector of length $P$, where $d_i$ is the number of links plus $\beta$ times the number of wavelength conversions used by lightpath $i$.

Minimize $D.S + \alpha \left( \sum_{m,n} z_{mn} + \sum_{l,m} j_{lm} \right)$ \hspace{1cm} (10)

Subject to

\begin{align*}
\sum_{l,wd} y_{lma}^{wd} & > u_{mn}^{wd} \hspace{1cm} (11) \\
\sum_{l,wa} y_{lma}^{wa} & < C_{max} u_{mn}^{wd} \hspace{1cm} (12) \\
\sum_{n,wd} y_{nma}^{wd} & > u_{lm}^{ws} \hspace{1cm} (13) \\
\sum_{n,wa} y_{nma}^{wa} & < C_{max} v_{lm}^{ws} \hspace{1cm} (14) \\
\sum_{l,wa} y_{lma}^{wa} + y_{lma}^{wd} - u_{mn}^{wd} & = z_{mn} \hspace{1cm} (15) \\
\sum_{n,wd} y_{nma}^{wd} - v_{lm}^{ws} & = j_{lm} \hspace{1cm} (16)
\end{align*}

Explanation of equations. Inequality (10) provides the objective function which aims to minimize the costs associated with traffic grooming and wavelength conversion devices. Inequalities (11) and (12) require the $u$ variables to indicate if any multiplexing has occurred. Inequalities (13) and (14) cause the $v$ variables to indicate if any demultiplexing has occurred. Inequalities (15) and (16) are just used to provide a smaller expression for the minimization function.

We believe that our mathematical formulation is very flexible and should be considered by network designers. This would give the option to route lightpaths through the optical network in a way that minimizes the cost of required traffic grooming and wavelength conversion devices. Careful traffic grooming allows conservation of wavelength resources so that more traffic can be added without the addition of new optical links. This allows one to keep an existing backbone all-optical network, and increase its capacity over that provided by wavelength routed networks that do not use traffic grooming or single-hop traffic grooming networks.

2.4. Illustrative numerical example

For Figs. 1 and 2, Table 1 presents the matrix of source-destination connection pairs that need to be established on the underlying optical network. In this section, we solve both the utilization and the cost problems for the given traffic table.

In this example, we assume that the maximum connection size is OC-48 and that each link has two available wavelengths. The solution for the cost problem does not use any wavelength conversion (because the traffic grooming cost is much less than the wavelength conversion
cost, and the connections can be routed without using wavelength conversion). Another observation is that traffic grooming is performed only on two of the nodes in the cost problem.

On the other hand, the solution for the utilization problem does use wavelength conversion. Unlike the cost problem, in the utilization problem grooming and wavelength conversion are encouraged since we are trying to minimize the total number of wavelengths used in the network. We see that the utilization problem does favor grooming over using multiple wavelengths and the cost problem always chooses using multiple wavelengths (when available). Of course, the reason for this is that we have no associated cost for using multiple wavelengths instead of grooming, but grooming does have an associated cost.

To compare our example and solutions with those of others, we need to examine other methods of routing the connections. Since 5 connections have node 1 as their source, we could say that this example requires more than two wavelengths unless there is at least end-to-end grooming. However, closer consideration shows that if we stipulate that we have no more than two available wavelengths, then there is contention for both links 2 → 4 and 3 → 5. The problem is that node 1 needs at least three connections to node 4 and one connection to node 6, node 2 needs one connection to node 4, and node 3 needs one connection to node 5 (that is, we need to route 5 connections over the two links which support only 4 total). We see that our example requires grooming in nodes other than end nodes, and grooming is not required on all of the nodes. In addition, wavelength conversion is not required on all of the nodes, and when the cost of wavelength conversion is higher than the grooming cost, grooming will be chosen over wavelength conversion. Another benefit is the amount of required grooming equipment. In the cost problem for this example we only need grooming equipment at two nodes.

3. Heuristic approaches

We propose two novel heuristics based on the assumptions in Section 2. Our objective is to minimize the total cost of required wavelength conversion and traffic grooming hardware that needs to be installed in the network without hindering the blocking performance of the network. The total routing cost is represented as:

\[ C = \sum_{i=1}^{M} D_i + xG_i + \beta V_i \]  

(17)

where:

- \( M \): Number of lightpath requests.
- \( D_i \): The number of hops for request \( i \).
- \( G_i \): The number of grooming devices used by request \( i \).
- \( V_i \): The number of wavelength conversions devices used by request \( i \).
- \( x \): The cost of a single traffic grooming device.
- \( \beta \): The cost of a single wavelength conversion device. It is assumed that \( x > \beta \) to reflect actual hardware cost.
- \( C \): Total cost of routing all \( M \) lightpaths request through the optical network. This cost includes the cost of wavelengths used to carry the lightpath from its source to the destination node plus the cost of all wavelength conversion and traffic grooming devices used by the lightpath.

3.1. Proposed wavelength assignment heuristic

Our proposed heuristic strives to avoid wavelength conversion and wavelength bandwidth fragmentation by using paths with the most contiguous wavelength resources first. Fig. 3 provides a flowchart of the proposed heuristic.

Most-contiguous (MC) heuristic

- **Definitions**
  - \( R \): Number of requests.
  - \( GetFirstPathPointer \): Function that returns a pointer to the first path maintained in the K-shortest path array for the given request.
  - \( GetLastPathPointer \): Function that returns a pointer to the last path maintained in the K-shortest path array for the given request.
  - \( AssignWavelengths \): Function that handles wavelength assignment for the given path by saving the assigned wavelength for each link in a vector. This function returns true if the wavelength assignment succeeds, otherwise it returns false.
  - \( SavePath \): Function that saves the path with its corresponding wavelength assignment.
  - \( GetSmallestPathCost \): Function that returns the lowest cost path.
  - \( GetNumberOfHops \): Function that returns the number of hops for the given path.
  - \( OR \): Function that performs bitwise -or- operation of all the wavelength availability masks from start-hop to current-hop.
**MASK**: Binary Vector of length equal to the number of wavelengths. Each bit in this vector reflects whether the individual wavelengths are used (1) or not (0).

**AllUsed**: Function that returns true if all the bits in MASK vector are used, otherwise it returns false.

**SaveAssignWavelengths**: Function that saves assigned wavelengths from start hop to current hop.

- **Pre-Processing**
  1: Generate uniform source-destination requests.
  2: Find K-Shortest Paths for every source-destination pair.

- **Main**
  1: for each r from 1 to R
  2: firstPathPtr = GetFirstPathPointer (r)
  3: lastPathPtr = GetLastPathPointer (r)
  4: for each path from firstPathPtr to lastPathPtr
  5: if (AssignWavelengths(path, selectedWavelengths)==true)
  6:  SavePath (path, selectedWavelengths)
  7: end if
  8: end for
  9: SelectedPath = GetSmallestPathCost()
  11: end for

- **Wavelength Assignment**

**AssignWavelengths**(pathPtr, selectedWavelengths)

**Start Procedure**

1: start = 1
2: current = 1
3: N = GetNumberOfHops(pathPtr)
4: While (current <= N)
5:  while (true)
6:   MASK = OR (start, current, pathPtr)
7:   if (AllUsed(MASK))
8:     break
9:   else
10:    current = current+1
11:  end if
12:  End while
13:  if (start == current)
14:   return false
15:  else
16:    selectedWavelengths = SaveAssignWavelengths(MASK, start, current)
17:  If (current == N)
18:   return true
19:  else
20:   start = current
21: end if
22: end if
23: end while
24: return true

**End Procedure**

It should be noted here that the proposed algorithm conserves the traffic grooming and wavelength conversion resources as much as possible, however, when a tie occurs between multiple wavelength assignment options, any of the simple pack/spread wavelength assignment schemes presented in [6] can be used to break the tie. We suggest using the first-fit wavelength assignment scheme to break such ties because of the simplicity and good performance of this scheme. Also, notice that the algorithm proposed here does not guarantee that it will always find the wavelength assignment with the lowest possible number of traffic grooming and wavelength conversion devices. The
algorithm strives to avoid wavelength bandwidth fragmentation in order to avoid increasing the network blocking performance. Also, the algorithm tries to keep the blocking performance as low as possible even at the expense of having more traffic grooming and/or wavelength conversion resources. A scheme that will always find the lowest number of traffic grooming and wavelength conversion resources can be computationally extensive and the scheme proposed here provides a good balance between simplicity and the efficiency of the found solutions.

To illustrate our most contiguous GRWA heuristic, let us assume that the following three lightpaths request need to be established on the network shown in Fig. 4:

- **Lightpath 1**: OC-3 from node 3 to node 4
- **Lightpath 2**: OC-3 from node 1 to node 5.
- **Lightpath 3**: OC-12 from node 2 to node 4.

Assuming that the maximum capacity of a single wavelength is OC-12, our proposed algorithm will use a traffic grooming device on node 3 to multiplex lightpaths 1 and 2 on one wavelength while lightpath 3 will be carried over a separate wavelength since wavelength 1 does not have enough bandwidth to carry that lightpath as illustrated in Fig. 4a. If the first fit wavelength assignment heuristic is used, lightpaths 1 and 2 will be groomed on wavelength 1 using a grooming device on node 3 as before but lightpath 3 will use wavelength 1 on the WDM link from node 2 to node 3 and wavelength 2 on the WDM link from node 3 to node 4 using a wavelength conversion device on node 3 as illustrated in Fig. 4b.

### 3.2. Genetic approach

The GRWA problem has been studied by several researchers before [7–9]. However, most of the studies

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**Table 1**

<table>
<thead>
<tr>
<th>Traffic to route on the network</th>
<th>1 → 4</th>
<th>1 → 6</th>
<th>2 → 4</th>
<th>3 → 5</th>
<th>4 → 3</th>
<th>5 → 6</th>
<th>6 → 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OC-1</strong></td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td><strong>OC-12</strong></td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td><strong>OC-48</strong></td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 1</th>
<th>The traffic to route on the network</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 → 4</td>
<td>OC-1 3 0 1 0 0 2</td>
</tr>
<tr>
<td>1 → 6</td>
<td>OC-12 0 2 0 1 2 1 0</td>
</tr>
<tr>
<td>2 → 4</td>
<td>OC-48 2 0 0 0 0 0 1</td>
</tr>
</tbody>
</table>
decompose the GRWA problem into three sub-problems; namely: traffic grooming, wavelength, and route assignment problems. In this work, we employ a new approach that is based on the genetic algorithm (GA) to solve the GRWA problem. Our approach solves the traffic grooming, wavelength, and route assignment problems jointly without decomposing them into three separate problems. Our GA-based approach is described in the following sections.

3.2.1. Chromosome encoding

A chromosome is a vector of pointers to entries in the routing and wavelength assignment enumeration table. The routing and wavelength assignment enumeration table enumerates all possible routing and wavelength assignment options for all given source-destination pairs. This table is generated by combining the K-shortest routes for each source-destination pair with all the possible wavelength assignments for that route. Each unique wavelength assignment on a route is considered as a unique lightpath. Each gene on a chromosome represents one of those unique lightpaths for the given source-destination pair. The total length of the chromosome is equal to the number of lightpath requests presented to the networks.

To help understand our chromosome encoding technique, consider the example depicted in Fig. 5 which represents a simple three node network. The figure shows an example of a two-gene chromosome that encodes two lightpaths. The first gene points to the 5th entry of the routing and wavelength assignment enumeration table while the second gene points to the 2nd entry of that table. Notice that the entries of the enumeration table have full routing and wavelength assignment information for the lightpath.

For example, the enumeration table indicates that the 2nd entry uses wavelength 1 on the WDM link from node 1 to node 2 and wavelength 2 on the WDM link from node 2 to node 3. Also, the 5th entry of that table indicates that the lightpath that uses that entry will reserve wavelength 1 on the link from node 2 to node 3.

3.2.2. Initial population

The first generation is formed from a combination of first-fit, most-contiguous, and completely random chromosomes. In our model, the size of the initial population is 150 chromosomes (i.e., 50 chromosomes based on each of the three GRWA heuristics mentioned above).

3.2.3. Fitness function

The fitness function of our GA model \( F \) includes a penalty component \( P \) as well as a cost component \( C \). A high value \( \gamma \) is added to the value of the penalty component each time the selected route violates the number of traffic grooming resources, wavelength conversion resources, or the wavelength capacity constraints. In our formulation, we make the assumption that \( \gamma \gg (\alpha, \beta) \), where \( \alpha \) and \( \beta \) represent the costs of single traffic grooming and wavelength conversion resources, respectively. The fitness function used in our model is defined as follows:

\[
F = C + P
\]  
\[
P = \gamma \sum_{j=1}^{M} \rho_i
\]  
\[
\rho_i = \sum_{j=1}^{M} \sigma L_{ij}
\]  
\[
\sigma = \begin{cases} 
1 & \text{if Link } L_{ij} \text{ violates the capacity or the resources} \\
0 & \text{otherwise}
\end{cases}
\]

where:

- \( C \): Same objective function discussed in Section 4.2.
- \( M \): Number of lightpath requests (chromosome length).
- \( L_{ij} \): The WDM links that the \( i \)th lightpath request traverses.
3.2.4. Crossover
In our model, crossover is performed between two parent chromosomes to produce two descendants using the two-point crossover technique. We chose the two-point crossover technique in our model in order to diversify the search within the large problem space.

3.2.5. Mutation
In our GA model, mutation is performed by walking through the genes that makeup the chromosome and modifying their value with a low probability (typically 0.1%). The resulting chromosomes need to be valid after mutation. If there is a chromosome that violates the routing constraints of a source-destination pair, we repair that chromosome by replacing the bad genes with valid ones in order to make a valid chromosome. The bad genes will be replaced by ones chosen from the list of valid genes based on a uniformly distributed selection process. This repair strategy guarantees that the gene will be selected from the range of enumerated lightpaths that belong to the given source-destination pair.

3.2.6. Selection
The chromosomes for crossover are chosen using the best selection method. This selection method picks the best chromosome among the $n$ chromosomes in a population in direct proportion to their absolute fitness. After crossover and mutation, new offsprings are reproduced then the best of those offsprings will be selected for the next generation. The offsprings with the worst fitness are discarded. The best selection method guarantees that the better chromosomes have a better chance to survive for the next generations.

Fig. 6 illustrates an example of our GA model when applied to Fig. 5. In this figure, the chromosomes encode three lightpath requests as follows:

- **Lightpath 1**: From node 2 to node 3.
- **Lightpath 2**: From node 1 to node 3.
- **Lightpath 3**: From node 1 to node 3.

In this example, after crossover, mutation, and applying the best selection method, we get a new chromosome for the same source-destination pairs, but without using any traffic grooming or wavelength conversion resources as can be seen from the routing and wavelength assignment enumeration matrix illustrated in Fig. 5.

4. Performance results
The performance of our proposed most-contiguous and genetic-based heuristics has been compared with that of the first-fit GRWA approach in networks with sparse traffic grooming and wavelength conversion capabilities. We chose to compare our proposed heuristics with the first-fit heuristic because of the simplicity of this heuristic. Further, it was demonstrated in the literature that the first-fit heuristic produces low blocking probabilities [6].

The proposed heuristics were compared in terms of their blocking probability and total path cost in terms of used traffic grooming and wavelength conversion resources. In this section, we study the performance of our genetic algorithm, most-contiguous and first-fit for static traffic. In addition, we present the performance of most-contiguous and first-fit under dynamic traffic.

4.1. Analytical results for static traffic grooming
With the static traffic model, the generated lightpath requests are known ahead of time and are generated between all possible source-destination pairs with equal probabilities. This means that the source and destination nodes of all lightpath requests are chosen with uniform probabilities. The capacity of the generated lightpath requests also follows a uniform distribution between 1 and the maximum capacity of a single wavelength. Our simulation tool generates $n$ lightpath requests to determine the blocking probability of the network and the total cost of the traffic grooming and wavelength conversion resources used by the offered lightpath requests.

We performed our performance evaluation study on the 16-node topology illustrated in Fig. 7. This figure reflects the structure of a reasonably complex mesh WDM transport network.

The performance of our proposed genetic-based GRWA heuristic is evaluated for a population size of 150 chromosomes, crossover rate of $1$, and mutation rate of $0.01$ for a total of 150 epochs. Figs. 8–10 plot the blocking probability versus the number of traffic grooming and wavelength conversion resources installed in the network for 70, 100, and 300 static lightpath requests, respectively. Those figures demonstrate that our genetic-based GRWA approach achieves the best blocking probability performance under the different traffic loads.
compared to the most-contiguous and first-fit heuristics. The blocking performance of our most-contiguous heuristic is better than that of the first-fit heuristic. Particularly, Fig. 10 shows that our simple most contiguous heuristic can perform better than our genetic-based GRWA approach under high traffic demands and low number of traffic grooming and wavelength conversion resources. Notice that Figs. 8–10 indicate that the difference between the three heuristics is higher under low traffic demands and low number of traffic grooming and wavelength conversion devices using 70 lightpath requests.
conversion resources. Fig. 11 compares the total cost of traffic grooming and wavelength conversion resources used by the three GRWA heuristics in networks with various degrees of traffic grooming and wavelength conversion capabilities. The study shown in Fig. 11 was conducted under the same blocking probability to make our comparison study fare and accurate. Again, we used the 16-node topology shown in Fig. 7 to conduct this study. The maximum connection size is OC-48 and each WDM link has four wavelengths. This study shows that the total cost of the traffic grooming and wavelength conversion resources used in our proposed most-contiguous and genetic-based GRWA heuristics is much better than that of the first-fit heuristic. It should be emphasized here that our heuristics achieved lower costs without hindering the blocking performance of the network. Notice that the

Fig. 9. Blocking probability vs. number of traffic grooming and wavelength conversion resources using 100 lightpath requests.

Fig. 10. Blocking probability vs. number of traffic grooming and wavelength conversion resources using 300 lightpath requests.
gap between our heuristics and the first-fit heuristic is higher in networks with sparse traffic grooming and wavelength conversion resources.

4.2. Simulation results for dynamic traffic grooming

Extensive simulations have been carried out to investigate the performance of the proposed MC algorithm considering the same network topology depicted in Fig. 7 for dynamic traffic. Each fiber link is assumed to carry 8 OC-48 wavelength channels. The flow dynamics of the network are modeled as follows:

1. The offered network load is given by:

   \[ L = 2H \]

   where:

   \( L \): Offered traffic load in Erlang.

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Fig. 11. Total cost vs. number of connections, number of traffic grooming and wavelength conversion resources.

Fig. 12. Comparison of the call blocking probability versus traffic load of the most-contiguous using (0, 5, and 75) traffic grooming and wavelength conversion devices.
\( \lambda \): Number of lightpath requests/hour.

\( H \): Average call holding time in hours.

2. The connection holding time is exponentially distributed with mean \( 1/H \). We assume the holding time \( (H) \) to be 5 min.

3. Lightpath requests arrive at a node following an exponential distributed process with a mean \( 1/\lambda \). The destination node is uniformly chosen from all nodes except the source node of the lightpath.

4. The capacity of the lightpath requests follows a uniform distribution between OC-1 and the maximum capacity of a single wavelength.

Fig. 12 indicates that increasing the number of grooming and conversion devices can significantly reduce the blocking probability for the most-contiguous heuristics especially when the network is heavily loaded. This could be explained with the fact that in the presence of more grooming and conversion devices, the algorithm is more likely to setup a lightpath for the source-destination pairs by utilizing the same resources to the extent possible.

In addition, Fig. 12 illustrates that the blocking probability for a traffic load of 50 Erlangs is the same when the average number of traffic grooming and wavelength conversion resources is increased from 5 to 75. This indicates that a network designer can reduce the network cost without affecting the network performance by carefully deploying a limited number of traffic grooming and wavelength conversion resources in the network. These results support our previous analysis under static traffic conditions.

Fig. 13 shows the blocking probability with different number of traffic grooming and wavelength conversion resources under a fixed heavy traffic load of 250 Erlangs. The purpose of this experiment is to study the performance implications of using traffic grooming devices vs. wavelength conversion devices. We observe that the performance of using traffic grooming devices only is much better than the performance of using wavelength conversion devices (because traffic grooming devices can also perform wavelength conversion but are more expensive). Also notice that increasing the number of conversion devices under this heavy load has no major impact on improving the blocking performance. This is due to the fact that the resource bottleneck is the number of wavelengths on each fiber-link and not the number of wavelength converters at each node.

Fig. 14 depicts the total cost of the paths selected by the most-contiguous and first-fit heuristics. As expected, we observe that the total cost of the most-contiguous approach is much better when compared to the first-fit heuristic. These results support our previous analysis under static traffic conditions. Fig. 15 shows that the difference between the average number of hops of the most-contiguous and first-fit heuristics is very small. This means that the most-contiguous heuristic can achieve a better cost than the first-fit heuristic without hindering the average number of hops.

Fig. 17 studies the performance of having the traffic grooming and wavelength conversion devices on the edge nodes only (i.e., single-hop traffic grooming), compared to the case where the resources are distributed throughout the network. We use the 16-node network depicted in Fig. 16, where we assume that nodes (1, 2, 5, 11, and 13) are the edge nodes. Our results demonstrate that having the traffic grooming and wavelength conversion...
devices on the edge nodes only, can achieve very close blocking performance to the case of having them on every node. This Figure also indicates that the blocking performance does not always improve as the traffic grooming and wavelength conversion devices are placed throughout the optical network. This implies that a similar blocking performance can be achieved by deploying less traffic grooming and wavelength conversion devices on the edge nodes only.

Fig. 18 compares the performance of our proposed Most-Contiguous with AGP and MinTHV heuristics in [10]. We chose to compare our proposed heuristics with AGP and MinTHV, because they were demonstrated in the literature that these heuristics produce low blocking probabilities. In order to have a fair comparison, we run the experiment where all the nodes have grooming capability but no wavelength conversion capability. On the other hand, we assume that each fiber link carries 16 OC-192 wavelength channels. We observe that the most-contiguous heuristic significantly improves the blocking performance compared to AGP and MinTHV heuristic. This is because our most-contiguous approach uses the network resources efficiently by distributing the traffic more evenly among all network links, which has a major impact on lowering the blocking probability significantly.
5. Conclusion and future work

5.1. Conclusions

In this work, we examined the problem of traffic grooming, routing, and wavelength assignment (GRWA) in WDM optical mesh networks with sparse traffic grooming and wavelength conversion resources under static and dynamic lightpath connection requests. First, the problem is formulated as an integer linear programming (ILP) problem. This ILP model is very powerful and is very flexible for small networks in terms of the number of nodes and the number of wavelengths. The GRWA problem is NP-Complete since it is a generalization of the RWA problem.
which was proven to be NP-Complete. Thus, we propose two heuristic solutions to solve the GRWA problem in large-scale networks with sparse traffic grooming and wavelength conversion resources. Our first heuristic, strives to avoid wavelength conversion and bandwidth fragmentation by using paths with the most contiguous wavelength resources first. The second heuristic is an adaptation of the genetic algorithm to solve the GRWA problem in networks with sparse traffic grooming and wavelength conversion resources. The strength of the proposed heuristics stems from their simplicity, applicability to large-scale networks, and their efficiency compared to other heuristics proposed in the literature.

Our results demonstrate that our proposed heuristics reduce the total number of traffic grooming and wavelength conversion resources without hindering the blocking performance of the network. Moreover, our results also show that the blocking performance does not always improve as the traffic grooming and wavelength conversion devices are placed throughout the optical network. This implies that a network designer can reduce the network cost without affecting the network performance by carefully deploying a limited number of traffic grooming and wavelength conversion resources in the network.

5.2. Future work

Areas of future work include the GRWA problem in optical mesh networks with protection requirements. Path protection approach requires finding a working path and a protection path that are link or node disjoint, so that the network is more survivable under various failure scenarios. Our proposed ILP formulations and heuristics can be extended to handle lightpath protection requirements. Furthermore, the performance of the proposed formulation and heuristics can be evaluated under such requirements.

Another attractive research problem is to design a multilayer sparse traffic grooming model. The main idea of this model is to have traffic grooming at the wavelength level then to group several wavelengths together as a band and switch the band using a single port whenever possible. To solve this problem, the ILP formulation, most-contiguous, and GA-based heuristics presented in this work need to be extended to handle optical bands.

References

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