Abstract—A power law relationship is established between wavelength usage and algebraic connectivity of backbone wavelength division multiplexing networks. From this observation, a concise prediction formula linking wavelength consumption to network topologies is derived and evaluated for real-world wide area networks. It is shown that the algebraic-connectivity-based wavelength usage estimation is more precise than evaluations relying on node degree variance, number of spanning trees, and average internodal distance.

Index Terms—All-optical networks; Networks, wavelength assignment.

I. INTRODUCTION

Most current high-capacity wide area networks (WANs) rely on wavelength division multiplexing (WDM) communications. An important aspect of WDM network provisioning is routing and wavelength assignment (RWA), since it ultimately determines the blocking probability and the capacity of the network. The RWA problem is known to be NP-complete (non-deterministic polynomial complete) [1] and is particularly difficult to solve. Thus, from a network designer and planner perspective, it is highly desirable to characterize networks and identify network topologies that minimize wavelength usage by relying on simple metrics.

The aim of this study is to establish statistical correlations between topological metrics and wavelength usage in WDM systems and to develop an empirical model linking the number of required wavelengths to the network topology. The objective is also to provide a reliable performance metric, allowing network designers to easily compare and classify candidate network topologies from a wavelength usage point of view.

The paper is organized as follows. In Section II, the RWA problem is summarized and a lower bound on the number of wavelengths is presented. In Section III, four different topological metrics are reviewed and defined. In Section IV, a random network generation algorithm for biconnected WAN networks is proposed. In Section V, a statistical analysis highlights the relationships between the considered metrics and the average number of wavelengths in randomly generated networks. Finally, in Section VI, an empirical model predicting the number of wavelengths as a function of the network topology is developed and validated on realistic networks.

II. ROUTING AND WAVELENGTH ASSIGNMENT

A. Problem Definition

WDM communication systems rely on the establishment of light paths throughout the network. In transparent networks, nodes are equipped with optical cross connect switches, capable of directing incoming wavelengths to any of their outgoing ports. The distinct wavelength constraint stipulates that two light paths sharing a common fiber should be assigned different wavelengths. Provisioning wavelength channels thus essentially consists in deciding on routes for each demand and assigning a wavelength to each of these routes. The goal of routing and wavelength assignment is to minimize the number of wavelengths required for a given traffic scenario.

Routing and wavelength assignment is usually performed in two distinct steps. First, paths are chosen for each connection in order to minimize link congestion. Congestion refers to the maximal number of paths using the same link. Because of the distinct wavelength constraint, the maximal number of paths
on any given fiber link determines the minimal number of wavelengths in the network. Second, a wavelength is chosen for each path. To perform this operation, a conflict graph is created and the problem is solved by a graph coloring algorithm.

The wavelength continuity constraint, which stipulates that a light path must utilize the same wavelength along its path, can be relaxed when wavelength converters are placed at certain nodes. In current WAN optical networks, this function is realized by optical-electrical-optical interfaces. This study is concerned with wavelength assignment in transparent WDM networks, operating without optical-electrical-optical nodes. Therefore it is assumed that no conversion mechanism is used. Furthermore, as in previous studies on the subject [2,3], full uniform traffic demands are considered, meaning that every possible node pair has a traffic volume corresponding to the capacity of a single wavelength.

B. Lower Bound

Let \( G(V, E) \) be an undirected graph representing the optical WDM network of \( n \) nodes and \( m \) edges, with \( V=\{v_1, v_2, \ldots, v_n\} \) the set of nodes and \( E=\{e_1, e_2, \ldots, e_m\} \), the set of edges. A light path between node \( i \) and \( j \) is represented by a path between node \( i \) and \( j \) of the graph. Since a full demand matrix is considered, there are \( P=n^2-n \) paths to establish. Assuming a routing setup represented by a binary variable \( \xi_{e,p} \) that equals 1 when link \( e \) belongs to path \( p \) and 0 otherwise, the congestion in the network is

\[
N_c = \max_i \sum_p \xi_{e,p}, \quad i = 1, 2, \ldots, m, \quad p = 1, 2, \ldots, P.
\]

The goal in design and wavelength assignment is to select a path for each demand that minimizes the overall congestion \( N_c \). This problem is NP-complete and is difficult to solve even for medium network sizes (20–30 nodes). However, a lower bound [2] can be used to determine the minimal required number of wavelengths in a WDM network:

\[
N_{\text{min}} = \max_{\text{All possible } C} \frac{k(n-k)}{|C|},
\]

where \( k \) and \( n-k \), are the number of nodes of the two disjoint and self-connected subgraphs resulting from the cut \( C \), and \(|C|\) represents the number of links in the cut.

In the statistical analysis that follows, more than a million random networks are generated. Relying on a heuristic algorithm to solve the RWA problem for each network would be time prohibitive. Instead, the lower bound is used to determine the number of wavelengths. Although the use of the lower bound restricts the study to uniform traffic models, it allows considering a much larger number of networks, thereby improving the statistical significance of the results. Furthermore, recent research results [4] have shown that efficient heuristics can almost always attain the lower bound, making it a precise indication of the required number of wavelengths in WAN networks.

III. TOPOLOGICAL METRICS

To the best of our knowledge, only two research papers [2,3] to date have examined the link between topological metrics and wavelength usage in WDM networks. Metrics such as connectivity, average internodal distance, node degree variance, and number of spanning trees have been studied. In this work, the use of algebraic connectivity is proposed.

Correlations between the network’s physical connectivity and wavelength usage are provided in [2]. The authors showed that an increase in the connectivity leads to an exponential decrease in the number of wavelengths. They defined the connectivity as \( \alpha = 2m/[n(n-1)] \). However, a higher degree of accuracy in the number of wavelengths estimation can be achieved by considering topological metrics such as the node degree variance \((\sigma^2)\) and the number of spanning trees in the network [3]. These metrics give a better approximation of the wavelength usage than simply relying on the measure of connectivity. In fact, for a given connectivity, they can partly explain the observed variation in the number of wavelengths. A power law relationship between the average number of wavelengths and the number of spanning trees is also described in [3]. Based on this observation, a general prediction formula is proposed, having as parameters the number of nodes, the number of edges, and the number of spanning trees. Details about the exact parameter values of the formula and its precision in evaluating the number of wavelengths for real network topologies are not provided. The routing algorithm used in [3] is essentially a shortest path allocation between each node pair. It should be noted that, generally, the shortest path routing yields a number of wavelengths that exceeds by far the lower bound expressed by Eq. (2), resulting in a poor estimate of the real wavelength consumption.

The graph’s Laplacian matrix is defined as

\[
L = \begin{cases} 
\deg(v_i) & \text{if } i = j \\
-1 & \text{if } v_i \text{ is adjacent to } v_j, i \neq j \\
0 & \text{otherwise}
\end{cases}
\]

From the modified Laplacian matrix \( L' \), which is obtained by removing a row and a column of \( L \), the number of spanning trees is computed as


\[ \tau = \det(L'). \quad (4) \]

In [2], it is shown that, similarly to wavelength usage, an increase in the connectivity leads to an exponential decrease of the average internodal distance. The average internodal distance is also used in [5] to compare random topologies to regular networks. The average internodal distance in hop counts is given by

\[ \beta = \frac{1}{P_{ij} \in V} \sum_{i \neq j} W(i,j), \quad (5) \]

where \( W \) is the link-weight matrix and contains the minimal number of hops between any two nodes \( i \) and \( j \). Calculation of the average internodal distance involves running a shortest path algorithm in terms of number of hops for each entry of \( W \), i.e., for each connection.

Algebraic connectivity is a topological metric that essentially measures the robustness of networks to link and node failures [6]. In order to determine its value, the Laplacian spectrum, the set of eigenvalues \( \mu_1 \preceq \mu_2 \preceq \ldots \preceq \mu_n \), is computed. The algebraic connectivity corresponds to the second highest eigenvalue \( \mu_2 \). Since both the robustness and the number of required wavelengths in WDM networks depend on path diversity, a high correlation between wavelength usage and algebraic connectivity is expected.

IV. RANDOM NETWORK GENERATION

To cope with node and link failures, the vast majority of WAN networks are biconnected; a node-disjoint path therefore exists for every connection. Although Waxman and Erdos-Reyni random graph generation algorithms are widely used, they do not produce biconnected graphs. The proposed random network topology generator is based on connecting all the nodes by a spanning tree [7]. Remaining edges are then added to attain a predetermined physical connectivity and to produce a biconnected graph, representative of real-world nationwide networks. More specifically, the network generation algorithm is described by the following steps:

1. Set network parameters:
   a. Number of nodes, \( n \);
   b. Number of edges, \( m \);
   c. Initial number of Euclidian neighbors, \( r_1 \). The \( r_1 \) neighbors of \( v_i \) are the \( r_1 \) nodes that are the closest to \( v_i \) in terms of Euclidian distance.
   d. Number of Euclidian neighbors, \( r_2 \);
   e. Maximum node degree, \( d_{\text{max}} \).
2. Assign a random physical location to each node.
3. Compute the distance separating each node and build the matrix \( H \) that contains the Euclidean distance between every pair of nodes.
4. Build a temporary adjacency matrix \( A' \) by connecting node \( v_i \) to its \( r_1 \) neighbors in \( H \).
5. Define a minimum spanning tree \( T \) from \( A' \); initialize the adjacency matrix \( A = T \).
6. Add an edge to all nodes of degree 1 by randomly choosing for every node of degree 1 among its \( r_2 \) adjacent neighbors; update \( A \).
7. Randomly add edges from the \( r_2 \) neighbors of \( v_i \) until the desired number of edges \( m \) is reached, so that the maximal node degree does not exceed \( d_{\text{max}} \); update \( A \).

It is argued in [2] that the connectivity of real-world meshed WAN networks varies between 0.16 and 0.23. Table I shows that for realistic networks with more than 30 nodes, the connectivity can be much lower than 0.16. This comes from the fact that, for WAN networks, the number of links does not scale exponentially as the number of nodes is increased. The density of the network (\( \delta \)), defined as the ratio of the number of edges to the number of nodes, provides a better characterization of WAN network physical connectivity and is therefore used here. As indicated by Table I, for WAN networks of 11–53 nodes, the density varies between 1.2 and 2.3.

V. METHODOLOGY AND RESULTS

Random graphs of orders ranging from 10 to 50 nodes are considered. For each network size, three sets of 100,000 random networks having densities of 1.5, 2, and 2.5 are generated. The number of wavelengths for each network is computed by using the lower bound, Eq. (2), and a modified version of the minimum cut contraction algorithm presented in [8]. The node degree variance, number of spanning trees, average internodal distance, and algebraic connectivity are then determined.

First, in this section, linear least mean square (LMS) curve fitting is used to evaluate the precision with which topological metrics estimate wavelength usage. Next, the behavior of the metrics when the density and the number of nodes of the networks are varied is studied. Finally, a prediction formula based on algebraic connectivity is proposed.

A. Wavelength Usage Estimation Accuracy

Figure 1 shows the average number of wavelengths as a function of the considered topological metrics and the linear LMS approximations for a set of 100,000 random networks of 30 nodes, with density \( \delta = 2 \). The number of spanning trees and the algebraic connectivity are plotted against a log-log axis, showing power law characteristics. Intervals used for the linear approximations are indicated in the legend of each plot.

Table II gives the mean error, the error variance, and the maximal error between the estimated and the
theoretical wavelength consumption, calculated by using the linear relationships described in Fig. 1. Table II indicates that estimations relying on algebraic connectivity have the lowest deviation and smallest maximal error, overall providing the best indication of wavelength usage.

**B. Metrics Behavior**

The topological metrics behavior is depicted in Fig. 2 for random networks of 20 and 40 nodes, with densities of 1.5, 2, and 2.5. Figure 2 displays the average number of wavelengths as a function of the considered metrics. For each network density, 100,000 randomly generated topologies are analyzed, resulting in 600,000 random networks per figure.

As proposed in [3] and apparent in Fig. 2(a), the number of spanning trees could be used to predict the number of wavelengths. However, Fig. 2(a) shows that the power law relationship depends both on the network order (the number of nodes) and on the network density. The associated prediction formula would have to explain the network order and network density nonlinear x-axis and y-axis translations. Figure 2(b) further shows that for the considered range of network densities, wavelength usage estimation based on the average internodal distance can hardly be accomplished by linear curve fitting. A prediction formula based on average internodal distance would therefore be very difficult to derive. Figure 2(c) indicates that node degree variance cannot be used to characterize networks of varying sizes and densities; for network densities of 2.0 and 2.5, the number of wavelengths remains constant, providing no information on wavelength usage. Last, and in contrast to the other considered topological metrics, Fig. 2(d) indicates that for a given network size, the algebraic-connectivity-based

### Table I

<table>
<thead>
<tr>
<th>Network</th>
<th>Connectivity (a)</th>
<th>Density (b)</th>
<th>Lower Bound (N_{low})</th>
<th>Estimation (N_{estimation})</th>
<th>Estimation Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euro-Core 11</td>
<td>0.45</td>
<td>2.27</td>
<td>4</td>
<td>4</td>
<td>0%</td>
</tr>
<tr>
<td>NSF 14</td>
<td>0.23</td>
<td>1.50</td>
<td>13</td>
<td>12</td>
<td>7.7%</td>
</tr>
<tr>
<td>German 17</td>
<td>0.18</td>
<td>1.47</td>
<td>30</td>
<td>32</td>
<td>6.7%</td>
</tr>
<tr>
<td>USA 18</td>
<td>0.21</td>
<td>1.72</td>
<td>20</td>
<td>23</td>
<td>15.0%</td>
</tr>
<tr>
<td>Sprint 18</td>
<td>0.18</td>
<td>1.50</td>
<td>20</td>
<td>23</td>
<td>15.0%</td>
</tr>
<tr>
<td>USA 19</td>
<td>0.13</td>
<td>1.21</td>
<td>30</td>
<td>34</td>
<td>13.3%</td>
</tr>
<tr>
<td>ARPANET 20</td>
<td>0.16</td>
<td>1.55</td>
<td>33</td>
<td>32</td>
<td>3.0%</td>
</tr>
<tr>
<td>EON 20</td>
<td>0.20</td>
<td>1.95</td>
<td>18</td>
<td>20</td>
<td>11.1%</td>
</tr>
<tr>
<td>USA 20</td>
<td>0.16</td>
<td>1.55</td>
<td>33</td>
<td>37</td>
<td>12.1%</td>
</tr>
<tr>
<td>Italia 21</td>
<td>0.17</td>
<td>1.71</td>
<td>28</td>
<td>40</td>
<td>42.9%</td>
</tr>
<tr>
<td>UKNet 21</td>
<td>0.19</td>
<td>1.86</td>
<td>19</td>
<td>22</td>
<td>15.8%</td>
</tr>
<tr>
<td>USA 23</td>
<td>0.14</td>
<td>1.52</td>
<td>32</td>
<td>36</td>
<td>12.5%</td>
</tr>
<tr>
<td>USA 24</td>
<td>0.16</td>
<td>1.79</td>
<td>32</td>
<td>39</td>
<td>21.9%</td>
</tr>
<tr>
<td>National 24</td>
<td>0.17</td>
<td>2.00</td>
<td>40</td>
<td>39</td>
<td>2.5%</td>
</tr>
<tr>
<td>Japan 25</td>
<td>0.13</td>
<td>1.52</td>
<td>72</td>
<td>72</td>
<td>0%</td>
</tr>
<tr>
<td>Euro 33</td>
<td>0.13</td>
<td>2.06</td>
<td>38</td>
<td>43</td>
<td>13.1%</td>
</tr>
<tr>
<td>USA 46</td>
<td>0.07</td>
<td>1.65</td>
<td>90</td>
<td>128</td>
<td>42.2%</td>
</tr>
<tr>
<td>USA 53</td>
<td>0.05</td>
<td>1.28</td>
<td>330</td>
<td>354</td>
<td>7.3%</td>
</tr>
</tbody>
</table>
estimation follows a power law that depends on only the number of nodes. Furthermore, when the network density is changed, the power law relationship remains the same. Also, it can be seen in Fig. 2(d) that the slope of the power law remains constant when the number of nodes is increased from 20 to 40. These characteristics enable the derivation of a simple prediction formula that only has to explain the $y$-axis network order-dependent translation.

C. Prediction Formula Derivation

The algebraic-connectivity-based wavelength consumption estimation for randomly generated network sets of 10, 20, 30, 40, and 50 nodes is provided in Fig. 3. As for previous analysis, for each network order and network density, 100,000 networks are generated, resulting in a total number of $1.5 \times 10^8$ networks. The linear fitted curves show that the power law slope remains constant and that a linear increase in the number of nodes translates in a linear $y$-axis translation of the fitted curves. From Fig. 3, the following prediction formula is derived:

$$N_{\text{estimated}} = \mu_2 \times 10^{an^2+bn+c},$$

(6)

where $n$ corresponds to the number of nodes, $a = -2.93 \times 10^{-4}$, $b=3.15 \times 10^{-2}$, $c=5.72 \times 10^{-1}$, and the power law slope $l=-0.8$.

The wavelength usage estimation provided by the prediction formula for realistic network topologies is given in Table I. For most of the listed networks the prediction formula is accurate, and the estimation error is less than 16%. The higher estimation error associated with the Italia21, USA24, and USA46 networks highlights the limitations of the prediction formula and is explained by the fact that the statisti-

<table>
<thead>
<tr>
<th>Node Degree Variance $(\sigma^2)$</th>
<th>Number of Spanning Trees ($\tau$)</th>
<th>Mean Internodal Distance ($\beta$)</th>
<th>Algebraic Connectivity $(\mu_2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean error</td>
<td>0.00</td>
<td>-0.22</td>
<td>-0.16</td>
</tr>
<tr>
<td>Error standard deviation</td>
<td>16.88</td>
<td>14.51</td>
<td>11.58</td>
</tr>
<tr>
<td>Maximal error</td>
<td>64.05</td>
<td>68.00</td>
<td>72.00</td>
</tr>
</tbody>
</table>

Table II: Topological Metrics Estimation Error and Deviation
cal model used for the formula derivation is based on average wavelength consumption. Accordingly, for most networks, the algebraic connectivity wavelength usage estimation will provide accurate results but, in some cases and especially for large networks, it may underestimate or overestimate the number of wavelengths. This is in accordance with the results presented in Table II for random network algebraic connectivity linear LMS estimation, where the average estimation and error standard deviation are low but the maximal error in number of wavelengths is non-negligible.

The statistical study shows that algebraic connectivity is more precise than the other topological metrics and that it can provide precious indications and trends on wavelength usage in relation to network topology. For example, Figs. 1 and 2 indicate that wavelength usage is minimized in networks with a high value of algebraic connectivity. As stated below, the routing and wavelength assignment problem is NP-complete and difficult to solve. Nevertheless, the results in Table I show that for most networks a simple topological metric can adequately estimate the resource consumption. This indicates that the algebraic connectivity could be used in conjunction with other metrics or tools to evaluate topologies and reduce the complexity of the network planning process. For instance, the maximization of algebraic connectivity could be used in topological design of WDM networks as an objective function instead of the often used congestion minimization. Since algebraic connectivity is obtained directly from the Laplacian matrix, it is much faster to compute than the congestion, which relies on path calculations between every node pair in the network. Using the algebraic connectivity would therefore decrease the convergence time and speed up the overall optimization process.

VI. CONCLUSION

In this paper, a review of topological metrics for wavelength usage estimation in transparent WDM
networks was presented. A random network generation algorithm that takes into account the specific properties of real-world WAN networks was proposed and used to compare the accuracy of wavelength usage estimation based on the number of spanning trees, the average internodal distance, the node degree variance, and the algebraic connectivity. It was shown that algebraic connectivity provides the most accurate wavelength usage estimation. A simple prediction formula was derived from the observed power law relationship between algebraic connectivity and wavelength usage. The proposed prediction formula was validated on real-world network topologies and shows the usefulness of algebraic connectivity as a performance metric to guide network designers in solving problems related to routing and wavelength assignment. Other potential applications for algebraic connectivity include the estimation of blocking probability, network cost, and restoration capabilities.

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REFERENCES


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generation of high-capacity line-of-sight military radios offered by the Canadian Marconi Corporation, which is now Ultra Electronics Tactical Communication Systems. The company has received, for this product, a “Coin of Excellence” from the U.S. Army for performance and reliability. Prof. Gagnon is a recognized leader in research management with an annual budget of $900,000, he supervises 18 graduate students and leads a brilliant team of 7 research professionals, and he maintains activities with more than 10 companies: Ultra, ISR Technology, Wavesat, ZTE, Ericsson, Lipso, Nortel, Bell, Octasic Semiconductors, Sierra Wireless, Boomerang, and IREQ. Prof. Gagnon was awarded last September the 2008 NSERC Synergy Award (Small and Medium-Sized Companies category) for the fruitful and long-lasting collaboration with Ultra Electronics TCS—an outstanding testimonial of Prof. Gagnon’s contribution to scientific research.

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