

MICRON – A Framework for Connection Establishment in Optical Networks*

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ABSTRACT

Traffic grooming in optical networks has gained significance due to the prevailing sub-wavelength requirement of end users. Optical networks get upgraded to the latest technology slowly with time, with only a subset of nodes being upgraded to the latest technology. The optical networks are thus comprised of nodes employing heterogeneous switching architectures. In this paper, we develop a framework, called Methodology for Information Collection and Routing in Optical Networks (MICRON), for connection establishment in WDM grooming networks with heterogeneous switching architectures. We illustrate with examples some of the information that could be collected from a link. The link information may be combined in a variety of ways to obtain different properties of a path. We complete the MICRON framework by providing a generic channel assignment procedure that may be adapted to implement different channel assignment schemes. The framework can be easily implemented with simple traffic engineering extensions to the already existing routing protocols in the wide-area networks.

Keywords: Optical networks, Traffic grooming, Dynamic routing, Heterogeneous switching architecture

1. INTRODUCTION

Optical communication employing wavelength division multiplexing (WDM) has emerged as a viable solution for satisfying the ever-increasing quest for bandwidth due to emerging Internet applications. WDM divides the available fiber bandwidth into multiple wavelengths each of which operates at peak electronic speed. Present day networks have a transmission capacity of up to 40 Gbps (OC-768) on a wavelength. However, the user requirements are of sub-wavelength capacity, typically ranging from 155 Mbps (OC-3) to 622 Mbps (OC-12), rarely in the range of a few gigabits per second. Hence, alternatives for provisioning of sub-wavelength traffic in WDM networks have received significant attention in the recent past. One approach to provisioning sub-wavelength traffic is to divide a wavelength into time slots that would allow multiple traffic to be time multiplexed on the wavelength. However, employing TDM at high transmission speeds in long-haul networks requires stringent synchronization across the network. Hence, Code Division Multiple Access (CDMA) approaches can be employed to share a wavelength bandwidth across multiple users. The resulting multi-wavelength multi-time slot or multi-code network is referred to as WDM grooming networks.

The merging of smaller capacity requirements into higher capacity lightpaths is called *traffic grooming*. Traffic grooming in optical networks can be performed in a static or dynamic manner. In static grooming, the source-destination pairs whose traffic requirements will be combined are pre-determined. In dynamic grooming, connections of different source-destination pairs are combined based on the existing lightpaths at the time of a request arrival. In this paper, we consider dynamic grooming.

Nodes in a WDM grooming network switch signals in one or more domain, namely fiber, wavelength, time slot, and code. Wavelength converter (WC) is a device employed to convert an optical signal from one wavelength to another. Similarly, a time slot interchanger (TSI) is a device employed to convert an optical signal from one time slot to another. The optical version of TSI is realized using fiber delay lines.^{1,2} CDMA code converters may be implemented using passive components such as fiber-Bragg gratings to achieve switching in code domain. All-optical implementations of the wavelength, time slot, and CDMA code converters are expensive solutions, hence cannot be implemented at all nodes in the network.

Nodes in a WDM grooming network can have different levels of grooming capability. For example, a node might employ TSI but not WC. Such nodes are referred to as wavelength-level grooming nodes as channels can be switched only within a wavelength. Similarly some other node might implement WC but not TSI, referred to as time slot level grooming node. A node

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employing both TSI and WC are referred to as full-grooming node. For the rest of the paper, we use the terminology of time slots, however the research developed in this paper is applicable to CDMA-based systems as well.

As the present day optical technology is not mature enough to make routing decisions dynamically, wide-area optical networks are expected to remain circuit-switched in nature. Operating a circuit-switched wide-area network involves establishing connections of a certain bandwidth between two nodes in the network. It is well understood that networks in future would comprise of nodes that have heterogeneous switching architectures. One of the reasons is that the upgrading of existing switch architectures to the latest optical technology takes both time and money. Financial constraints limit the network upgrade procedure to enhancing the capability of only a few nodes or increasing the capacity of only a few links depending on the traffic flowing through them. The networks are thus heterogeneous in nature as they constantly evolve with time. Hence, it is important to address the issue of connection establishment in heterogeneous networks.

Connection establishment in a connection-oriented network consists of two steps: *path selection* and *channel assignment*. Path selection refers to selecting a path from source to destination based on certain criteria. Channel assignment refers to assigning one or more channels depending on the requirement of the call on every link of the chosen path. Path selection can be carried out in several ways. If a source-destination pair has one pre-selected path, then it is referred to as *fixed-path* approach. If a path is selected depending on the network status from a pre-selected set of candidate paths, then it is referred to as *dynamic path selection*. The set of candidate paths remain the same at all times and do not change with the network status. If the candidate paths are chosen based on the network status, the path selection process is referred to as *exhaustive routing*. Channel assignment refers to allocation of specific resources on every link of a chosen path, for example: (a) fiber, wavelength, and time slot assignment on the links in a WDM grooming network; and (b) fiber and wavelength assignment in a multi-fiber wavelength-routed network. Irrespective of the path selection or channel assignment strategy employed in the network, obtaining information along a path to assess the availability of resources to establish the connection becomes the fundamental requirement. Information collection in WDM grooming networks involve identifying available resources on the links and grooming capabilities of intermediate nodes on a specific path to identify resource availability on the path.

Connection establishment has been extensively studied in the context of wavelength-routed WDM networks.³ However, this issue has received very little attention in the context of WDM grooming networks. In our earlier work,⁴ we have developed extensions to Dijkstra's shortest path algorithm to multiple metrics in a homogeneous WDM grooming network. In another of our work,⁵ several routing algorithms have been analyzed for their performance in a wavelength-level grooming network. To the best of our knowledge, there has not been any research that addresses the issue of dynamic routing and channel assignment in heterogeneous WDM grooming networks. In this paper, we develop a framework for connection establishment in WDM grooming networks, called Methodology for Information Collection and Routing in Optical Networks (MICRON), specifically emphasizing on what and how information is collected on the links, the aggregation strategy to obtain information on a path considering the different grooming capabilities of intermediate nodes, and mechanisms for path selection and channel assignment. Several routing and channel assignment strategies may be derived from the framework developed in this paper.

The remainder of the paper is organized as follows: Section 2 describes the network model, node architecture, and notations employed. Section 3 describes an example network that is used throughout the paper to illustrate the features of the MICRON framework. Section 4 describes the various aspects of the framework with illustrations. Section 5 concludes the paper.

2. NETWORK MODEL

We consider a WDM grooming network with nodes employing heterogeneous switching architecture. The nodes in the network are connected using links. Each link is assumed to carry F fibers, each fiber carrying W wavelengths. Each wavelength is divided into frames which are further sub-divided into T time slots. Every slot within a frame is denoted by a 4-tuple, (l, f, w, t) , where $1 \leq l \leq L$, $1 \leq f \leq F$, $1 \leq w \leq W$, and $1 \leq t \leq T$. For example, the tuple $(1, 1, 2, 1)$ (read from right to left) denotes first time slot in a frame on the second wavelength of the first fiber on the first link. A *channel* on a link is defined as a collection of a particular time slot across successive frames. The number of channels in a link is the same as the number of slots in a frame. Hence, each channel is also represented by a 4-tuple, (l, f, w, t) .

2.1. Node architecture

A WDM grooming network with nodes employing heterogeneous switching architecture is modeled as a Trunk Switched Network (TSN).⁶ A TSN is a two-level network model in which every link in the network is viewed as a set of channels.

A node in a TSN classifies the channels with similar characteristics in a link into groups called *trunks*. Figure 1 shows the node architecture in a TSN. The node in the figure is assumed to have three links attached to it and views each link as a set of

K trunks. The trunks are first de-multiplexed from the link. The trunks from different links are then sent to their respective trunk switches where the channels are switched. We impose trunk-continuity constraint at a node, i.e., a channel in a trunk on a link can be switched to a channel that falls within the same trunk definition on another link. Such a restriction stems from the architectural point of view. The complexity of realizing a full permutation switching architecture is very high. In a WDM grooming network, a full permutation switching would require switching in fiber, wavelength, and time domain. Therefore, switch designs in the near future are likely to be based on simple architectures that work on a restricted set of channels from every incoming link. In this paper, it is assumed that a full-permutation switch is employed for every trunk in a node, i.e., a free channel of a trunk at the input of the switch can be switched to any free channel of the same trunk at its output. This assumption is relaxed in the later sections of the paper.

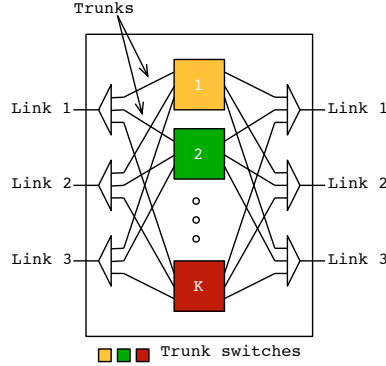


Figure 1. Node architecture in a Trunk Switched Network.

A TSN is said to be *homogeneous* if the collection of channels that constitute a trunk at a node is the same for all the nodes in the network. Otherwise, it is said to be *heterogeneous*. A node i in the network views a link connected to it as a set of K_i trunks with S_i channels in them. Let χ_{ix} denote the channels on a link that fall within trunk x at node i . Let Θ_{xy}^{ij} denote the channels on link (i, j) that fall within trunk x at node i and trunk y at node j , i.e., $\Theta_{xy}^{ij} = \chi_{ix} \cap \chi_{jy}$. The group of channels that fall within a set Θ_{xy}^{ij} is referred to as a *sub-trunk*.

Calls arriving in the network request for a connection to be established from a source to destination. The connection establishment involves selection of a path and assigning channels on the path such that the channel on one link can be switched to the successive link on the path by the node connecting the links. In a TSN, connection establishment consists of three steps: (1) selecting a path; (2) assigning a sub-trunk on every link, or equivalently assigning a trunk at every node; and (3) assigning one or more channels depending on the call requirement on every sub-trunk on every link. Hence, a connection in a network is represented by a sequence of link and sub-trunk pair, or equivalently as a sequence of node and trunk pair. If every node in the network employs full permutation switching for every trunk, then any free channel that falls within the selected sub-trunk on a link can be chosen for establishing the connection.

2.2. Modeling an optical network as a Trunk Switched Network

A single-fiber wavelength-routed WDM network employing W wavelengths can be modeled as W trunks with one channel per trunk. A multi-fiber multi-wavelength wavelength-routed network with F fibers and W wavelengths with no wavelength conversion can be viewed as W trunks with F channels per trunk. If full-wavelength conversion is available, then a link can be viewed as a single trunk with FW channels.

Now, consider WDM grooming network. Let the links in the network employ three fiber, three wavelengths per fiber and two time slots per wavelength ($F = 3, W = 3, T = 2$). Figure 2 shows the eighteen channels that are available on a link. The shapes of the figures represent the time slots, the shades of the shapes represent wavelengths, and the number of shapes of a certain shade represents the number of fibers.

If time slot interchange and wavelength conversion are not permitted, a node i views a link ℓ as WT trunks where each wavelength and time slot combination forms a trunk. Every trunk has F channels as shown in Figure 3(a). If time slot interchange is permitted, but not wavelength conversion, a node i views a link ℓ as W trunks where each wavelength forms a trunk. Every trunk has FT channels as shown in Figure 3(b). If full-wavelength conversion is permitted, but not time slot



Figure 2. Representation of eighteen channels in a link having three fibers, three wavelengths per fiber, and two time slots per wavelength. Shapes represent time slots, shades represent wavelengths, number of shapes of a certain shade represents the number fibers.

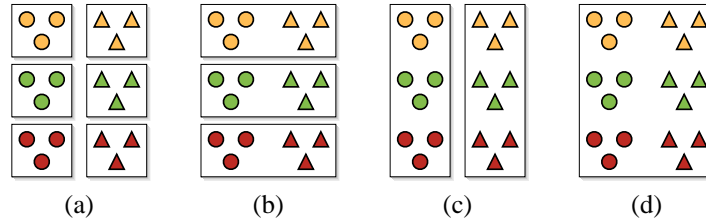


Figure 3. Possible grouping of channels in a link as trunks. (a) Wavelength-Time slot trunk (b) Wavelength trunk; (c) Time slot trunk; and (d) Link is a trunk.

interchange, then for a given link l , a time slot on all the wavelengths can be grouped to form a trunk. Every trunk has FW channels as shown in Figure 3(c). If both full-wavelength conversion and time slot interchange are permitted, then the entire link is treated as one trunk with FWT channels, as shown in Figure 3(d).

3. EXAMPLE NETWORK

Consider the example two paths from node 1 to 5 in a network shown in Figure 4(a). Let the nodes be connected using 3 fibers each carrying 3 wavelengths and 2 time slots per wavelength. Also assume that nodes 1, 3, 6, and 7 are wavelength-level grooming nodes; nodes 2 and 5 are time-slot-level grooming nodes; and node 4 is a full-grooming node. Wavelength-level grooming nodes view the link as 3 wavelength trunks (denoted by W_1 , W_2 , and W_3) with 6 channels in each, time slot-level grooming nodes view a link as two time slot trunks (denoted by T_1 and T_2) with 9 channels in each, and a full-grooming node views a link as one trunk (denoted by F_1) with 18 channels.

Figure 4(b) shows the expanded view of the network indicating different trunks at the nodes. For example, consider trunk W_1 of node 1 and trunk T_1 of node 2. The number of channels in the link 1–2 (denoted by ℓ_{12}) that belongs to both the

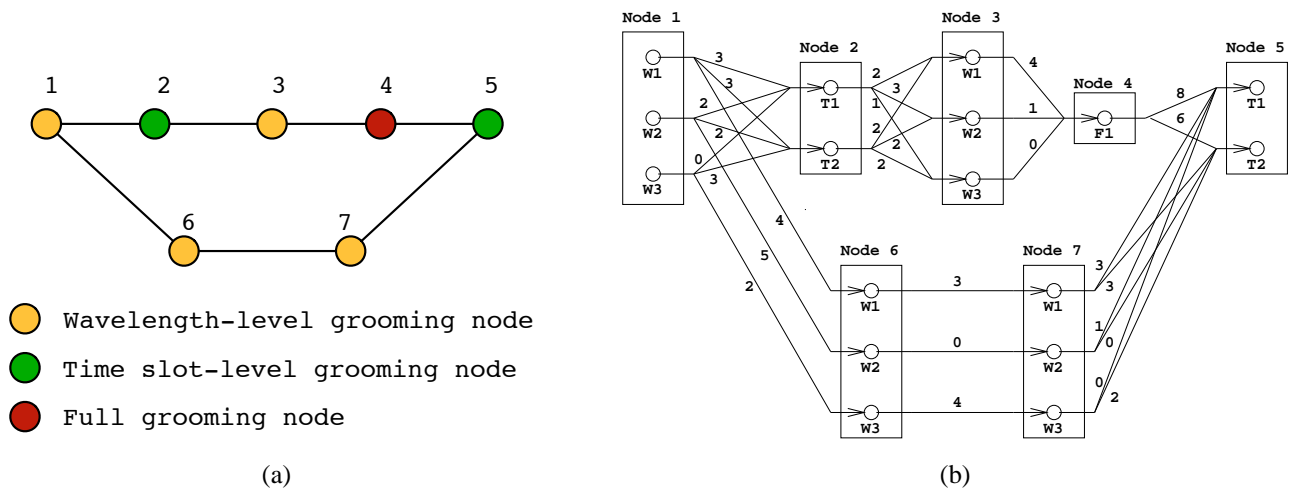


Figure 4. (a) An example network showing two paths from node 1 to node 5. (b) Expanded view of the network with channel occupancy information.

trunks is 3. The channels are $(\ell_{12}, 1, 1, 1)$, $(\ell_{12}, 2, 1, 1)$ and $(\ell_{12}, 3, 1, 1)$, each channel belonging to a distinct fiber. The arrow connecting trunk W1 of node 1 to trunk T1 of node 2 indicates the number of free channels that belong to both the trunk definitions. A value of 3 indicates that all the channels belonging to both the trunk definitions are free.

Assume that the network is observed at some instant of time during its operation and the channel availability in the links are known. Let $(l, f, w, t).Availability$ denote the availability of the channel: denoted by 0 if occupied by a connection, 1 if the channel is free. Let $(l, f, w, t).Status$ denote if the channel is assigned for a primary (or working) connection (denoted by PRIMARY) or a backup connection (denoted by BACKUP). Let $(l, f, w, t).BackupList$ denote the set of requests that share the channel (l, f, w, t) for their backup paths. This implies that the primary paths of these requests are link-disjoint. Consider a request, say r , with a primary path already assigned. Let $(l, f, w, t).LinkDisjoint(r)$ indicate if the request r has its primary path link-disjoint with the primary paths of all the requests that have their backup assigned on the channel (l, f, w, t) (denoted by 1 if it is link disjoint, 0 otherwise). If the channel is not assigned to either a primary or a backup connection, the value is set to 0. Such an information strictly identifies if the channel can be “shared” with already allocated backup connections.

4. MICRON FRAMEWORK

The MICRON framework developed in this paper addresses in detail information representation on a link, combining them to obtain the path information, selection of a path, and sub-trunk assignment in WDM grooming networks with heterogeneous grooming capability. Each of these steps are described in detail in the following subsections.

4.1. Link information

A link connecting node i to node j is represented by a $K_i \times K_j$ matrix, denoted by $L_{ij} = [l_{xy}]$, where K_i and K_j are the number of trunks at nodes i and j , respectively, and each element l_{xy} denotes a certain property about the channels in the link that belong to Θ_{xy}^{ij} . For example, consider the Link 1–2 in the example network shown in Figure 4(a). Node 1 views each wavelength as a trunk, hence has 3 trunks. Node 2 views each time slot as a trunk, hence has 2 trunks. Hence, L_{12} is a 3×2 -matrix. The matrix may denote different properties of the channels. We discuss two specific examples in this paper.

Case 1: Connectivity

In this case, every element l_{xy} of the matrix L_{ij} is denoted by 1 if the total number of free channels that belong to Θ_{xy}^{ij} has a capacity of at least B . The matrix L_{ij} is defined as:

$$l_{xy} = \begin{cases} 1 & \text{if } \left(\sum_{(l,f,w,t) \in \Theta_{xy}^{ij}} (l, f, w, t).Availability \right) \geq B \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where $1 \leq x \leq K_i$ and $1 \leq y \leq K_j$. It is observed that the matrix gives the connectivity information to route a call that requires a capacity of B , without splitting the connection. For a request of one channel capacity ($B = 1$), the matrices for different links in the example network are shown in Figure 5.

$$L_{12} = \begin{bmatrix} 1 & 1 \\ 1 & 1 \\ 0 & 1 \end{bmatrix} \quad L_{23} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \quad L_{34} = \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} \quad L_{45} = [1 \quad 1] \quad L_{16} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$L_{67} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad L_{75} = \begin{bmatrix} 1 & 1 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Figure 5. Link information matrices indicating if there is at least one free channel in a sub-trunk.

Case 2: Available capacity

In this case, every element l_{xy} of the matrix L_{ij} is defined as the number of free channels that belong to Θ_{xy}^{ij} , represented as:

$$l_{xy} = \sum_{(l,f,w,t) \in \Theta_{xy}^{ij}} (l, f, w, t).Availability \quad (2)$$

$$\begin{aligned}
L_{12} &= \begin{bmatrix} 3 & 3 \\ 2 & 2 \\ 0 & 3 \end{bmatrix} & L_{23} &= \begin{bmatrix} 2 & 3 & 1 \\ 2 & 2 & 2 \end{bmatrix} & L_{34} &= \begin{bmatrix} 4 \\ 1 \\ 0 \end{bmatrix} & L_{45} &= [8 \quad 6] & L_{16} &= \begin{bmatrix} 4 & 0 & 0 \\ 0 & 5 & 0 \\ 0 & 0 & 2 \end{bmatrix} \\
L_{67} &= \begin{bmatrix} 3 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 4 \end{bmatrix} & L_{75} &= \begin{bmatrix} 3 & 3 \\ 1 & 0 \\ 0 & 2 \end{bmatrix}
\end{aligned}$$

Figure 6. Link information matrices indicating the number of free channels in a sub-trunk.

where $1 \leq x \leq K_i$ and $1 \leq y \leq K_j$. The matrix representation for different links in the example network in Figure 4(b) are shown in Figure 6.

Note that the matrices obtained using the available sub-trunk capacity also contains the information of the matrices representing connectivity information. Depending on the level of information that is required in the network, different matrix representations may be employed.

Case 3: Backup sharing

In this case, it is assumed that a path for establishing a primary connection has been selected. A backup path for the request has to be computed, hence the matrix is filled with information related to the backup capacity that is freely available. This implies that the capacity has already been allocated as backup to some other connection in the network and the current request can be overloaded on that capacity as their primary paths are link disjoint. The matrix L_{ij} is defined as:

$$l_{xy} = \sum_{(l,f,w,t) \in \Theta_{xy}^{ij}} (l, f, w, t).LinkDisjoint(r) \quad (3)$$

For example, assume that the link information depicted in Figure 4(b) denotes the capacity that has already been allocated as backup to other connections in the network with which the backup for the request under consideration could be shared. The matrix representation in this case would be the same as that described for case of available information in Figure 6.

4.2. Path information

The information about a certain path from a node i to node k that span multiple links may be obtained by combining the link information in the path. The matrix representation for a path is defined in a manner similar to that of a link. A path matrix from node i to k through node j is obtained as a matrix multiplication of individual path segments P_{ij} and P_{jk} as:

$$P_{ik} = P_{ij}P_{jk} \quad (4)$$

We employ a generalized version of matrix multiplication to compute the path metric. An element p_{xy}^{ik} (the superscript ik denotes the matrix to which the element belongs to) is obtained as:

$$p_{xy}^{ik} = (p_{x1}^{ij} \otimes p_{1y}^{jk}) \oplus (p_{x2}^{ij} \otimes p_{2y}^{jk}) \oplus \dots \oplus (p_{xK_j}^{ij} \otimes p_{K_j y}^{jk}) \quad (5)$$

The operators \otimes and \oplus , denoted as a tuple (\otimes, \oplus) , may be defined in different combinations so that several meaningful results are obtained. It can be observed that when \otimes is multiplication and \oplus is addition, the above equation denotes the traditional matrix multiplication.

To illustrate the significance of different operators, we take the two example matrix representation of links and apply two different set of operators to obtain different information from the network.

Case 1: Arithmetic operators

In this case, we consider multiplication (\times) and addition ($+$) as the operators for \otimes and \oplus , respectively. Consider the matrix representation shown in Figure 5. Applying the operators on the path 1–2–3–4–5, we obtain the path information matrix as:

$$P_{1-2-3-4-5} = \begin{bmatrix} 4 & 4 \\ 4 & 4 \\ 2 & 2 \end{bmatrix} \quad (6)$$

An element p_{xy} of the above matrix denotes the number of distinct sub-trunk selections available from trunk x of node 1 to trunk y of node 5. For example, consider the element in the first row, first column. A value of four indicates that there are four distinct trunk assignments that start at trunk W_1 of node 1 and end at trunk T_1 of node 5. The trunk assignments on the path are represented as a set of tuples containing node numbers and the trunk number on that node through which the connection passes. The four possible trunk assignments on the path, denoted by P_1 through P_4 , are:

$$P_1 : \{(1, W_1), (2, T_1), (3, W_1), (4, F_1), (5, T_1)\} \quad P_2 : \{(1, W_1), (2, T_1), (3, W_2), (4, F_1), (5, T_1)\}$$

$$P_3 : \{(1, W_1), (2, T_2), (3, W_1), (4, F_1), (5, T_1)\} \quad P_4 : \{(1, W_1), (2, T_2), (3, W_2), (4, F_1), (5, T_1)\}$$

The existence of trunk assignment for other trunk pairs can be easily verified from Figure 4(a).

Consider the link information as shown in Figure 6. Applying the operators $(\times, +)$ on these matrices results in the path information matrix for path 1–2–3–4–5 as:

$$P_{1-2-3-4-5} = \begin{bmatrix} 504 & 378 \\ 336 & 252 \\ 240 & 180 \end{bmatrix} \quad (7)$$

An element p_{xy} of the above matrix denotes the number of possible channel assignment combinations for a call with one channel capacity requirement on the path that start at a certain trunk x on node 1 and end at a trunk y on node 5. On every sub-trunk on the path the number of ways of assigning a channel is the same as the number of channels in the sub-trunk. Hence, the number possible channel assignments on a specific trunk assignment on the path is the product of the number of channels on the assigned sub-trunk on every link. The number of possible channel assignments on the four possible trunk assignments P_1 through P_4 that start the connection at trunk W_1 at node 1 and end at trunk T_1 at node 5 are 192, 72, 192, and 48, respectively, adding up to 504 possible ways of channel assignment.

Case 2: Selection operators

In this case, we assume that the operator \otimes indicates the minimum of the two operands while the operator \oplus indicates the maximum of the two operands. Applying this set of operations to the matrix representation in Figure 5, we obtain the matrix representation for the path 1–2–3–4–5 as:

$$P_{1-2-3-4-5} = \begin{bmatrix} 1 & 1 \\ 1 & 1 \\ 1 & 1 \end{bmatrix} \quad (8)$$

An element p_{xy} of the matrix indicates the existence of a channel allocation scheme for one channel capacity call that would start at trunk x at node 1 and end at trunk y at node 5. Note that matrix in Equation (8) can be obtained from the matrix in Equations (6) or (7) by replacing every element in the matrix by 1 if it is non-zero.

Applying this set of operations to the matrix representation in Figure 6, we obtain the maximum capacity that can be routed from node 1 to node 5 without splitting the connection. The matrix representation for the path is obtained as:

$$P_{1-2-3-4-5} = \begin{bmatrix} 2 & 2 \\ 2 & 2 \\ 2 & 2 \end{bmatrix} \quad (9)$$

For example, consider the four possible trunk assignments P_1 through P_4 that start the connection at trunk W_1 at node 1 and end at trunk T_1 at node 5. It is observed from Figure 4(a) that the trunk assignments P_1 and P_3 have the link connecting node 2 to 3 as bottleneck with two channel capacity. The trunk assignments P_2 and P_4 have the link connecting node 3 to 4 as bottleneck with one channel capacity. Hence, a connection with a maximum of two-channel capacity requirement can be routed from node 1 to 5 starting at trunk W_1 at node 1 and ending at trunk T_1 at node 5 without splitting the connection.

Now, assume that the link information depicted in Figure 4(b) indicates the capacity available on each sub-trunk that has already been assigned to other connections as backup and could be shared with the request that is under consideration. By employing the operator set (min, max) , we obtain the path matrix shown in Equation 9. In this scenario, the elements of the matrix denote the maximum backup capacity that could be shared on the path by the connection.

4.3. Two-pass approach to connection establishment

When a call arrives at a node, a request for connection establishment is sent along a set of candidate paths. The connection establishment is carried out in two passes: *Forward pass and Reverse pass*.⁷ During the forward pass, the connection request is forwarded to the nodes along the path along with a vector, called Path Information Vector (PIV). The path information vector at a node k for a path p with source i and destination k , denoted by V_{ik} is of dimension $1 \times K_k$. V_{ik} is obtained as a product of the path information vector at the source node and the information matrix of the path connecting nodes i and k as $V_{ik} = U_i P_{ik}$, where U_i denotes the path information matrix at the source node which is always set as a unit row vector.

Assume that the path from node i to k passes through node j . Re-writing the above equation gives the relationship between the PIVs at nodes j and k .

$$V_{ik} = U_i P_{ik} = U_i P_{ij} P_{jk} = V_{ij} P_{jk} \quad (10)$$

The matrix-vector multiplication employed above is similar to the generalized matrix multiplication proposed earlier in the paper with the operator tuple (\otimes, \oplus) . The elements of PIV at a node indicates specific properties about paths that end at a certain trunk. For example, if the link information matrix represented in Figure 5 and operator $(\times, +)$ are employed, then the resulting PIV at each node indicates the number of possible trunk assignments on the path that would terminate the connection on a certain trunk at that node.

During the forward pass of the connection establishment, a node j on the path p with source i can forward either the path information matrix P_{ij} or the path information vector V_{ij} to its neighboring node. Forwarding the latter has the advantage of minimizing the amount of information forwarded. Note that the reduction information exchange will be significant when the number of trunks at a node is large.

4.4. Path selection

The path information vector may be used to select a suitable path from a given source-destination pair. For example, consider the two paths from node 1 to 5: 1-2-3-4-5 and 1-6-7-5. Employing the matrix information represented in Figure 5 and operator $(\times, +)$, we obtain the path information vector for the two paths as:

$$V_{1-2-3-4-5} = [10 \quad 10] \quad V_{1-6-7-5} = [1 \quad 2]$$

With these matrices known at the destination, one may employ different comparison algorithms to select a path. For example, the total number of trunk assignments possible on a path is obtained by summing all the elements of the matrix. A path that has the maximum value for this metric may be chosen for establishing the connection. The rationale behind such an approach is that the path with the maximum value is likely to be the least loaded path.

If the matrix representation in Figure 6 and operator (max, min) are employed, the path information vector for the two paths are obtained as:

$$V_{1-2-3-4-5} = [2 \quad 2] \quad V_{1-6-7-5} = [3 \quad 3]$$

It can be observed that the path 1-6-7-5 can route a call for three channel capacity request without splitting, while the other path cannot. Hence, if traffic requirements in the network are diverse and destination-based path-selection is employed, then the path 1-6-7-5 would be chosen so as to minimize the blocking at that instant of time.

4.5. Sub-trunk assignment

At the end of the forward pass, the destination node has the path information vector for the different paths probed and selects a path based on a certain path selection algorithm. Once a path is chosen, a sub-trunk has to be selected on every link of the path in order to complete the channel establishment. The sub-trunk assignment is carried out in the opposite direction of the path starting with the destination node and ending at the source node.

Consider the information matrix represented in Figure 5 and operator $(\times, +)$. The path information vectors obtained at different nodes are shown in Figure 7.

The trunk assignment to end the connection at the destination node may be made using the path information vector. Several trunk selection schemes such as first-fit, best-fit, random, etc. may be employed. In this paper, we illustrate the random sub-trunk assignment. Let x_k denote the trunk that is chosen to accommodate the connection at node k .

$$\begin{aligned}
V_{11} &= [1 \ 1 \ 1] \\
V_{12} &= [1 \ 1 \ 1] \begin{bmatrix} 1 & 1 \\ 1 & 1 \\ 0 & 1 \end{bmatrix} = [2 \ 3] \\
V_{13} &= [2 \ 3] \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} = [5 \ 5 \ 5] \\
V_{14} &= [5 \ 5 \ 5] \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} = [10] \\
V_{15} &= [10] [1 \ 1] = [10 \ 10]
\end{aligned}$$

Figure 7. Path information vector computed at the nodes along the path 1–2–3–4–5.

In order to select a sub-trunk on link $j - k$, a *ratio vector* is computed at node k . The ratio vector, denoted by R_{jk} , is obtained as the product of the vector at the path information vector previous node, V_{ij} and the column vector of the link information matrix L_{jk} corresponding x_k :

$$R_{jk} = V_{ij} \times L_{jk}^T(x_k) = [v_1 \ \dots \ v_{K_j}] \circ [l_{1x_k} \ \dots \ l_{K_j x_k}] = [v_1 \circ l_{1x_k} \ \dots \ v_{K_j} \circ l_{K_j x_k}] \quad (11)$$

where $L_{jk}^T(x_k)$ denotes the transpose of the column vector corresponding to the column x_k of the matrix L_{jk} and the operator \circ denotes the element-wise operation on the row vectors. Again, one may define different operators depending on the construction of the information matrix. Since the input trunk at node k is decided, the choices of output trunk at node j is also dictated by the channel occupancy of the channels that fall within $\Theta_{yx_k}^{jk}$. The output channel at node j may be selected in various ways using the ratio vector.

Consider a connection that needs to be established on the path 1–2–3–4–5 with the path information vectors as computed in Figure 7. As node 5 is the destination, it selects a trunk for the connection to terminate. We illustrate the random sub-trunk assignment here. We assume that the operator \circ denotes integer multiplication[†].

The PIV at node 5 indicates that there are 20 possible sub-trunk assignments with each trunk being able to terminate 10 each. Hence, one of the two is chosen with equal probability. In general, if p_x sub-trunk assignments are possible on the path that would terminate the connection at the destination node at trunk x , then the trunk x is chosen with a probability $\frac{p_x}{\sum_{y=1}^{K_d} p_y}$, where K_d denotes the number of trunks at the destination node d . In the example considered here, one of the two trunks is selected with equal probability. Assume that the trunk chosen is $T2$.

The output trunk at node 4 is then assigned by computing the ratio vector for the link 4–5 as:

$$R_{45} = [10] \circ [1] = [10] \quad (12)$$

In this case, as only one output trunk is available, it is selected. Hence, on link 4–5, a channel that belongs to trunk $F1$ of node 4 and trunk $T2$ of node 5 is selected.

Similarly, the trunk assignment at node 3 is performed by computing the ratio vector for link 3–4 as:

$$R_{34} = [5 \ 5 \ 5] \circ [1 \ 1 \ 0] = [5 \ 5 \ 0] \quad (13)$$

R_{34} vector denotes the selection ratio for the three output trunks at node 3. Note that although there are 5 possible paths that could end at trunk $W3$ at node 3, there are no free channels on link 3–4 that fall within trunk $W3$ of node 3 and trunk $F1$ of node 4. This information is reflected in the ratio vector R_{34} as a zero entry corresponding to the ratio for trunk $W3$. Thus, it is evident that the path information vectors, by themselves, do not have sufficient information to perform sub-trunk assignments on the reverse path. On the link 3–4, trunk $W1$ or $W2$ is selected with equal probability. Assume that trunk $W2$ is selected at node 3.

[†]The operator \circ is the same as operator \otimes since the element-wise operation that is evaluated here is similar to the matrix-vector multiplication employed for computing path information vector.

The ratio vector R_{23} is computed as:

$$R_{23} = \begin{bmatrix} 2 & 3 \end{bmatrix} \circ \begin{bmatrix} 1 & 1 \end{bmatrix} = \begin{bmatrix} 2 & 3 \end{bmatrix} \quad (14)$$

The trunk assignment at node 2 is chosen in the ratio of 2:3, i.e, trunk $T1$ is selected with a probability of 0.4 while trunk $T2$ is selected with a probability of 0.6. Assume that trunk $T1$ is chosen. It is worth noting at this point that the elements of the ratio vector indicates the ratio in which the trunks must be chosen for a random trunk assignment, hence the name for the vector.

The ratio vector R_{12} is computed as:

$$R_{12} = \begin{bmatrix} 1 & 1 & 1 \end{bmatrix} \circ \begin{bmatrix} 1 & 1 & 0 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 \end{bmatrix} \quad (15)$$

One of the trunks W_1 or W_2 is chosen with equal probability. Assume that W_1 is chosen. Now, the path established for the connection can be written as a set of node-trunk pair assigned at each node on the path $\{(1, W_1), (2, T_1), (3, W_2), (4, F_1), (5, T_2)\}$ or equivalently as a set of link and sub-trunks pair on the path $\{(\ell_{12}, \Theta_{W_1 T_1}), (\ell_{23}, \Theta_{T_1 W_2}), (\ell_{34}, \Theta_{W_2 F_1}), (\ell_{45}, \Theta_{F_1 T_2})\}$. Any channel belonging to the sub-trunk assigned at a link can be chosen for establishing the channel as every node has full-permutation switching capability within a trunk.

It can be observed that such a trunk selection strategy selects with uniform probability a possible sub-trunk assignment on the path. In the above trunk selection process, if the information matrix representation shown in Figure 6, operator $(\times, +)$, operator \circ set to multiplication, and random channel assignment within a chosen trunk on each link, then the resulting channel assignment algorithm selects a channel uniformly from the set of all possible channel assignments possible on the path.

Several other channel trunk selection approaches may be derived by selecting the trunk that has the minimum or maximum value in the selection ratio vector, that would have effect similar to packing or spreading, respectively, the connections across the available sub-trunks in the path. In order to implement a first-fit sub-trunk assignment, the first available trunk is chosen from the ratio vector. The framework may be used to implement and evaluate the performance of the different path selection and sub-trunk (hence, channel) assignment schemes on different network architectures.

4.6. Modeling blocking trunk switches

The framework assumes that the trunk switch employed at every node has full-permutation switching capability. This implies that any channel on a trunk on a link can be switched to any other channel on any output link but within the same trunk. In such a scenario, a connection cannot be accommodated on a trunk only due to lack of capacity on the trunk and not due to switching. All-optical implementation of full-permutation switches would require a large number of stages of switching, hence may not be practical due to power and synchronization issues. Hence, simpler but blocking switching architectures that involves fewer stages of switching may be considered for implementation.

For example, consider the node architecture shown in Figure 8. The node is assumed to have three incoming and outgoing links. Different trunks are de-multiplexed from the link. The trunks from different links are then switched using a channel-space-channel switch. The first and the third stages of switching have full-channel interchangers (FCI) that can convert any channel on the trunk on a link to any other channel on the same trunk on the same link. The FCI stages at the input and the output of the node allows the node to operate in an autonomous manner. Connections are assigned channels on the links. These channels are mapped by the FCI to channels within the node for switching. The node may re-arrange the connections for switching at the input and output of the switch autonomously as long as the channels allocated to the connections on the links (before the first FCI stage and after the last FCI stage) are retained.

For example, consider a wavelength-level grooming node in a WDM/TDM network. Assume that the link has three fibers, three wavelengths per fiber, and two time slots per wavelength. A wavelength-level grooming node would view the link as three trunks with six channels in each. The channel-space-channel architecture would refer to a time-space-time switch employed for every wavelength. Consider a channel that belongs to an input link, say $(l, f, w, t)_{in}$. At a wavelength level grooming node, the channel is mapped in the first stage of switching to another channel, say $(l, f, w, t)_1$, where $l_{in} = l_1$ and $w_{in} = w_1$. The space switch maps the channel $(l, f, w, t)_1$ to another channel $(l, f, w, t)_2$, where $w_1 = w_2$, and $t_1 = t_2$. The last stage of FCI maps the channel $(l, f, w, t)_2$ to $(l, f, w, t)_{out}$ where $l_2 = l_{out}$ and $w_2 = w_{out}$. It is to be noted that the channel-space-channel switching employed here is a blocking switch. Therefore, the number of channels that could be switched from an input link to an output link could be less than the minimum number of free channels on the link.

Every node maintains a vector for every input-output link pair at the node, referred to as *switching constraint vector*. This vector at a node i has a dimension $1 \times K_i$, denoted by $X_{\ell_{in} \ell_{out}} = [x_1, x_2, \dots, x_{K_i}]$. Every element in this vector denotes the number of channels that could be switched from input link ℓ_{in} to ℓ_{out} . Now, consider a path from node i to k through j . Assume

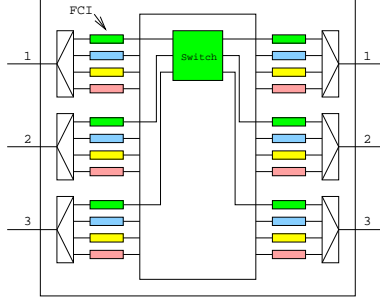


Figure 8. Channel-Space-Channel switching architecture at a node in a TSN.

that node j employs channel-space-channel switching architecture. The path information vector that is forwarded from node j to node k , denoted by V_{ij} , is obtained as $V_{ij} = (V_{ii} \cdot L_{ij}) \circ X_{i-j,j-k}$, where \circ refers to an element-wise operator on the two vectors. This operator may be chosen in many ways depending on the information collected on the path. For example, if the available capacity is stored in the matrices and the operator set (min, max) is employed to identify the maximum capacity that could be routed on the path without splitting the connection, then the operator \circ can be made to be element-wise minimum. Thus, information on a path could be obtained where intermediate nodes need not have full-permutation switching capability.

It is worth noting at this point that the FCI at the input and output stages of switching eliminates channel-continuity constraint within a trunk. Therefore, it is sufficient to carry information about the number of channels that could be switched by the node. However, if the FCI stages are not present, then exact information on which channels can be switched must also be considered. In such a case, the elements in the switching constraint vector and the link information matrix will be matrix (or vectors) themselves.

4.7. Modeling trunk-routing networks

The framework for connection establishment assumes that switches employed for every trunk at a node has the capability of switching individual channels across different links but within the same trunk. In other words, different channels on a trunk at a link can be switched to channels on different links but in the same trunk. However, some switches may have further restricted switching capability in which an entire trunk is switched from one link to another. For example, consider a wavelength-routed WDM/TDM network. A wavelength-routing node that does not employ wavelength conversion would switch an entire wavelength from one link to another. Another example of such a switching node is a photonic slot routing node⁸ that would switch all the wavelengths in a time slot from one link to another. Therefore, either all or none of the channels are switched from one link to another. Such a node in which either all or none of the channels are switched from one link to another are referred to as *trunk-routing* nodes.

In order to model a trunk-routing nodes, we again employ a switching constraint vector. The individual elements are computed depending on whether node i is a source, destination, or an intermediate node. If node i is a source, then the input link refers to the link through which the local traffic is inserted. In such a case, the information corresponding to a trunk x in the switching constraint vector is set to 1 if the node is allowed to transmit on the corresponding trunk, otherwise, it is set to 0. If the node i is the destination node, then the elements of the switching constraint vector are set to 1 if the node is allowed to receive on the specific trunk. If node i is an intermediate node, then the value corresponding to trunk x is set to 1 under any of the following conditions: (a) trunk x is routed from link ℓ_{in} to ℓ_{out} ; (b) node i can receive on trunk x from link ℓ_{in} and transmit on trunk x on link ℓ_{out} . Otherwise, it is set to 0. It is to be noted that in case that trunk x from link ℓ_{in} is routed to a link other than ℓ_{out} , the value is set to 0.

The switching constraint vector is maintained at a node and need not be exchanged with other nodes in the network. Upon receiving a connection establishment request, the node computes its path information vector as described in the earlier section. Before forwarding it to the neighboring node in the network, the path information vector and the switching constraint vector are combined using element-wise multiplication. The resultant vector denotes the updated path information vector that also takes into account the switching capability at a node.

Consider the example network shown in Figure 4(b). Assume that node 5 is photonic slot routing node and that the trunk T1 on link 4–5 is routed to another link (not shown in figure). Therefore, node 5 cannot receive information on trunk T1. Assume that node 5 is receiving information on trunk T2. This information is available at node 5 as the switching constraint

vector, denoted by $[0 \ 1]$. Consider the path information vector obtained on the path 1-2-3-4-5 at node 5 using connectivity information and employing the operator set $(\times, +)$. The path information vector $[10 \ 10]$ indicates that there are 10 possible trunk assignments that would end on trunk T1 and T2 each. When this information is combined with the switching constraint vector at node 5, we obtain the resultant vector as $[0 \ 10]$ indicating that there are no possible trunk assignments that could end on trunk T1 at node 5.

4.8. Reductions to simpler networks

The MICRON framework applied to a WDM grooming network where all the nodes in the network are wavelength-level grooming nodes results in the link information matrix being a diagonal matrix. In such a scenario, the matrix can be reduced to a vector, thus simplifying the operations to be performed to obtain the path information. Such a reduction of the MICRON framework has been adopted in our earlier works.^{5,9} In case of networks with all the nodes equipped with full-grooming capability, hence every node viewing each link as one trunk, the MICRON framework further reduces to a single metric. The proposed methodology then reduces to well-known information aggregation methods established in traditional networks. The framework may be easily extended with other metrics such as delay, cost, etc. and may be employed to derive a plethora of routing and channel assignment algorithms based on information collected using link-state protocols in WDM grooming networks with heterogeneous grooming capability.

5. CONCLUSIONS

In this paper, we develop a framework for dynamic routing and channel assignment (trunk selection) in a WDM grooming network with heterogeneous switching architectures. We illustrate with examples the various information that could be collected from the links and various operators that could be used to obtain information on a path. These information can be used to select a path dynamically depending on the network status. We complete the framework by providing a generic channel assignment procedure that may be employed to derive different channel assignment schemes. The proposed framework may be implemented with simple traffic engineering extensions to the existing routing protocols in the wide-area networks.

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