Optical Bypassing Using a WDM-Gridconnect Patchwork

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***Abstract*— In this letter, the properties of transparent wavelength routed transport networks are analyzed which are based on a wavelength-divsion multiplexing (WDM)-Gridconnect patchwork and compared to networks built on a conventional fiber infrastructure. The patchwork represents an example of a partitioned wavelength routed fiber-optic transport network using optical bypassing. The cumulative transit traffic and path length statistics are calculated. Based on these results, recommendations for the transparent network partition size and the number of wavelengths are given.**

***Index Terms*—Communication system economics, communication system routing, communication system traffic, interconnected systems, space-division multiplexing, wavelength-divsion multiplexing, wide-area networks.**

I. Introduction

THE PHYSICAL limits of wavelength-division multiplexed (WDM) transmission [1] are a severe restriction for path layered fiber-optic communication networks that are designed to cover large areas. The maximum length of the transparent optical paths should be chosen such that the capacity of the transmission paths does not decrease due to chromatic dispersion, crosstalk [2] or other limits like noise, polarization mode dispersion or nonlinearities. These difficulties can be circumvented e.g., by partitioning the network into several fully meshed sub-networks. The subnetworks have a limited coverage area and as a consequence, reduced wavelength path lengths. The different partitions are connected with each other via electro-optical or optically regenerating interfaces located at nodes which belong to two or more different partitions. Therefore, such an arrangement is a multihop network.

There are different architectures known to implement path layered fiber-optic communication networks. One approach is to use optical switches for flexible wavelength path allocation (agile wavelength routed networks) [3]. Alternatively, the ability to reconfigure the network optically is sacrificed in an attempt to ease the transmission technology [4]. Furthermore, in the absence of optical switches no additional network management for the optical layering is needed.

In this letter, a system is discussed which combines several WDM-Gridconnects [5] in a patchwork-like network cluster. This configuration serves as a means to quantify the gain of optical bypassing in terms of transit traffic and the mean-hop number. The findings apply to both static and agile path layered networks as far as partitioning is concerned. As a special case, the conventional meshing (one hop per cable section) is regarded for comparison purposes.

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II. System Model

The system model is based on the use of the WDM-Gridconnect [5]. The node interconnections are implemented by space division multiplexing (SDM) as well as by WDM. The WDM-Gridconnect has a regular grid topology which might be interpreted as the virtual topology on the multiplex section layer of the network.

To avoid a waste of fiber capacity (e.g., due to a variable path length) no optical switches are employed. The passive routing is static without any automatic rearrangeability. All the switching requirements (reconfiguration and protection switching) are fulfilled by an overlay transport system [e.g., systems according to the standards of the synchronous digital hierarchy (SDH) or the asynchronous transfer mode (ATM)] which can be implemented either electrically or by using optical time division multiplexing.

A. Topology

Consider an $M \times N$ rectangular grid topology as depicted in Fig. 1 in which the nodes are denoted as k_{ij}, $(i, j) \in \{1, \cdots, M\} \times \{1, \cdots, N\}$, with i and j representing the row and column index respectively, and $M, N \gg 1$. The nodes are interconnected with multifiber cables (cables that contain several fibers) along the rows and columns of the grid topology.

A network partition consists of a WDM-Gridconnect in which up to s^2 nodes are fully connected through up to s rows and s columns. We call such a topology a WDM-Gridconnect of size s. To cover all $M \times N$ nodes completely $\lceil (M-1)/(s-1) \rceil \lceil (N-1)/(s-1) \rceil$ network partitions are connected to a network cluster in a patchwork-like fashion, where $\lceil x \rceil$ denotes the integer equal or larger than x. Three different types of nodes can be identified: 1) inner nodes which belong to one partition only; 2) border nodes which belong to two partitions; and 3) nodes of the third type (corner nodes) belong to four partitions.

B. Routing

As a routing algorithm, it is assumed that a connection from node k_{ij} to node k_{xy} is established along the row i and along the column y. The routing from the row to the column fiber cable is performed at the node k_{iy} which does not correspond to a shortest path assignment. The rationale behind the algorithm is rather to avoid high-transit traffic load

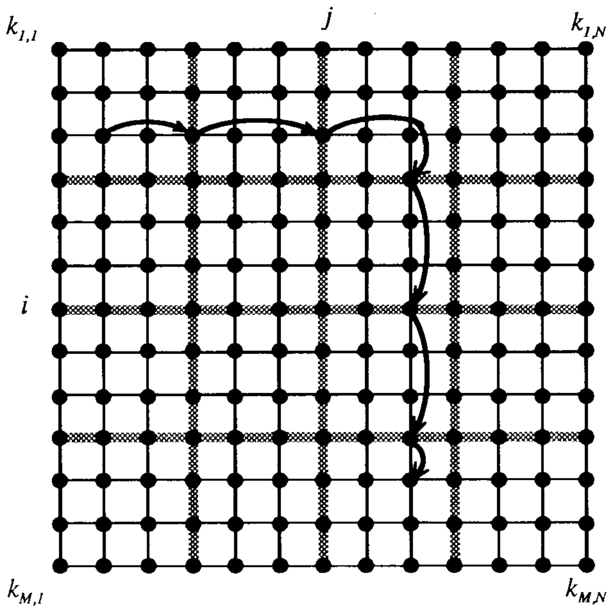

Fig. 1. The rectangular grid topology and a sample connection (6 hops) from node $k_{3,2}$ to node $k_{11,9}$ according to the routing rule adopted in this paper ($s = 4$, $M = N = 13$).

in the central diagonal links of the cluster.

Within each separate transparent network partition, the destination node is encoded by an address which is a pair (μ, ν) of a specified fiber μ and wavelength ν according to the WDM-Gridconnect concept [5].

In this letter, we define the transit traffic at node k_{ij} by the following constraints: It neither originates nor terminates at k_{ij} nor optically bypasses the node along statically arranged waveguide crossconnections. The transit traffic must be handled (switched) by the overlay transport system. If k_{ij} and k_{xy} do not belong to a common network partition the connection established must use an electrooptical or an optically regenerating interface and switching function at a certain number of border or corner nodes.

C. Traffic Modeling

The distance between two arbitrary nodes k_{ij} and k_{xy} is defined as

$$d_{ij,xy} = d_u \cdot \sqrt{(i-x)^2 + (j-y)^2} \tag{1}$$

where d_u is a unit distance characterizing the node density in the patchwork. The average traffic between any two nodes decreases exponentially with their distance, namely

$$T = T^{(o)} e^{-\alpha d} \tag{2}$$

where $T^{(o)}$ is a traffic constant and α a real positive constant accounting for the decreasing traffic as a function of distance.

III. Performance Analysis

A. Transit Traffic Analysis

Due to the optical bypassing, no transit traffic needs to be switched by the inner nodes. In practice, these can be used to relay transit traffic, but this just adds one more hop and the relayed transit traffic still has to be handled by border or corner nodes. Here, we consider the transit traffic on border nodes with the above-mentioned routing algorithm. Let k_{ij} be a column border node. All the traffic with origin $(k_{i1}, \cdots, k_{i(j-1)})$ and destination $(k_{xy}, x \in \{1, \cdots, M\}; y \in \{j+1, \cdots, N\})$ as well as those originating at $(k_{i(j+1)}, \cdots, k_{iN})$ and destined to $(k_{xy}, x \in \{1, \cdots, M\}; y \in \{1, \cdots, j-1\})$ would pass through k_{ij}, so that the transit traffic $T_{ij}^{(T)}$ handled by k_{ij} is

$$T_{ij}^{(T,\text{col})} = T^{(o)} \left[\sum_{w=1}^{j-1} \sum_{x=1}^{M} \sum_{y=j+1}^{N} e^{\alpha d_{iw,xy}} + \sum_{w=j+1}^{N} \sum_{x=1}^{M} \sum_{y=1}^{j-1} e^{-\alpha d_{iw,xy}} \right]. \tag{3}$$

Note, that a column border node does not handle transit traffic along the column, so that there is no transit traffic along the column entering the above formula. The total local traffic generated and received, respectively, at k_{ij} is given by

$$T_{ij}^{(L)} = T^{(o)} \left[\sum_{x=1}^{M} \sum_{y=1}^{N} e^{-\alpha d_{ij,xy}} \right] - T^{(0)}. \tag{4}$$

The transit traffic for a row border node k_{ij} can be obtained similarly, given by

$$T_{ij}^{(T,row)} = T^{(o)} \left[\sum_{w=i+1}^{M} \sum_{x=1}^{i-1} \sum_{y=1}^{N} e^{\alpha d_{xy,wj}} + \sum_{w=1}^{i-1} \sum_{x=i+1}^{M} \sum_{y=1}^{N} e^{-\alpha d_{xy,wj}} \right]. \tag{5}$$

If k_{ij} is a corner node, it serves as both, a row and a column border node. The resulting transit traffic equals

$$T_{ij}^{(T)} = T_{ij}^{(T,\text{col})} + T_{ij}^{(T,\text{row})}. \tag{6}$$

Therefore, the transit to local traffic ratio is obtained as

$$R_{ij} = T_{ij}^{(T)} / T_{ij}^{(L)}. \tag{7}$$

In Fig. 2, R_{ij} is plotted for nodes along a diagonal trace $(i = j)$ through a network cluster larger than in Fig. 1 $(M = N = 25)$. For $s = 2$, transit traffic is switched in each node. For $s = 4$ the inner nodes are free from transit traffic to be handled by the overlay transport system. Note that the transit traffic at the border and corner nodes remains unchanged for different partition sizes s. Furthermore, if N, M and α are sufficiently large, $T_{ij}^{(T)}$ remains constant. Moreover, the total transit traffic in the network cluster is nearly proportional to $1/(s-1)$.

B. Mean-Hop Number

By definition the mean-hop number of the connections to the node k_{ij} is given by

$$\mu_{ij} = \frac{\sum_{x=1}^{M} \sum_{y=1}^{N} H_{ij,xy} e^{-\alpha d_{ij,xy}}}{\left(\sum_{x=1}^{M} \sum_{y=1}^{N} e^{-\alpha d_{ij,xy}} \right) - 1} \tag{8}$$

where $H_{ij,xy}$ is the number of hops required for the node k_{ij} to reach an arbitrary node k_{xy} in the network. A numerical evaluation of (8) reveals both an exponential decay of μ_{ij} for

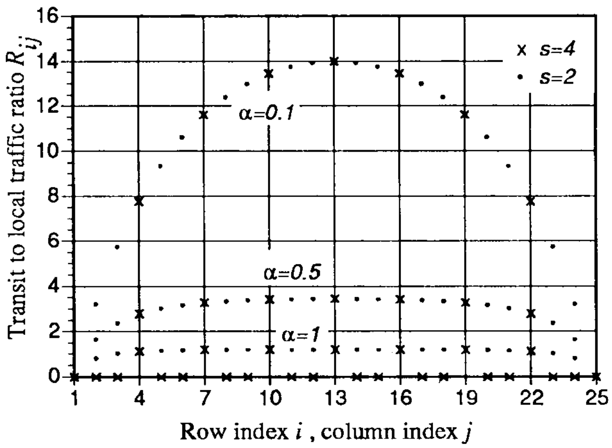

Fig. 2. The transit to local traffic ratio R_{ij} being characterized by certain values (α, s) obtained for a diagonal trace through the network cluster $(i = j)$.

increasing α with the limiting hop number of $\lim_{\alpha\to\infty} \mu_{ij} = 1$ and a dependency approximately proportional to $1/(s-1)$. The latter finding shall also be shown by analytical expressions for a lower and an upper bound of μ_{ij} if the parameter α is chosen to be zero (i.e., global village scenario). For simplicity, we set $M = N = 2n(s-1) + 1$. A total of $4n^2$ WDM-Gridconnects are interconnected with each other as shown for $2n = 4$ in Fig. 1. First, the minimum mean-hop number is obtained regarding the center node $k_{\chi\psi}$ ($\chi = n(s-1)+1$ and $\psi = n(s-1)+1$), which is a corner node in this particular example. Owing to the chosen row-to-column routing algorithm, the parameter $H_{ij,xy}$ can be further decomposed as

$$H_{ij,xy} = H_{jy}^{(\text{row})} + H_{ix}^{(\text{col})} \tag{9}$$

where $H_{jy}^{(\text{row})}$ and $H_{ix}^{(\text{col})}$ are the number of hops required in the row and column directions, respectively. After some algebra we obtain

$$\mu_{\min} = \frac{1}{M^2-1}\sum_{x=1}^{M}\sum_{y=1}^{M} H_{\chi\psi,xy} = \frac{Mn+1}{M+1}. \tag{10}$$

Thus, for a large M we have $\mu_{\min} \simeq n$, which is reasonable according to the chosen routing algorithm. Additionally, an upper bound of the mean-hop number can be found considering the four outermost corner nodes. With the same reasoning as before, we obtain

$$\mu_{\max} = (2Mn+1)/(M+1). \tag{11}$$

For a large M, we have $\mu_{\max} \simeq 2n$, which is about twice the mean-hop number of the center node. For a large network, the above results reveal that the mean-hop number only depends on the parameter $n = (M-1)/[2(s-1)]$. For the conventional network with point-to-point links only, the two bounds can be obtained as

$$\mu_{\min} = M/2, \quad \mu_{\max} = M^2/(M+1). \tag{12}$$

C. Discussion

For large networks and a sufficiently large α both the total transit traffic and the mean-hop number exhibit a decay proportional to $1/(s-1)$. Thus, a small increase in s turns out to be sufficient for the reduction of both performance measures. For example, for $s = 4$ the total transit traffic and the mean-hop numbers are cut by already more than 60% as compared to the conventional case. Moreover, the complexity $C(s)$ represents an antagonist of these criteria and if $C(s)$ is assumed to raise monotonously with increasing s, the minimum of an objective function $A = C(s) + \gamma/(s-1)$ would be found for a rather small $s = s_{\text{opt}}$. The positive real factor γ characterizes the cost impact of capacity requirements and WDM-technology relative to traffic pattern. Therefore, γ is small for large α (i.e., local traffic dominates). Optical bypassing bears the largest potential for cost savings at the nodes of a transport network (i.e., γ large) if α is small, capacity demand is high and WDM-technology cost is low. In purely wavelength routed multihop approaches, the number of wavelengths is lower bounded by $N_\lambda \geq s^2 - 1$. The same consideration applies for purely space routed multihop networks where the number of fibers per node satisfies $N_f \geq s^2 - 1$. The WDM-Gridconnect approach makes a well balanced use of both space and wavelength routing and requires therefore merely $N_\lambda = s$ different wavelengths.

IV. Conclusion

A comparison between wavelength routed multihop networks and conventional fiber-optic networks with respect to optical bypassing has been made. For this purpose, the WDM-Gridconnect approach was chosen as an example to use its regularity as an advantage to simplify the analysis. Optical bypassing was shown to be an efficient means to reduce the overall transit traffic to be handled by the overlay transport system. A reduction of the total transit traffic and the required hop number was shown to be most efficient for a rather small number of nodes per network partition. Therefore, in a system with both, wavelength and space routing, a few different wavelengths appear to be sufficient for optical bypassing purposes.

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