2001

Translucent Optical WDM Networks for the Next-Generation Backbone Networks

Byrav Ramamurthy
University of Nebraska-Lincoln, bramamurthy2@unl.edu

Srinath Yaragorla
University of Nebraska-Lincoln

Xi Yang
University of Nebraska-Lincoln

IEEE Global Telecommunications Conference, 2001. GLOBECOM '01.
Volume: 1 Digital Object Identifier: 10.1109/GLOCOM.2001.965080
Publication Year: 2001 , Page(s): 60 - 64 vol.1

Translucent Optical WDM Networks for the Next-Generation Backbone Networks

Byrav Ramamurthy, Srinath Yaragorla, Xi Yang
Department of Computer Science and Engineering, University of Nebraska-Lincoln
115 Ferguson Hall, UNL, Lincoln, NE 68588-0115

***Abstract*-This paper proposes an alternate approach to fully transparent and fully opaque optical networks for operating a wavelength routed optical network. In this paper, the architecture of the regeneration node that performs sparse regeneration (or translucency) is discussed. The regeneration demands generated from call blocking and signal quality requirements are addressed. Two implementation strategies for incorporating sparse regeneration are introduced and their relative merits are studied.**

***Keywords* WDM, Optical Networks, Transparency, Sparse Regeneration, Translucency, Blocking Probability, BER.**

1. Introduction

In the past decade, computer and telecommunication networks have experienced dramatic growth. With the growth of the Internet technology, there is a huge demand for network bandwidth. This demand is aggravated by the advent of new applications, such as multimedia communications on the Internet. The low-loss region in an optical fiber can provide bandwidth of up to 50 terabits per second. WDM (Wavelength Division Multiplexing) is a promising technique to utilize the huge bandwidth of optical fibers. A WDM wavelength routing network (WRN) differs from conventional networks in that its traffic has a coarser granularity, i.e. on a wavelength level, and that it uses an optical signal for both transmission and switching.

Recent research has validated the deployment of WDM equipment on national-scale and metropolitan-scale telecommunications networks. In such networks, wavelength cross-connect switches (XCSs) can be used to construct wavelength-routed nodes, which route end-to-end data along the lightpaths between access stations. However, it is still unclear what the detailed networking model will be in the sense of transparency (explained below).

1.1 Transparent vs. Opaque vs. Translucent Optical Network

Transparency, using a strict definition, implies that the lightpath should support end-to-end communication of data, independent of bit rates and signal formats. WDM optical networks have been classified into transparent and opaque based on transparency. In a **transparent** optical network, a call bypasses the expensive electronic signal processing at intermediate nodes. However, transparent optical networks are difficult to be practically deployed on a large scale. The reason for this is the effect of transmission impairments on the signal quality after a call travels through several optical components [7]. There are still no satisfactory methods to overcome the impairments in the optical domain. A long-distance lightpath may require electronic signal regeneration, in order to clean it up and improve its quality. An extreme case of this approach is the **opaque** optical network [3]. An opaque optical network incorporates such signal regeneration at every intermediate node along the lightpath. Hence in opaque optical networks, a single optical hop of a lightpath never spans more than one physical fiber link in the network. Electronic regeneration is expensive in WDM optical networks because every wavelength needs electronic to optical and optical to electronic conversions at all the intermediate nodes. An important point to be considered in the case of opaque optical networks is the overhead due to regeneration.

This paper investigates an alternate method to both fully transparent and fully opaque networks and terms it as **translucent** optical networks [1]. In a translucent optical network, a signal is made to traverse as long as possible before its quality falls below a threshold value. Because a signal is regenerated only if necessary, we need fewer regeneration resources. Such a type of regeneration is termed **sparse regeneration**, which we will describe in more detail in the later sections.

2. Regeneration Architecture

First, we introduce the concepts of a call and a lightpath here. A call is defined as a request for assignment of a wavelength from a source node to a destination node. A lightpath is a set of free wavelengths along a given route from source to destination.

2.1 Concept of Regenerator

For our purposes, a regenerator is basically a node along with extra pairs of transmitters and receivers (T-R pairs). As shown in Figure 2.1, it has the capacity of converting a signal from optical to electronic and again from electronic to optical domains. To meet the requirements of signal quality, a regenerator may perform a so-called 3R signal regeneration (regenerate, reshape and retime) in electronic domain. The concept of regenerator gives rise to the question of the bottleneck, i.e. limited electronic peak speed, due to the O/E and E/O conversions. This question forms the basis of the development of **sparse regeneration**. Because of this bottleneck and the cost of O/E and E/O conversion, the regenerators are sparsely distributed in the network.

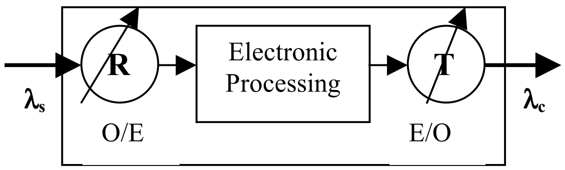


Fig 2.1 A basic regenerator

2.2 Regeneration Resources in a Node with XCS

Sparse regeneration implies that we can make use of the regeneration resources sparsely distributed in the WDM optical network rather than attach a regenerator to each node. In a typical WDM network we study, most access nodes are also intermediate nodes for other calls. Such a node can be modeled as an XCS, which cross-connects the wavelengths, plus an access station that adds/drops some calls from/to the electronic branches. The node has inherent regeneration resources because it provides the basic regeneration resource of T-R pairs. When these T-R pairs cannot meet all demands for regeneration, signal regeneration is achieved by employing an additional array of T-R pairs. The architecture of a node with embedded/extended regeneration resources is shown below (see Figure 2.2).

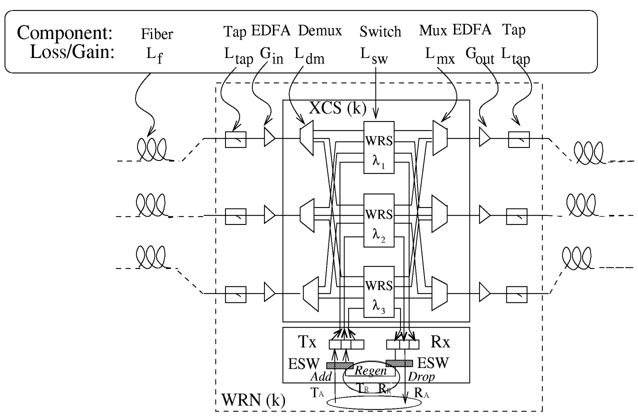


Fig. 2.2 XCS node architecture to allow for signal regeneration

- $\mathbf{T_X}$ and $\mathbf{R_X}$ stand for the whole transmitter and receiver arrays.
- $\mathbf{T_A}$ and $\mathbf{R_A}$ stand for transmitter and receiver arrays used for access functions.
- $\mathbf{T_R}$ and $\mathbf{R_R}$ stand for transmitter and receiver arrays extended for regeneration.
- **XCS** drop/adds a call to/from the access part for branching or regeneration.
- The electronic switch (**ESW**) performs a simple switching function to decide whether to regenerate or add/drop the call.

The $\mathbf{T_X}$ and $\mathbf{R_X}$ can be statically or dynamically assigned into three sets, $\mathbf{T_A}$, $\mathbf{R_A}$ and $\mathbf{T_R}/\mathbf{R_R}$. If the call is at its source, it enters the $\mathbf{T_A}$ set. If the call is at its destination, it enters the $\mathbf{R_A}$ set. If the call is at an intermediate node, a T-R pair is occupied in the $\mathbf{T_R}/\mathbf{R_R}$ set.

If a call is traversing a node described by Fig. 2.2 and a demand for regeneration is generated, this call, say, using λ_s, is then dropped at the XCS and is directed to an available receiver in the receiver array of $\mathbf{R_R}$. The receiver is tuned to the wavelength λ_s, performs O/E conversion and sends the signal to ESW. Then ESW switches the electronic signal to an available transmitter in $\mathbf{T_R}$, which performs the E/O conversion. The transmitter gets tuned to the wavelength of λ_s (or λ_c if wavelength conversion is needed) and transmits the cleaned call with original power and without loss on the output fiber.

To simplify the description, once the resources of a node is used to regenerate a lightpath, we call the node a regenerator. After regeneration, the lightpath consists of two separate optical connections, termed sub-connections.

3. Implementaion

To implement sparse regeneration and utilize regeneration resource in a WDM optical network, the problems of recognizing regeneration demands and satisfying these demands need to be addressed.

3.1 Regeneration Demands

The first demand arises from the signal quality requirements. This is the most common reason for regeneration. To support high-speed end-to-end data communication in a large-scale WDM network, a lightpath may traverse a long distance using wavelength routing. The quality of the signal degrades as it travels through several fiber spans and optical components. The optical fiber amplifiers, e.g. erbium-doped fiber amplifier (EDFA), may complement some loss, but introduce noise at the same time. Furthermore, at each node a wavelength cross-connect switch (XCS) is used to route the wavelength, which also introduces insertion loss. In addition the switch may allow cross-talk (from other channels) to interfere with a particular channel. To overcome these impairments, a long-distance lightpath may resort to regeneration in the electronic domain, to "clean-up" the signal. In our study, we use the bit error rate (BER) to evaluate the signal quality [6]. BER can be measured by tapping a portion of the signal on a lightpath [4]. If the BER of a lighpath is above some threshold value, a regeneration demand is generated. If enough resources are not available for regeneration, this call is blocked.

Call blocking due to limited resources creates another demand for regeneration. A simple way to set up end-to-end data communication is to establish a lightpath with a single wavelength along all the fibers in the route. But this may cause higher call blocking probability because only a limited number of wavelengths are allowed in an optical fiber. In a large-scale WDM network, the probability that several calls using the same wavelength compete to traverse the same fiber segment may be quite high and hence may cause high call blocking probability. One resolution is using wavelength conversion devices [5]. However, wavelength conversion implemented completely in optical domain remains expensive and difficult. Since electronic regeneration is inevitable in a large-scale WDM optical network considering the signal quality requirements, it is natural to use the electronic regeneration resource to do wavelength conversion. Figure 2.1 supports such an implementation.

3.2 Implementation Strategies

In actual implementation, demands due to signal quality and call blocking are not independent. Failure in satisfying signal quality requirements may block a call. But if we satisfy the signal quality requirements at first, some shared regeneration resources in intermediate access stations may be occupied and the blocking probability may also rise. On the other hand, if we use the regeneration resources at a node to do wavelength conversion for blocked calls, some other lightpaths may fail to obtain regeneration at this node, and may have to generate new demands for regeneration at other nodes to satisfy the signal quality. In this study, two strategies are proposed to satisfy them following different demand orders.

3.2.1 Fragmentation

Fragmentation, as the name suggests, is the strategy of fragmenting a call into two different calls at an intermediate node and trying to transmit them through the network over the two sub-connections of lightpaths independently. A call is fragmented if it cannot be assigned a continuous wavelength after a route is assigned to it. To fragment a call, a search is made to find a regenerator along this route to convert the wavelength and retransmit the call. After finding the regenerator, an attempt is made to assign wavelengths and relevant resources to both the sub-connections. After a wavelength is assigned to a sub-connection, its signal quality requirement, i.e. BER, is verified. If either of the sub-connections cannot satisfy the BER threshold, both the calls leave the network by releasing the wavelengths and other resources they were assigned. Only if both the sub-connections are successfully established, is the parent call accepted.

3.2.2 Trace Back

Trace Back strategy comes into picture after the call has found a route to the destination. But the call cannot be accepted because the cumulative BER, at the destination, is greater than the threshold value. Hence Trace Back strategy is different from Fragmentation because of the resources allocated to the call. Trace Back can be visualized as a method of retracing the path and providing regeneration. In this case, the call is not broken into sub-connections with different wavelengths. Instead the call is cleaned up at a regenerator node and is retransmitted. This strategy makes use of the same resources initially allocated to the call and hence is quite simple to implement in practice.

3.3 Regenerator Placement Algorithm

Regenerator placement is another implementation aspect that plays a prominent role in the blocking performance of network using sparse regeneration. Because space considerations, we only provide the following algorithm, named ***static with topology***, to place the regenerators. We refer the interested readers to [2] for additional details.

The most useful information that describes a network is the topology, including the nodes, the links and the capacity on fibers. The most promising candidate for a regenerator under this situation is the node that is at the "center" of the network. We define the "center" as a node that has the largest number of pass-through paths, which is the number of out-links minus the access branches counted by wavelength. A "center" is probably at the half way node of several calls. Another reason to place regenerator at the "center" is that the crosstalk at such a node is higher than at other nodes and hence a call may suffer higher BER and need regeneration.

1 For each node V_i, calculate the pass-through number of paths by subtracting the access branches from out-links.
2 Sort all N nodes according the non-increasing order of the number of the pass-through paths.
3 Select the first M nodes from the sorted nodes as the regenerators.

4. Simulation And Analysis

In this section we incorporate the sparse regeneration implementation strategies and the regenerator placement algorithm, as discussed earlier, into a proven optical network simulation system, SIMON [8]. SIMON allows the simulation of physical level network by modeling the network components such as amplifiers, wavelength converters, links, switches, transmitters and receivers. We can easily design an optical network with various components and modify the network topologies and dynamically assign the resource at network nodes.

4.1 Simulation Model

Blocking probability is a measure for the performance evaluation of this study. Blocking probability is defined as the ratio of the number of calls blocked to the number of offered calls [9] [10]. Our simulation studies are based on the variation of blocking probability with load. Load is defined as the ratio of arrival rate to service rate. The measure of blocking probability implicitly includes the impact of signal quality requirement. If a call cannot satisfy the BER threshold, it is blocked. When calculating BER, SIMON takes into account most of the significant transmission impairments like crosstalk, ASE at amplifier etc.

To simulate the practical sparse regeneration, the ***static with topology*** regenerator placement algorithm is incorporated with the implementation strategies. Other factors in the simulation include the level of load, the number of regenerators and the number of T-R pairs of each regenerator. We denote the set of simulation as $S = M \times L \times R \times P$.

M is the set of implementation strategies. Because the Fragmentation strategy only covers the part of blocked calls that cannot be assigned a continuous wavelength, we focus our study on comparing the strategy of Trace Back (TB) with the strategy using both Trace Back and Fragmentation (TB&F). To contrast them with the ordinary strategy, we add in the strategy using neither of them (OR). So ***M* = {TB, TB&F, OR}. *L*** includes the deferent levels of load, by Erlang, under which we run simulation. ***L* = {5, 10, 20, 40, 60}**. ***R*** is the set of the numbers of regenerators sparsely placed in the network. The possible values depend on the network scale. Suppose that the number of nodes in the network is N. Typically we let ***R* = {5%N, 10%N, 20%N, 30%N}**. The element in ***P*** is the number of T-R pairs we assign to each regenerator. ***P* = {1, 2, 3, 4}**. So each element in the set ***S*** is a quintuple that represents an experiment producing a result for the blocking probability.

In this study, we also use some fixed conditions in the simulation. The topology is that of the Pacific Bell network in figure 4.1. (So in this network, ***R*** = {1, 2, 3, 4}) Pacific Bell network is a 15-node meshed network with 100 km inter-node links. Each link in this network can support 8 wavelengths. For each experiment in the simulation set ***S***, we offer 10,000 calls, which were uniformly distributed over all source-destination pairs. For each source-destination pair, the calls arrive by a Poisson distribution and with holding time following an exponential distribution. Those calls failing to satisfy the BER threshold are blocked. The guaranteed threshold value for BER is set to 10^{-12}.

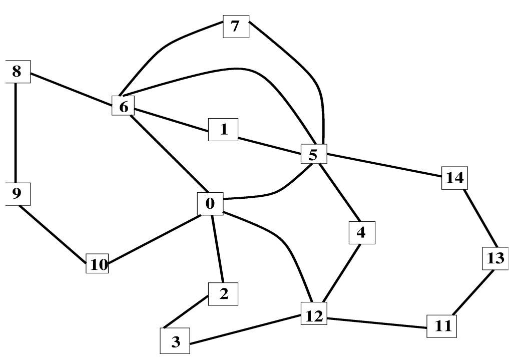
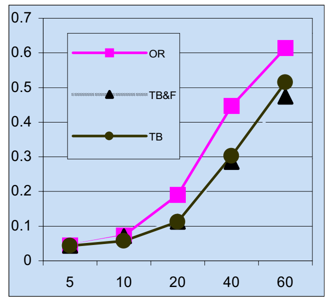


Fig 4.1 Pacific Bell network

Since $|S| = |M| \times |L| \times |R| \times |P| = 3 \times 5 \times 4 \times 4 = 240$, we must calculate $240 \times 10{,}000 = 2.4\times10^6$ calls. It is difficult to explore the complete simulation set. We experiment on the representative subsets of ***S*** and present the results in the following subsections.

4.2 Strategies for Regeneration Implementation

This subsection deals with the results based on the different strategies for implementing regeneration. The results are based on 3 regenerators and each regenerator has 2 T-R pairs. The Figure 4.2, 4.3 and 4.4 provide a clear description of the results. The blocking probability is plotted with respect to load for the original, TB&F and TB implementations.



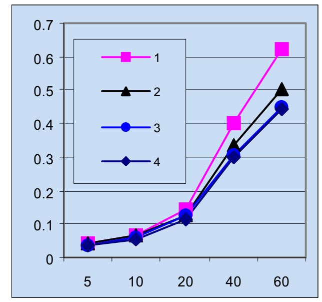
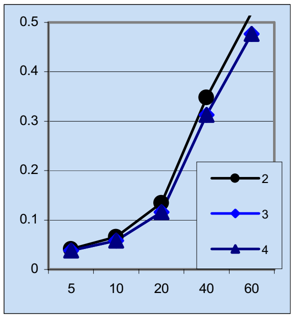


Fig 4.2 Blocking probability vs. load for implementation strategies. **Fig 4.3** Blocking probability vs. load for number of regenerators.

- The results indicate that TB and TB&F have almost overlapping curves, i.e. *Fragmentation* has only a very small advantage as far as the overall network performance is concerned. When compared to the original performance, i.e. without regeneration, there is enormous improvement in the performance of the network.
- The main reason for the failure of ***Fragmentation*** when combined with ***Trace Back*** is that under a low load, very few calls are blocked due to unavailability of a continuous wavelength. When loads increase, ***Fragmentation*** may result in more crosstalk at the regenerator because a call is split into two calls here and the blocked calls due to signal quality requirement may increase.
- The improvement in blocking probability can be observed distinctly at medium loads (20-40 Erlangs). When the loads continue to increase, the improvement decreases relatively. This is expected because, under heavy load, the impact of signal quality degrades and competition for wavelengths will definitely increase even after making each node a regenerator (i.e. a fully opaque network).

4.3 Number of Regenerators and T-R Pairs

This subsection deals with the behavior of the network for different number of regenerators and T-R pairs. It may appear that by increasing the number of regenerators and T-R pairs we can drastically improve the efficiency of the network. But the results are not quite encouraging as far as this expectation is concerned. The experiments are conducted for 1, 2, 3 and 4 regenerators with 2 T-R pairs each. The results are plotted in Figure 4.3. Then we fix the number of regenerators to 1 and 2 and observe whether the blocking probability can decrease when we assign more T-R pairs (see Figure 4.4).



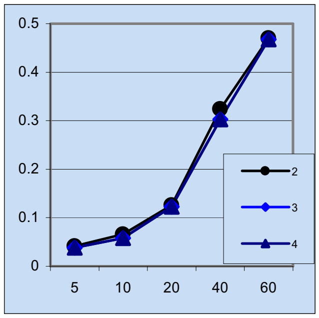


Fig 4.4 Blocking probability vs. load for different number of T-R pairs (a. 1 regenerator, b. 2 regenerators).

- Obviously 1 regenerator for the whole network produces poor results. Increasing the number of regenerators can decrease the blocking probability. However, when we increase the regenerator number above 3, we obtain little improvement in performance. Similarly, assigning more than 3 T-R pairs for 2 regenerators does not result in noticeable improvement.
- It can be noticed that there is not much improvement achieved in the blocking probability, by increasing the number of regenerators at a low load. As the load increases, the improvement also increases. For example at a medium load of 40 Erlangs, the blocking probability with 1 regenerator is 0.407 while that with 3 regenerators is 0.3136. This is because regeneration is needed more when the network has increasing traffic that competes for network resources.
- The Figure 4.4 has almost same curves for the blocking probability with 1 regenerator and 4 T-R pairs as with 2 regenerators and 2 T-R pairs.

5. Conclusions

This section presents the conclusions of this study on sparse regeneration.

- Regeneration can drastically decrease the blocking probability under the consideration of satisfying signal quality requirements. The regeneration architecture discussed in Section 2, the proposed implementation strategies show great improvement on performance.
- Sparse regeneration is feasible in a WDM optical network. The simulation results indicate that when the number of regenerators exceed beyond 20% of the total network nodes, there is only a very little additional improvement.
- *Fragmentation* strategy does not show its advantage under both low and high loads when combined with *Trace Back* strategy in implementation. Crosstalk contributes to the failure of *Fragmentation* under high loads.
- The number of regenerators is an important factor affecting the network performance. The 15-node network needs only 3 regenerators, but we can expect that a larger scale network needs much more regenerators. Furthermore, the number of T-R pairs assigned to each regenerator affects the performance similarly. When there are not enough regenerators in the network, adding the number of T-R pairs may improve performance.
- A general observation for all experiments is that the results under different strategies, regenerator numbers and T-R pair numbers have little difference at very low loads. Under high loads, although the absolute improvement still increases, the relative improvement decreases. Our conclusion is that sparse regeneration is much more important under medium loads.
- It is important to remember that our simulation results are based on a network with 15 nodes. When we apply the conclusions here to a larger network, some differences may arise.

As already discussed, these conclusions validate the implementation of sparse regeneration. When constructing the next-generation optical backbone networks, translucent WDM optical networks are quite cost-effective among the candidates. Based on sparse regeneration, such a network can reduce the optical impairments introduced in a fully transparent network and provide satisfactory signal quality with a much lower (about 20%) extra cost compared with a fully opaque network.

References

[1] B. Ramamurthy, H. Feng, D. Datta, J. P. Heritage, and B. Mukerjee, “Transparent vs. opaque vs. translucent wavelength-routed optical networks”, *Optical Fiber Communication* (OFC ’99) *Technical Digest*, San Diego, CA, Feb. 1999.

[2] Srinath Yaragorla, “Sparse regeneration on a translucent WDM optical network”, Master ’s Thesis, University of Nebraska-Lincoln, Lincoln, May 2000.

[3] E. Goldstein, J. Nagel, J. Strand, and R. Tkach. National-scale networks likely to be opaque. Lightwave Xtra!, Feb. 1998.

[4] B. Mukherjee, “Optical Communication Networks”, McGraw-Hill, 1997.

[5] B. Ramamurthy and B. Mukherjee, "Wavelength Conversion in WDM Networking", Journal on Selected Areas in Communicaitons, Sept. 1998.

[6] D. Datta, B. Ramamurthy, H. Feng, J. P. Heritage, and B. Mukerjee, “BER based call admission in wavelength-routed optical networks”, Optical Fiber Communication (OFC ’98) *Technical Digest*, San Jose, CA, Feb. 1998.

[7] B. Ramamurthy, H. Feng, D. Datta, J. P. Heritage, and B. Mukherjee, “Impact of transmission impairments on the teletraffic performance of wavelength- routed optical networks,” IEEE/OSA Journal of Lightwave Technology, 1999.

[8] B. Ramamurthy, D. Datta, H. Feng, J.P. Heritage, and B. Mukherjee, ``SIMON: A Simulator for Optical Networks," Session on Simulation Tools and Validation for Optical Devices and Networks in the Fifth annual Conference on All-Optical Networking, Sept. 1999.

[9] B. Ramamurthy, “Efficient design of wavelength-division multiplexing (WDM)- based optical networks,” Ph.D. dissertation, University of California, Davis, July 1998.

[10] B. Ramamurthy, "Design of Optical WDM Networks: LAN, MAN and WAN Architectures", Kluwer Academic Publishers, Boston, MA, Dec. 2000.