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NETWORK ARCHITECTURE FOR AN ALL-OPTICAL INTERNET

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1. Summary

To meet the growing need for higher capacities, a new architecture for an all-optical Internet is proposed. Based on traffic statistics and number of available wavelengths in the WDM trunks at network nodes, wavelength allocation and assignment is performed. Distribution of wavelength allocation decisions is accomplished using signaling messages encapsulated in optical "labels" or "tags" associated with each wavelength channel. Signaling messages are generated and modulated onto the individual wavelength channels at the nodes. These messages are then used to reflect changes in the network configuration at each optical element. Wavelength-selective and wavelength-interchanging cross-connects form the basic building blocks of an all optical network. In response to the signaling commands, each optical cross-connect reconfigures itself based on pre-determined wavelength assignments, generates and forwards new signals to the downstream elements. Since labels are associated with wavelength channels, they may be exchanged across wavelength changers without modification. Exchange of allocation commands and wavelength updates are performed periodically. The assignment of WDM wavelengths remains unchanged until traffic at the access points to the network differ significantly from the previous decision interval and also based on the wavelength routing process.

In this architecture, for the purpose of reading signaling message contents or for encapsulating new commands onto the labels, conversion of the bearer optical signals to electrical and vice versa is not required. Thus, this architecture offers transparency with respect to the information bit rate, format, and bearer channel protocols. A novel technique for cost effectively generating, reading, and writing signaling messages onto the optical wavelength channels have been experimentally demonstrated. Unless absolutely necessary, for example for signal regeneration forced because of impairments, O-E-O conversion is avoided.

2. Introduction

The unprecedented explosion of traffic growth over the Internet has resulted in profit opportunities for service providers and equipment vendors alike. However, meeting the challenges of such growth requires new and increasingly sophisticated network elements leading to the future network architectures. Such architectures should be scaleable, reliable, and manageable [1]. These objectives can be achieved with creative combination of new and existing technologies. Optical transmission, cross-connects, optical add/drop multiplexers, high capacity switches and other network elements are among these technologies. Dense Wave Division Multiplexing (DWDM) can provide multiple wavelengths each at 100's of Mbps to 10's of Gbps transmission capacity at a reasonable cost over fiber links. Switching and routing architectures based on custom ASICs that avoid extensive use of software particularly for ATM and IP achieves high capacity switching which complements the high capacity transmission over fiber links. Wavelength cross-connects (OXC) or other Optical Network Elements (ONE) allow reconfiguration of network connectivity at optical cross-connects upon command with a very short response time. A sophisticated combination of these technologies provides a scaleable architecture. When supplemented with SONET—like protection mechanisms and network management methods, it can meet the challenges of the internet traffic growth.

In this paper using these elements, a wavelength allocation and assignment method is proposed which avoids optical/electrical conversion since such conversion results in expensive equipment and questionable performance at the switches and routers. Periodically, traffic demands at access points to the network are measured and the number of wavelengths corresponding to the demand is determined. Traffic measurement, and cross-connect rearrangement commands are exchanged among network elements using signaling messages encapsulated in optical labels. At cross-connects or ONEs, except for label processing required for wavelength routing and cross-connect rearrangement, traffic is not converted electronically and/or processed. In this manner, high-speed traffic is not switched electronically, except at access points. Wavelength re-arrangement at cross-connects responds to network traffic changes over appropriate time intervals. Local router/switch processes traffic electronically at the access points.

In connection oriented applications (such as ATM), call setup between access points (i.e, source/destination) requires establishment of a path. In IP routing using destination-based methods particularly over the Internet, even though connectionless but traffic tends to aggregate on certain paths [2]. These observations and other intuitions with respect to improved performance in the presence of lower traffic volume at switching/routing elements, resulted in the concepts introduced in this paper. Specifically, a traffic flow between two access points is assigned to a path established using a wavelength channel (or a concatenation of several wavelengths) across an optical backbone. Establishment of the wavelength path, assignment of the flow to the path, and finally dis-establishment of the path is the focus of this paper.

The paper is organized as follows: Section (3) describes the mechanism of modulation and demodulation of optical labels. Optical labels are used to carry signaling messages among optical elements of an all-optical backbone network for path establishment. Section (4) provides an overview of all-optical network architecture with the major elements that form the access and cross-connects. Section (5) is a brief method of operation with a subset of signaling message formats. Section (6) is on the comparison of end-end performance when using a wavelength path between source-destination end points compared with the case when traffic is added and dropped at least at one router/switch in the network. Section (7) concludes the paper.

3. Optical Label

In order to provide per channel signaling, it is required to tag or label each (wavelength) channel with a unique ID. This label contains specific information about the wavelength channel similar to the header/trailer information that is used with data packets. This ID label not only provides source and destination addresses, but also contains other signaling information. In addition, the label is read, written and modified by OXC and other network elements. By analogy in transportation industry, such a label is used for tracking packages end-to-end and is read (and possibly modified) at hubs and distribution stations.

In the optical network, the signal (of any bit rate, format, and protocol) riding on one of the wavelength channels may originate at an edge (any point, A), in the network and leave the network at any other point, B. Along the route from A to B, that wavelength may pass through several optical network elements such as OXCs and OADMs, and will temporarily co-exist with wavelengths conveying other information on the same fiber. Further, the wavelength may change several times by wavelength interchanging network elements.

One way to embed the label in the wavelength channel is to use digital bit stream, similar to SONET/SDH overhead and/or digital wrapper. But this technique requires the access to the bit stream and consequently entails converting the wavelength channels from optical to electrical. O-E-O conversion of the high-speed payload signal defies the concept of optical routing.

Alternatively, low frequency tones (subtones) or possibly high frequency supertones can be used to identify each channel with only a limited amount of information. The optical label in this paper is based on the use of subcarrier modulated tones attached to each optical channel. Each channel is labeled with a tone that is modulated with low bit rate digital ID. It has been experimentally demonstrated that the subcarrier modulated tone can be economically and simply read /written/modified or refreshed without requiring conversion of the optical payload signal contained within the wavelength into electrical [3].

This approach is depicted in the block diagram of Figure (1). Although the diagram shows a feedback scheme, a feed-forward implementation is also possible. Further, structures for per wavelength labeling of a multi-wavelength bundle read/write are also realizable. In this approach, the digital label that is attached to the high-speed optical signal has a significantly lower speed than the payload. This means that the payload and the overhead, although riding together, are quite different in bit rate and format. As a result, inexpensive electronics are used for processing of the label information.

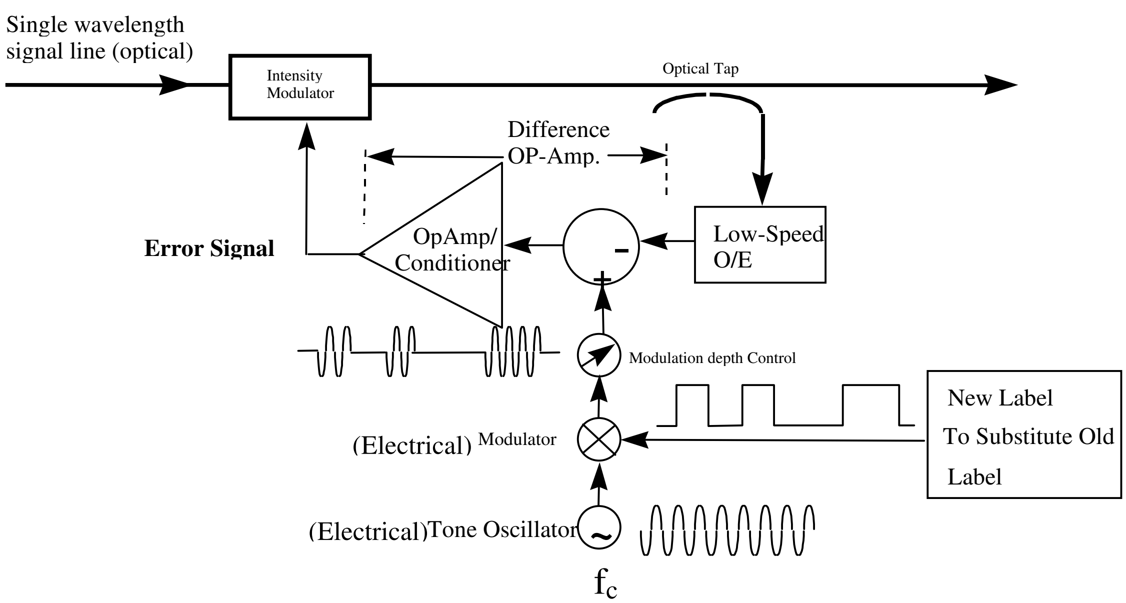

Figure (1): Optical Label reader/writer/modifier

The operation of the circuit of Figure (1) is as follows: Based on a series optical modulator such as an electro-absorption (or any other type of) modulator, the amplitude of the high-speed optical signal is modulated with the desired label (with modulation depth or index m < 10%). A fraction of the resultant signal is tapped off, converted to electrical signal using a low-speed (and low cost) photo detector and used in a feed back circuit to drive the modulator. This detected low speed modulation is compared with the desired (new) label by the difference amplifier. The resultant error signal drives the optical modulator. In this manner the signal can be read, replaced or refreshed [3].

As shown in the lower part of the figure, the desired (new or replica of the old) digital label modulates a low frequency subcarrier of frequency f_c (this can be AM, FM, QAM, etc.). This new signal forms the control signal for the differential feedback amplifier to generate the error signal stated earlier. This technique allows read/write/modification of the label without accessing the high bit rate optical payload signal, which is used as the channel label (tag) in the all-optical network architecture.

4. Network and Node Operation

A network consisting of access devices connected to routers and WDM fiber channels between cross-connects forms the backbone of an all-optical Internet. Backbone elements consist of fiber transmission links and optical cross-connects (OXCs) with no opto-electronic conversion inside the network (except for the optical label processing), as shown in Figure (2). End user access to the all-optical Internet is through electronic multiplexers, high capacity routers, and using Wavelength Selection and Muxing (WSM) devices, as shown in Figure (3). As shown in this figure, user traffic at various multiplexers at the access points is routed at router/switch ports before interfacing to the WSM. The electronic side of WSM receives router traffic destined to the access points throughout the network. At WSM, individual router ports destined for the same destination access points, or access points selected as the first choice next hop, are multiplexed onto the different wavelengths. The choice of wavelength, number of wavelengths routed to the next OXC or WSM, and the interval of time over which such decisions are made depend on the traffic measurements at WSM as well as the routing algorithm.

The architecture described here is in contrast with the traditional ones where interface from user devices to a backbone is through a multiplexer and/or router. In that architecture, multiplexer/router then submits

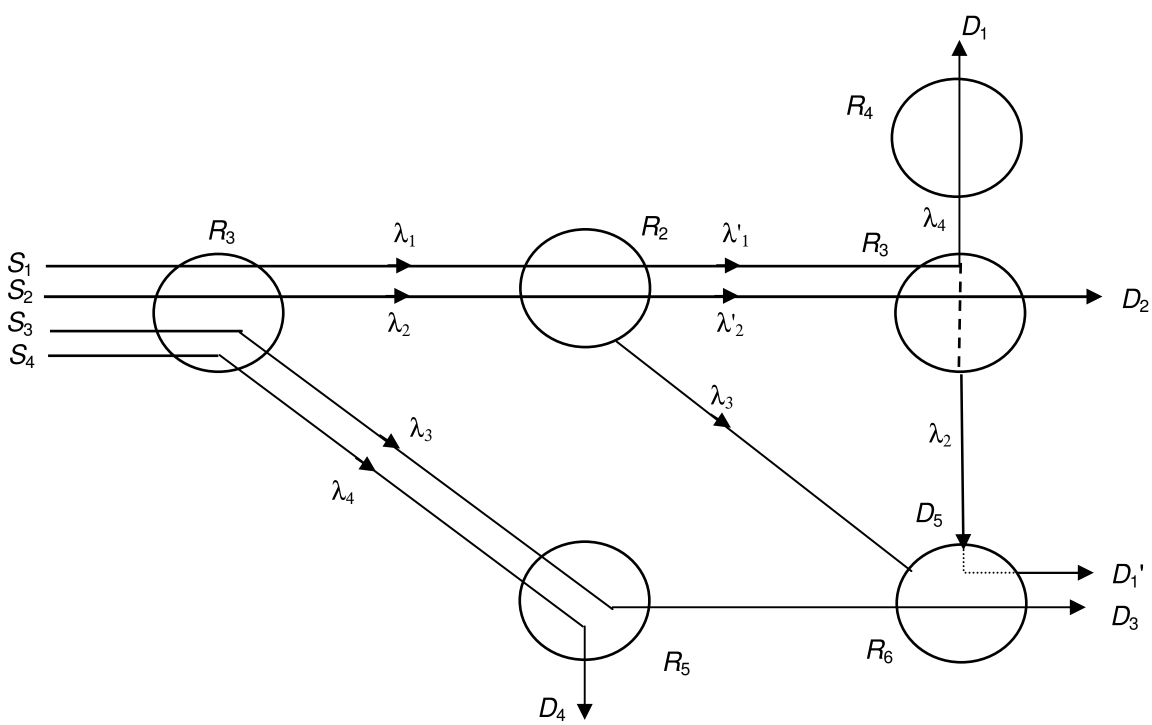

Figure (2): Support of Different End Points user traffic to an ATM switch, which in turn interfaces to the optical network using an ADM (case of IP over ATM). In this paper however we assume that the ADM is an integral part of WSM as in Figure (3), and that router/switch is shown as a combined unit. For the purpose of the concepts introduced in this paper, it is not absolutely necessary to carry Internet traffic over ATM, or to distinguish among the various traffic types. The concept introduced here allows establishment of wavelength paths over an optical backbone for ATM, IP, or other traffic types.

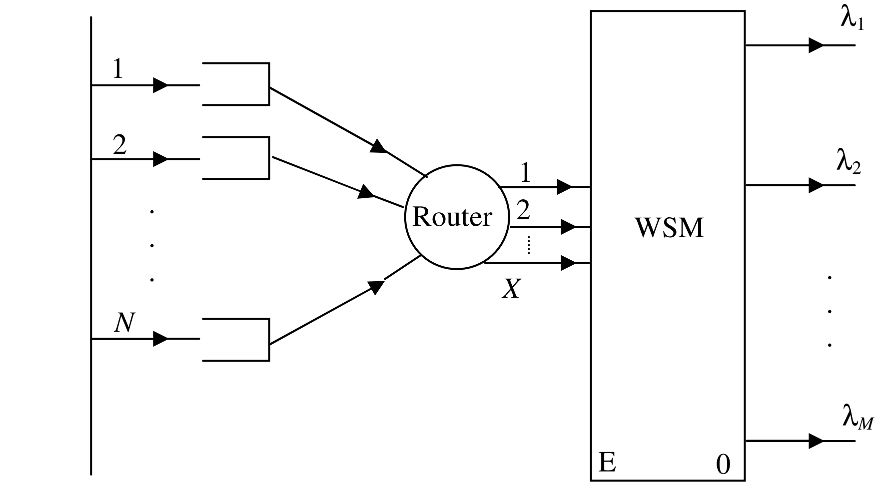

Figure (3): User Interface to Wavelength Selection and Multiplexing

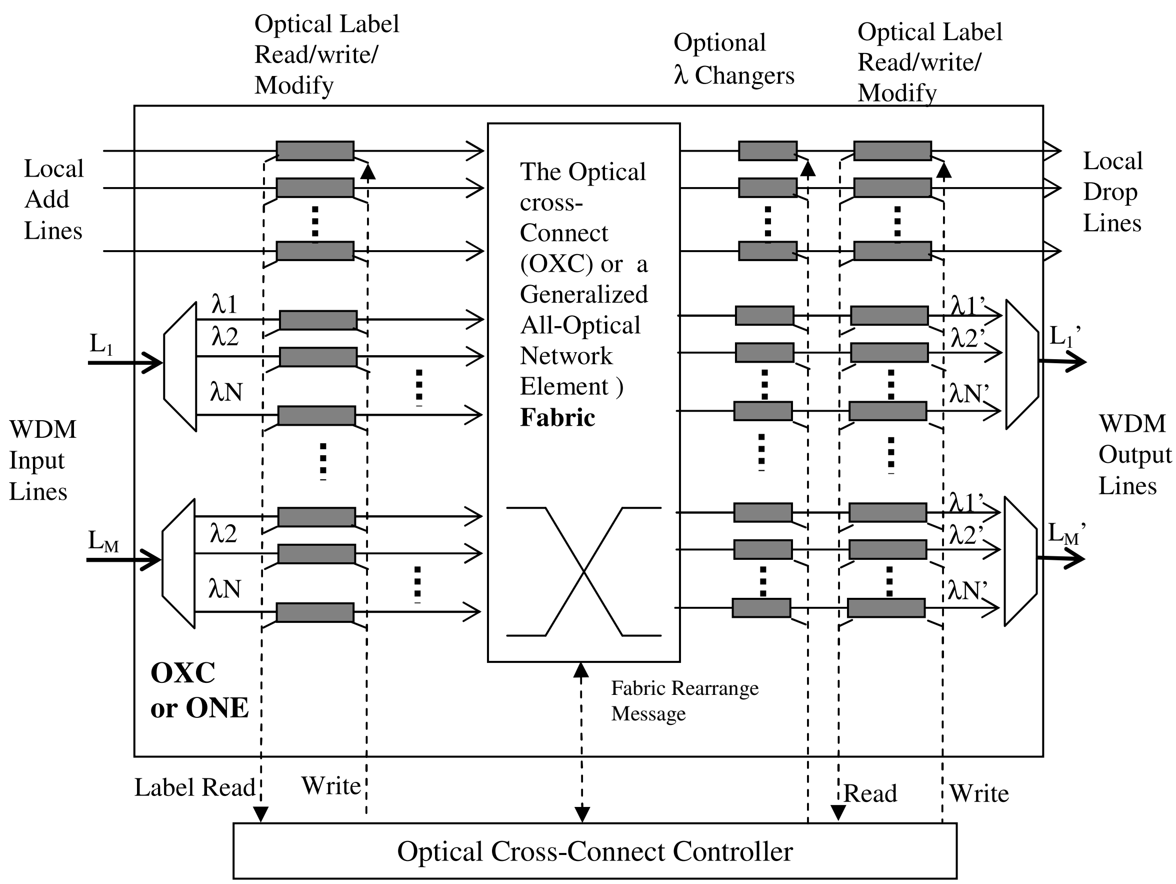

Figure (4): Optical Router

Network rearrangement and wavelength assignment uses a set of signaling messages between access point WSMs and backbone OXCs. Signaling messages are specifically designed for this purpose and are carried in optical labels generated at WSMs and OXCs. Figure (4) shows the block diagram of the generalized OXC. It consists of an optical cross-connect fabric, optical label read/write elements one for each wavelength at the input and output of the fabric, respectively, possibly a set of wavelength changers, and a cross-connect controller. The WSM shown in Figure (3) is identical to the OXC in Figure (4). When it is intended to refer to it for the purpose of access, it is called a WSM for convenience. When the backbone element is intended, it is referred to as OXC. User traffic submitted to an all-optical network is added through the router interface shown in Figure (3), through the "ADD" lines shown in Figure (4). At the destination access point, the user traffic exiting the network through an electronic router, interfaces to the router at the "DROP" lines shown in Figure (4). Signaling messages carried in optical labels are

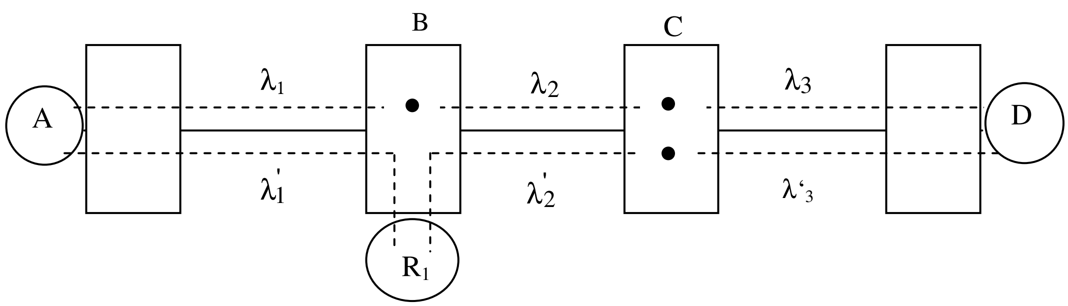

Figure (5): Model of Wavelength Concatenation to Form a Path between Routers A and D

received and read by the optical label reader in Figure (4) and are sent to the cross-connect controller for processing. New signaling messages are generated by the cross-connect controller and are sent to the optical label read/write element, which in turn modulates the label onto a given wavelength for transmission to the next OXC en-route to an access point WSM.

Cross-connect controller exchanges "Fabric Rearrange Message" with the OXC fabric as shown in Figure (4). This message is generated as a result of optical signaling exchange with the access WSM and the backbone OXCs as described in the next section. It causes the input/output wavelength connection at the OXC fabric.

5. Method Of Operation

In order to establish a wavelength channel path from router/switch (A) in Figure (5) to router/switch (D), a Path Set up Request (PSR) message similar to that shown in Figure (6) is originated at WSM (A). This

Source WSM/OXC Address	Destination WSM/OXC Address	Wavelength 1 At Source WSM/OXC	Wavelength 2 At Source WSM/OXC	. . .	Path QoS

Figure (6): Path Set Up Request (PSR) Message

message contains source WSM address, destination WSM address and the set of wavelengths assigned at WSM (A) for the path set up (e.g., λ_1). This message is originated upon call set up request, such as Initial

Address Message (IAM) in SS7 received at WSM or upon receiving an Internet IP packet destined for the destination access point (D). WSM (A) examines the destination address in IP packet, or the URL of the server contained in the IP message to which the request is addressed. When IP packets are delivered on ATM, connection requests are used as a means of initiating PSR messages at the source WSM. Upon receiving a PSR at OXC (B), either (a set of) unused wavelengths to a next OXC/WSM en-route to (D) are available (e.g., λ_2), or traffic from (A) is multiplexed onto an existing wavelength used by other traffic destined to OXC (C) (e.g., λ_2'). The decision whether to share λ_2' with other traffic at OXC (B) is made at OXC (B) and depends on the path QoS and other performance requirements specified in the original PSR. If the path set up request at OXC (B) is accepted, a table similar to Table (1) at OXC (B) controller is populated with the incoming/outgoing wavelength information (e.g., first entry of Table (1)). This represents the case of an unused wavelength λ_2 at OXC (B). When no unused wavelength is available at OXC (B) and wavelength λ_2' is shared with the traffic from router R_1, an item similar to the second entry in Table (1) is populated.

Incoming Wavelength	Access Router at B	Outgoing Wavelength
λ_1	--	λ_2
λ_1'	R_1	λ_2'

Table (1): Routing Table at OXC (B)

The decision at OXC (B) as to which and how many wavelengths to use in order to reach (D) is based on the routing procedure used at (B) for this purpose, as well as on wavelength availability and QoS measures. Wavelength allocation process is discussed later. Since each WSM/OXC may support multiple access routers/switches, it is necessary to specify which router/switch should handle the traffic in response to the original PSR. In case no wavelength is available at OXC (B), either an unused or a shared one, a negative acknowledgement message for the original PSR is returned to (A) in an optical label. If an available wavelength at (B) is found, the entry in Table (1) controller is marked as "Reserved" until confirmed (confirmation occurs after all segments of the path to (D) are also reserved). After completion of setup of the first segment of the optical path, OXC (B) controller initiates a Pending PSR (PPSR) to the next OXC, namely (C) in Figure (5). Format of a PPSR message is shown in Figure (7). This message is a replica of PSR with the addition of 2 extra fields for each OXC encountered en-route to (D). A similar entry at a routing table at OXC (C) controller is also created if the PPSR is accepted. If the request is denied, a negative acknowledgment message is returned by OXC (C) to OXC (B) using an optical label. This message is subsequently forwarded to WSM (A). If the request is accepted, OXC (C) forwards its PPSR to the next OXC/WSM, in this case (D). Upon completion of the path set up between (A) and (D) an acknowledgment is returned by (D) in an optical label to (A) via (C) and (B). When receiving the path set up acknowledgment, each OXC/WSM, removes the "Reserved" status from the appropriate routing table entry. Upon receiving the path set up acknowledgment message at source (A), transmission between (A) and (D) commences. The process of wavelength assignment (next section) and path set up request is performed over relatively long time intervals. As such, the signaling delay in setting up paths is negligible compared with the interval of time over which the wavelength assignment and allocation is performed.

Original /Source WSM/ OXC Address	Destination WSM/OXC Address	Wavelength at Source WSM/OXC	Path QoS	First OXC Address	Wavelength At First OXC	Second OXC Address	Wavelength At Second OXC	. . .

Figure (7): Pending Path Set up Request (PPSR) Message

5.1 Wavelength Assignment and Allocation

The traffic measurement and wavelength assignment model is shown in Figure (8). User buffers are periodically observed. Based on observations and subsequent measurements, a number of wavelengths (n), $0 \le n \le N$ are assigned so that a path QoS objective can be met. The set of candidate wavelengths for assignment consists of N wavelengths and is formed from among wavelengths available (unused) at the source WSM or intermediate OXCs. The wavelength assignment decision at a WSM can be made independently (autonomous) or in conjunction with other nodes in the network (integrated). In the latter case, the number of available wavelengths are chosen from a set of those currently used for paths to access points, and which will become available. OXC/WSM on a wavelength path can decide to release wavelengths as indicated by their measurement observation and an overall network cost/performance objective.

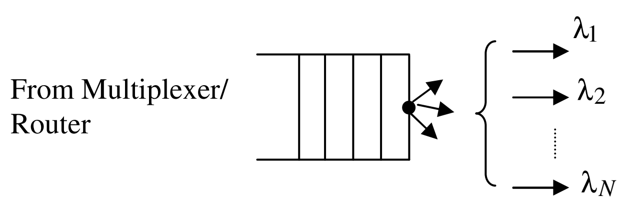

Figure (8): Wavelength Assignment Model

When packet loss in the autonomous model is used as a QoS measure, a loss probability p^* is specified as the objective. In this case, probability of (M) packets in a buffer with (n) assigned wavelengths is [4]:

$$p_M = \begin{cases} p_0 \dfrac{(n\rho)^M}{M!} & \textit{for} \quad M \le n \\[2ex] p_0 \dfrac{\rho^M n^n}{n!} & \textit{for} \quad M \ge n \end{cases}$$

where

$$p_0 = \left[\sum_{k=0}^{n-1} \frac{(n\rho)^k}{k!} + \left(\frac{(n\rho)^n}{n!} \right) \left(\frac{1}{1-\rho} \right) \right]^{-1}$$

and ρ is the channel utilization.

In this case, (n) the number of wavelengths to be assigned is determined so that $p_M \le p^*$. Other QoS measures such as delay may also be used.

6. End-to-End Performance

In order to compare delay performance of a typical IP packet on an end-end path using the wavelength allocation method, the model shown in Figure (5) is considered. In the first option, an IP packet flow from source access router/switch (A) to destination router/switch (D) requires a path consisting of a concatenated set of wavelengths λ_1, λ_2 and λ_3. The second option used here for comparison, is called add/drop where λ_1' on A-R_1 link, λ_2' and λ_3' from R_1 to (D), are used to complete a path. λ_1' and λ_2' form a concatenated wavelength between router R_1 at OXC (B) and WSM (D). At OXC (B), a portion of traffic from (A) is dropped at R_1 (destination router) and new traffic is added for the destination (D). It is assumed that utilization of the concatenated wavelengths in both options remains the same. However, in the case where traffic from (A) to R_1 is carried on λ_1', this wavelength is assumed to be only 30% utilized. Figure (9) shows comparison of the end-end delay for a 120-byte IP packet for the two options.

This example highlights the reason for avoiding add/drop transmission in conjunction with wavelength allocation. In some respect, it demonstrates performance advantage of the proposed all optical backbone over the add/drop option that is currently widely adopted.

7. Conclusions

The challenge of meeting the Internet traffic growth requires sophisticated mechanisms based on existing opto-electronic components. Due to the dynamic nature of the Internet traffic, it is very difficult to systematically predict future traffic growth. These lead to methods of utilizing DWDM and high-speed switching/routing along with dynamic wavelength allocation and assignment to meet the challenges.

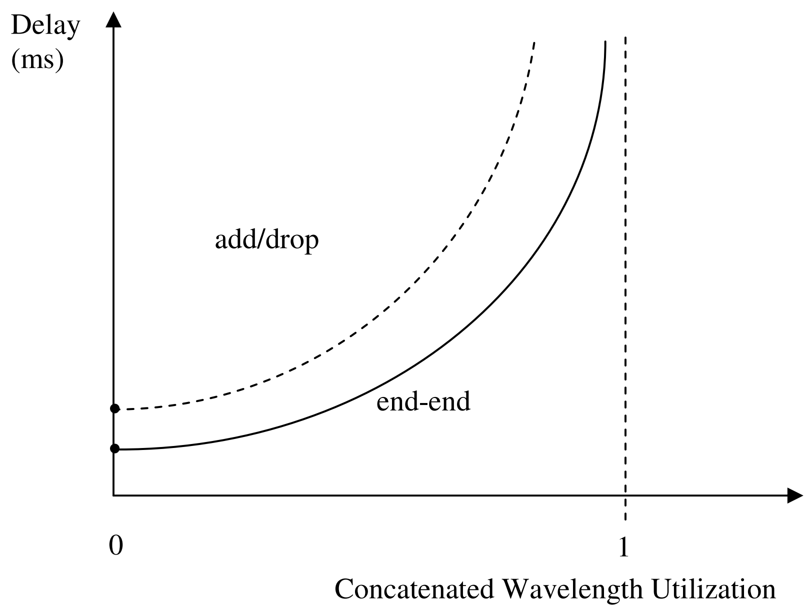

Figure (9): Performance Comparison

In this paper, a mechanism for the design and operation of an all-optical Internet is devised. Sample signaling messages which are encapsulated in optical labels are shown. Exchange of such messages among optical cross-connects and routers allow dynamic allocation of bandwidth in order to meet network performance objectives. A number of open issues such as network management, protection switching in case of failure, and QoS on the basis of individual connections (rather than an entire path) needs to be investigated.

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