Digital container: a mechanism for heterogeneous traffic transport over an all-optical network

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ABSTRACT

In order to move toward the goal of a true all-optical network, two objectives should be met: (i) signaling for dynamic path set up and removal should be independent of the payload traffic; (ii) a mechanism should be devised for the simultaneous transport of heterogeneous (particularly IP) and other traffic on the same wavelength. The first objective insures that the network reconfiguration and capacity allocation is performed cost effectively and independently of the payload, and the second objective assures that the optical network can carry a mix of legacy traffic. Both objectives should be considered simultaneously so that the E-O-E conversion in the network can be minimized (preferably avoided) which also contributes to the cost effectiveness of an all-optical network. Furthermore since optical flip-flops, memory, and processors are only possible in a distant future, these objectives guarantee a smooth transition to future networks consisting of optical switches with no electronic conversion.

In this paper, a vision for an intelligent all-optical network based on the existing network components, such as edge devices (routers and multiplexers) and optical cross-connects is offered. This vision assumes that the edge devices and routers multiplex traffic for a given destination edge device, and transport across the backbone with minimal O-E-O conversion. A set of signaling messages for setting up and removal of the optical paths using optical labels is designed. Optical labels are modulated onto the individual wavelengths and are carried out-of-band with respect to the payload. A Digital Container approach for carrying a mix of heterogeneous traffic over a wavelength without the need for SONET/SDH/ATM is also introduced.

The vision offered in this paper contemplates the design and implementation of an all-optical network, such as all-optical Internet with capability to carry heterogeneous traffic.

1 Introduction

Future networks should carry a mix of several traffic types. Predominantly, optical networks will carry data and comparably lower volume of voice over the same infrastructure. The specific nature, mix, and characteristics of these traffic streams due to their evolutionary nature are not well known at this time. However, they are expected to range from *monomedia* where only one type of session is supported, to *multimedia,* where a session will consist of multiple monomedia sessions. The former case is comparable to the traditional circuit or packet networks where voice, data, or video sessions are established. In the current internet, early versions of multimedia sessions are observed. For example, upon gaining access to a server, an end user is permitted to access video and audio clips (as well as establishing real-time connections such as voice and video) along with data exchange. However, the existing networks which provide this service consist of legacy switches, cross-connects, and transmission equipment that hardly meet the performance needs of the end users. Furthermore, in addition to the exponential growth in network traffic volume fueled by the introduction of new applications and services, service providers are faced with significant protocol incompatibility in the case of internetworking among heterogeneous systems. Such systems include access to cellular and wireless services as well as transport of legacy wireline applications and services such as voice on TDM and data on TCP/IP. Many service providers face the expensive task of equipment re-deployment as a response to the future capacity growth and other means of combating the needs of their customers and end users. This approach is not feasible for the majority of service providers, and "re-deploy" is not a solution, but a work-around.

In response to these challenges, development and deployment of all-optical networks view can take three possible paths:

- Electronic routers with optical transport: The traditional approach to incrementing capacity that can be obtained from fiber transmission cables, and by terminating fiber cables at electronic routers and processors. This approach faces the problem of bottleneck due to the O/E/O conversion and electronic processing, since processing should be performed at these points on individual entities such as packets or connections. While this approach only partially serves the need of packet services, it does not offer an acceptable solution for the TDM traffic.
- Optically mimicking electronic switching and routing: The vision for of an all-optical equivalent of today's electronic router approach may be a long-term one. It assumes availability of high-density high-speed optical flip-flops and logic devices. Elementary logic devices and flip-flops have been demonstrated at the laboratory [13], but have a long way to be commercially viable.
- A practical view: The view that is offered in this paper, suggests using all-optical network elements and components, such as all-optical cross-connects, and to minimize (or preferably eliminate) E-O-E conversion and opto-electronic devices except at certain points in the network. This view also relies on dynamic reconfiguration of wavelength channels, preferably uses out-of-band signaling, and prepares for the design and implementation of all-optical networks. It should be designed in a way that can accommodate a mix of heterogeneous traffic for the legacy systems.

Given the breakthroughs in wavelength-division multiplexing (WDM) and dense WDM (DWDM) as well as the ability to reach terabit capacity and higher on fiber links, the high capacity requirements of future networks demand that they be built based on optical transmission, optical cross-connects, and possibly all optical switches [1, 2, 3]. The addition of future new services should be accomplished in a very short time frame and impeded by the existing infrastructure. Future networks should be traffic transparent, and new traffic types should be accommodated with, at most, minor developments at the interface to the network infrastructure. Furthermore, it should be possible to incrementally add and/or remove capacity in places where dictated by traffic demand. In order to improve network performance, the components involved in processing of traffic should also be minimized. Lastly, but most importantly, such networks should be cost effective. This last requirement may be satisfied by avoiding (or minimizing) E-O-E conversion. Most such conversions can be avoided through use of a separate signaling network, which does not involve O-E-O at the cross-connects or at the switches.

In this paper, a new approach to traffic transport based on the third approach is proposed. Traffic may be packet or circuit data and is transported over optical links. Furthermore, the signaling traffic can be carried in optical labels and modulated onto each wavelength using a separate subcarrier. The signaling network, on the other hand, may be carried in a separate electronic network for commands and responses. This method carries mix of heterogeneous traffic and differs from that of using SONET/SDH in the following two ways: first, it does not require as much transmission overhead as in SONET/SDH [4]; secondly, it allows signaling to be used in the establishment of paths between end points. This new method can be used for the transport of any mix of traffic from a variety of applications/services in transport entities called ***Digital Containers.*** The core network is transparent to the details of specific protocols carried within the Digital Containers.

The remainder of this paper is organized as follows: Section (2) gives an overview of the digital container, Section (3) provides network signaling out-of-band and gives an example using optical labels, Section (4) gives the node architecture view, Section (5) is a review of the digital container format, addressing technique, and its transport of heterogeneous traffic. Section (6) discusses one method of wavelength allocation which can be incorporated with the digital container technique. Section (7) concludes the paper.

2 Digital Container

Using the existing format for packet and TDM transport, this paper presents a new method whereby heterogeneous packet and non-packet information can be transported in Digital Containers of preferably fixed size. Each Digital Container carries an identifier called *Optical Logical Channel Identification (OLCI)* field (Figure (7)), containing the destination address of the edge router to which the Digital Container is addressed. Each Digital Container carries multiple heterogeneous packets and/or non-packet information only for the end users served at the same destination edge router. In this manner, except for occasional routing (at the intermediate edge routers, if necessary) and information extraction from the Digital Containers upon receipt (at the destination edge routers), individual packet processing, which is the most processor intensive task at routers is avoided. Digital Container processing at the edge router is limited to the process of individual Container delineation and forwarding of units of information in it to the individual end user routers.

Containers can be dedicated to a particular end user and/or shared among end users connected to an edge router. When no data is available from an end user at the source edge router, or if there is no data to transmit on a particular wavelength, Digital Containers with a universal OLCI may be transmitted so that transmission synchronization can be maintained between connected end routers. Digital Containers can also be used for the transport of maintenance, operations, and performance monitoring information. An OLCI for the same destination edge router can be used for the transport of information from the source edge router multiplexed from many users over an available wavelength. This feature allows on-demand bandwidth allocation from the pool of available wavelengths. Through end-to-end wavelength setup between source and destination edge routers, routing at intermediate routers is avoided. When absolutely necessary, routing tables at intermediate edge routers allow looking up for the OLCI of the incoming Digital Containers and determining whether they should be forwarded to another edge router on a wavelength or be forwarded to an end user at the destination edge router. In the latter case the packets are identified as in the current routing/switching methods. By allowing Digital Container processing rather than individual packet processing, the edge router capacity improves. With this approach, an assumption is that optical link is responsible for reliable transport of information and that packet processing is the sole responsibility of the end user devices. This separation of functionality has been shown to be crucial for combining scalability and flexibility that is desirable in all-optical networks [5]. Packets within a Digital Container are handed to the end users, processing at the end user devices commence, and remains the same as in legacy systems. No changes to the hardware or software at the end user devices would be required. Figure (1) shows the interface between an edge router represented by the users accessing an optical network and the optical cross-connect (OXC). OXC is used for wavelength grooming and traffic transport.

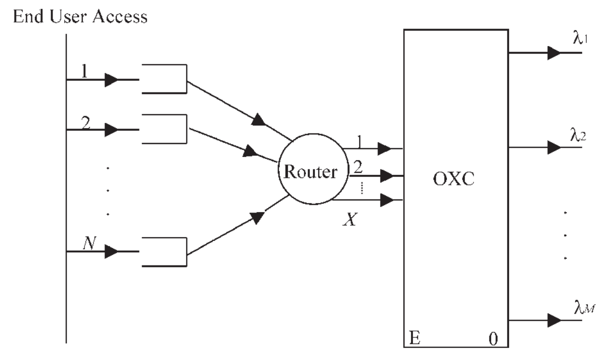

Figure (1): End User Interface to an Optical Network.

For the purpose of connection establishment among end devices, signaling among intermediate optical cross-connects and end devices is devised. This allows establishment of concatenated end-to-end wavelengths between source and destination end devices. In this case, Digital Container routing at the intermediate cross-connects is avoided. With the exception of possible buffering of Digital Containers at the source and destination end devices, and processing of Digital Containers at the destination end device, no other processing at intermediate optical cross-connects is performed. Therefore, a greater measure of QoS can be provided to the end users.

3 Signaling Out-of-Band

The preferred technique for wavelength reconfiguration and allocation of wavelengths based on traffic demand, is by using out-of-band signaling methods. In band signaling particularly when implemented using the optical wavelengths relies on O-E-O conversion at individual network elements; thus not cost effective. Two approaches for out-of-band signaling are as follows:

- Use of a separate electronic signaling network such as SS7 for carrying command and responses for the optical cross-connect reconfiguration. In the case of today's networks, such signals may be carried in an Internet over TCP/IP and terminated at optical elements. This approach relies heavily on an external network, which may not be cost effective, or reliable.
- Use of a separate signaling network in conjunction with the wavelengths that carry bearer traffic. Effective approaches have been proposed in [12, 14]. These approaches require further study to verify their feasibility in a large network. One approach, however, due to its cost effectiveness and simplicity of implementation is described below.

Optical Label: In order to provide per channel signaling, it is required to tag or label each (wavelength) channel with a unique ID. This would contain specific information about the wavelength channel similar to the header/trailer information that in data packets. Labels not only provide source and destination addresses, but also contain signaling information. In addition, the label is read, written and modified by OXC and other network elements.

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, the 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. Furthermore, 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 these techniques require access to the bit stream and consequently entail 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 [12, 14]. 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 ID and signaling information. 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 [12].

This approach is depicted in the block diagram of Figure (2). 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.

The operation of the circuit of Figure (2) is as follows: A series optical modulator such as an electro-absorption (or any other type of) modulator modulates the amplitude of the high-speed optical signal 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 differential amplifier. The resultant error signal drives the optical modulator. In this manner the signal can be read, replaced or refreshed [12].

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

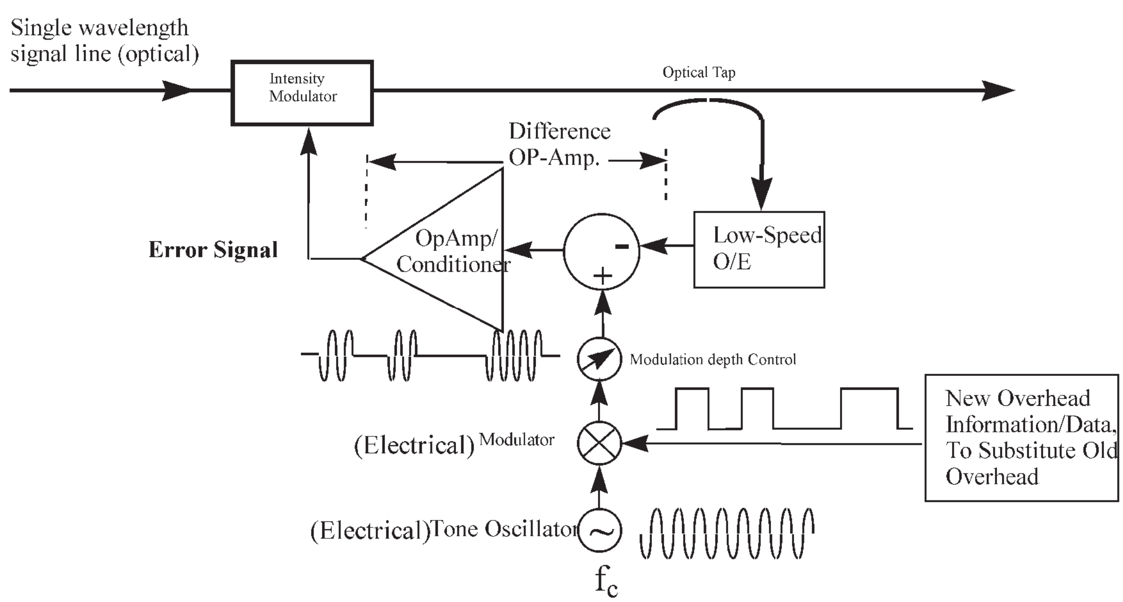

Figure (2): Optical Label reader/writer/modifier.

bit rate optical payload signal, which is used as the channel label in the all-optical network architecture.

4 Node Architecture

Figure (3) shows the principal elements of the core node architecture. It consists of an Optical Cross-Connect (OXC) interfacing with the electronic edge devices and interconnected with fiber links. Each fiber link multiplexes several wavelengths in DWDM mode. Each wavelength may have a capacity of several Gbps or higher. The total capacity of a fiber link is in the order of several terabits per second. The electronic end devices consist of circuit switches, packet switches, and or dedicated end user links such as DS-1, DS-3, E1, etc. which terminate at the customer premises equipment. The switching nodes as end user systems may consists of mobile switching systems in the case of wireless and cellular systems, base stations, or multiplexers which combine traffic from multiple end user devices and transport them onto the optical cross-connects.

Network rearrangement and wavelength assignment use a set of signaling messages between access point OXCs and backbone OXCs. Signaling messages are specifically designed for this purpose and can be carried in optical labels generated at OXCs. Furthermore, OXC includes optical label read/write elements one for each wavelength at the input and output of the fabric, respectively, possibly a set of wavelength changers (in order to optimize the capacity utilization), and a cross-connect controller. User traffic submitted to an all-optical network is added through the router interface shown in Figure (3), through the "ADD" lines. At the destination access point, the user traffic exiting the network through an electronic router, interfaces to the router at the "DROP" lines. Signaling messages carried in optical labels are received and read by the optical label reader and are sent to the cross-connect controller for processing. New/regenerated signaling messages are generated by the cross-connect controller and sent to the optical label read/write elements which in turn modulate the labels onto wavelength for transmission to the next OXC en-route to an OXC. Cross-connect controller exchanges "Fabric Rearrange Message" with the OXC fabric. This message is generated as a result of optical signaling exchange with the access and backbone OXCs as described in the next section. It causes the input/output wavelength connection at the OXC fabric.

When an optical cross-connect cannot be reached directly from another OXC, the concatenated wavelengths interconnect the edge devices that are connected to them. However, in cases where such direct links do not exist, provision is made for the routing table at the edge devices to receive the Digital Containers from the incoming wavelength and transmit them onto the outgoing wavelengths toward the destination edge device. Thus, for example, traffic from A destined for D are routed to R_1 at B and are subsequently routed to D. The process of *routing at the edge* device is by using the Optical Logical

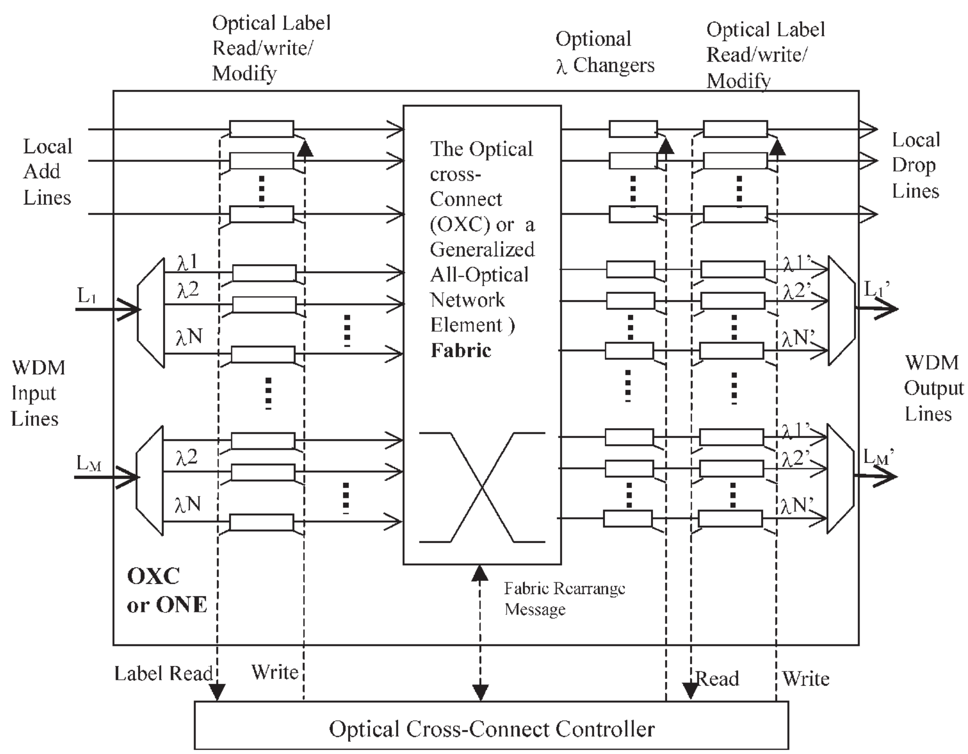

Figure (3): Optical Router.

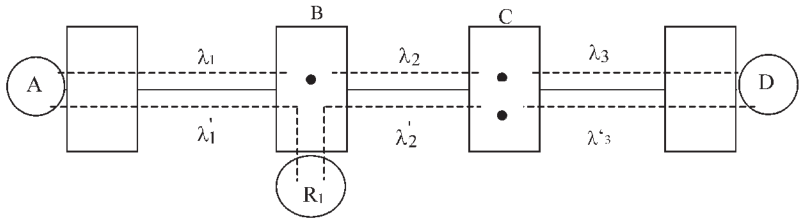

Figure (4): Model of Wavelength Concatenation to Form a Path Between Routers A and D.

Channel Identifier (OLCI). A table look-up at R1 allows the incoming Digital Containers to determine the next edge device to which the Digital Containers are to be forwarded to. Optionally, the outgoing wavelength is also indicated in the table.

In a preferred method, the wavelengths are allocated end-to-end between source-destination end device OXCs and routing of individual Digital Containers at intermediate edge devices is avoided. In the current implementation of the Digital Container, the OLCI field is not updated as the Digital Container travels through the network. However, the option of updating the contents of incoming OLCI and re-writing its contents at intermediate edge device is not excluded. A field in the Digital Container indicates whether the entire Digital Container is dedicated to a particular end user (addressed by the OLCI) or contains a number of packets (ATM/IP/Frame Relay, etc.) for end users at the same destination edge device. The format and types of digital containers are described in Section (5).

In order to establish a wavelength channel path from router/switch (A) in Figure (4) to router/switch (D), a Path Set up Request (PSR) message similar to Figure (5) is originated at OXC (A).

This message contains source OXC address, destination OXC address, and the set of wavelengths assigned at OXC (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 OXC or upon receiving an Internet IP packet destined for the destination access point (D). OXC (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 OXC. Upon receiving a PSR at OXC (B), either (a set of) unused wavelengths to a next OXC en-route to (D) are found (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 on 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) is populated with the incoming/outgoing wavelength information (e.g., first entry of Table (1)). This represents the case of an available wavelength λ_2 at OXC (B). When no unused wavelength is available at OXC (B), λ'_2 is shared with the traffic from router R_1, an item similar to the second entry in Table (1) is populated.

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), as well as on wavelength availability and QoS measures. Wavelength allocation process is discussed later. Since each 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 the 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 (4). Format of a PPSR message is shown in Figure (6). 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 is returned by OXC (C) to OXC (B) in the label. This message is subsequently forwarded to OXC (A). If the request is accepted, OXC (C) forwards its PPSR to the next OXC, in this case (D). Upon completion of the path set up between (A) and (D) an ac-

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

Figure (5): Path Set Up Request (PSR) Message.

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)

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

Figure (6): Pending Path Set up Request (PPSR) Message.

knowledgment is returned by (D) in an optical label to (A) via (C) and (B). When receiving the path set up acknowledgment, each OXC, 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 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.

5 Digital Container Format

Content of Digital Container is transparent to the OXC and the end devices. This is a major departure from the traditional internet packet switching and routing, but is similar (but not identical) to the Synchronous Optical NETwork (SONET) transport [6, 7].

In SONET a variety of mechanisms are provided for provisioning and maintenance as well as payload within the 125-microsecond frame. SONET does not provide a mechanism for routing at the cross-connects and/or switch/routers. Nor does it provide signaling for path setup between source/destination end devices. Furthermore, in order to extract the information from SONET, the payload is processed through embedded pointers in its path and section headers. With Digital Container transport, however, a signaling mechanism for path set up between end devices is devised, and for simplicity in packet processing, the entire payload is addressed to the same destination edge device, which may support several end users. Thus, no intermediate processing of the payload at OXCs or router/switches is required. Furthermore, we consider packet re-transmission and error recovery to be a rare event on an optical link. Most recovery techniques can be delegated to the end devices and end user applications, particularly in the case of multimedia.

Three types of Digital Containers are proposed: *dedicated Digital Container* to an end user, *shared Digital Container* which carries payload for several end users, and the *signaling Digital Container.* The signaling container is only used when a method of out-of-band signaling for path establishment is unavailable. The dedicated Digital Container is also referred to as a *free format Digital Container*, which carries information for a single end user. This information is not shared with other end users. Shared Digital Container carries information for end users of the same destination edge router. The Digital Container is shared in a statistical multiplexing manner. In the signaling Digital Container, the content is dedicated to all the end users at the destination edge router. Thus content is not read/modified at the intermediate edge devices. Containers are preferably of fixed size (such as 125 microseconds). Depending on the packet sizes at the source edge devices, a number of possibly heterogeneous packets can be combined into a Digital Container. Since packets are associated with end user applications in legacy systems, with their own error recovery and retransmission mechanisms, the transport method on optical links based on Digital Containers does not require a separate error recovery technique.

As shown in Figure 8b, when the Digital Container is dedicated to a particular end user, such as when it carries video bit stream, its identification field (OLCI) indicates address of the end user. This field is shown in Figure 2. The OLCI consists of 2 sub-fields: Source Edge Router Address (SERA), and the Destination Edge Router Address (DERA). As shown in Figure (7), a third field referred to as the Destination End User Address (DEUA) can also be used which is principally for the dedicated containers. For a dedicated Container the Payload Control Field (PCF) is set to 1 indicating that it only carries 1 "unit" of information for a specific end user. The "payload" format of the Digital Container in this case is free. When PCF is set to a value greater than 1, then this indicates that the Digital Container is allocated to multiple end users at the Edge Device (see Figure 8a). Depending on the container size, there can be unused portions of it that may not contain packet or end user information.

Packet boundary delineation and assessment of contents is the responsibility of the end user and is only minimally performed at the destination edge router (i.e., packet sorting and forwarding to the end user devices). A method of using destination end user address as a label has also been suggested, which precedes each packet or user information field. The destination edge device extracts the individual packets from the Digital Container and forwards them to the end users connected to it only based on the individual packet addresses. The Container boundary can be determined using the OLCI field. The OLCI and Digital Container size, in addition to other available synchronization information, can be used for network synchronization and clock recovery when necessary.

In cases where a packet is larger than the remaining size of a Container, it can overflow to a next Container. An overflow indication field called Overflow Field (OVF) is included.

Source Edge Router Address (SERA)	Destination Edge Router Address (DERA)	Destination End User Address (DEUA)	...

OLCI

Figure (7): Digital Container OLCI.

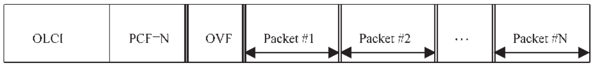

Figure (8a): Digital Container Format (PCF > 1).

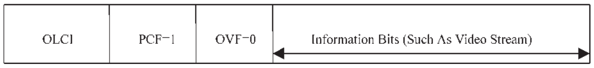

Figure (8b): Digital Container Format (PCF = 1).

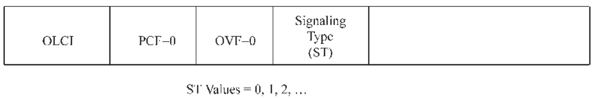

Figure (8c): Digital ContainerFormat with PCF = 0.

The signaling container is identified by the PCF field, in which case it is set to zero. The OVF field for this type is ordinarily set to zero also. In this case, an additional field called Signaling Type (ST) is also included (Figure (8c)). In addition to the optical network signaling for wavelength path setup through container signaling, end user applications and devices may utilize their own signaling technique, after a path between source and destination has been established. For example, using the existing optical network infrastructure, call set-up messages can be encapsulated in Containers for SS7 signaling exchange between the end devices (such as circuit switches at the source and destination OXCs).

In the following sections, the procedure for end-to-end optical wavelength setup between source-destination edge devices, and the process of logical channel establishment when Digital Containers are processed at intermediate edge devices is described. The latter is used when end-to-end optical wavelengths between source-destination edge devices are not available.

5.1 Addressing and edge device routing

Since packets within Containers have their own addresses, at the destination, individual packets are forwarded to the end user devices. End user devices are identified through the port to which the user device is connected, or a virtual address contained in the packet (as is the case with ATM cells). When the entire Container is dedicated to an end user, the address of the end user is indicated in the second part of the OLCI field, as shown in Figure 7 (DEUA). Initially when a container is generated at the source edge router, the DEUA field is set to the address of the final destination edge device. Alternatively, DEUA field can be set to the address of the edge router next to be visited in the path to the destination edge device. In the former case as the Container hops through the network, the DEUA field remains the same and is not modified. In the latter case as the Container arrives at the next edge device, its DEUA field is updated based on information at a routing table. The former method requires less processing at intermediate edge devices and may be preferred for certain applications/services. In the case where the Container is shared among multiple end users, the DEUA field remains unused. A field next to the OLCI, called Packet Counter Field (PCF), indicates the number of packets contained in the Digital Container. When the entire Container is allocated to the same end user, PCF field is set to 1 and the Digital Container DEUA is set to the address of the end user device. Details of edge device processing of a Digital Container are not presented here.

The overflow (OVF) field is used as follows:

OVF = 0 For signaling (PCF=0) and free format (PCF=1) Digital Containers.

OVF = 1 When PCF > 1 and the Digital Container contains the first part of an incomplete packet along with other packets.

OVF = 2 When PCF ≥ 1 and the container contains the latter portion of an incomplete packet. If a packet size exceeds the size of two consecutive Containers, then the one containing the first portion of packet sets PCF > 1 and OVF = 1, the next Container sets PCF = 1 and OVF = 2. The third Container will have PCF > 1 and OVF = 2.

In order to prevent the last part of an incomplete packet carried with the first part of another incomplete packet in the same Container, the container that carries the last part of an incomplete packet is released without a new packet included in it. Dedicated containers have PCF = 1 and OVF = 0. Packets are loaded into the Containers at the source edge device and are extracted at the destination edge device. In another implementation, a Container Counter (CC) field is included in the header for sequentially numbering the dedicated containers addressed to an end user.

5.2 Handling heterogeneous traffic

DESTINATION EDGE DEVICE At the destination edge device, Containers destined for the end users connected to it are forwarded to the end user ports. Upon receiving a Digital Container with PCF > 1, the edge device takes the responsibility of removing the individual packets from the Digital Container and forwarding them to the end user ports on the edge device.

In order to properly identify individual packets, at the source edge device where packets are loaded, a unique byte (such as a flag in the form '01111110') can be added between each two consecutive packets. At the destination edge device, as the unique pattern is encountered, it is assumed to be the boundary between two packets and each one is sent to the appropriate processor for handling. For example, the process of identification for two types of packets, ATM and IP, might be as follows: One copy is submitted to the ATM cell processor. In this case the process of delineating the ATM cell is performed as it is done in an ATM switch or destination device. If a packet is not recognized by any of the processes which identify incoming packets, then two cases are considered:

1. A packet of a type unrecognizable by the destination edge device is transmitted.
2. A packet or combination of packets were corrupted during Container transmission or processing and are not recognized by the destination edge devices.

In either case, a decision is made as to either request retransmission of the entire Container or portions of it or to discard the contents entirely. Such issues will be handled by the exception routine at the edge device.

Among other candidates for which processing at the destination edge device is performed are: SONET frames, packets from wireless end points, and TDM samples for voice or other applications. The process (hardware/software) which handles the content is assumed to be the responsibility of the edge device. Furthermore, all such processes occur in parallel in order to minimize the task of processing packets at the destination. Packet ordering, and handling of network transport level tasks is the responsibility of the end user.

SOURCE EDGE DEVICE At source edge device, packets are loaded into Containers destined for a given destination edge device. As packets appear at the edge device input ports, the edge device determines whether an end-to-end wavelength is available. If so, the packet is included in the outgoing Digital Containers and handed to the output port at the edge device. Incoming packets may be included in a Digital Container on a first-come, first-served basis (in which no priority is defined), or precedence can be given to the higher priority packets. A unique bit pattern (such as '01111110' used as the HDLC flag) is inserted between two consecutive packets for delineation. As packets are assigned to the different Containers, the Digital Container is released at every frame interval whether it is full or not. If a packet size is such that portion of it is included in one Container and the remainder in the next Container, it is the responsibility of the destination edge device and user application to reassemble them. In this case, the Container in which the first part of the incomplete packet is loaded into has its OVF set to 1. The OVF is set to 2 for the subsequent Container(s) carrying the remainder of the packet. Ordinarily when free format (dedicated) Digital Container is used, or there is no packet overflow out of, or into a Digital Container, OVF is set to zero.

Voice traffic from incoming TDM trunks are loaded onto the Digital Containers either as packet (after conversion at the source edge device, such as in the form of Voice over IP, or Voice over ATM, etc.), or directly as TDM voice samples. The former case is handled as a regular packet. The latter is handled in a free format Digital Container (PCF = 1). In the latter mode, handling of DS1, DS3, and various SONET rates is expected.

5.3 Quality of service

During connection establishment, wavelengths at different cross-connects are concatenated so that an end-to-end connectivity between source and destination edge routers can be maintained. Thus, ordinarily there is no buffering at the intermediate edge devices. On occasions where sufficient bandwidth may not be available (all Containers are full) and/or no end-to-end wavelengths are available between source and destination edge devices, Containers are stored and forwarded at the intermediate edge routers. This requires conversion from optics to electronics in order to determine the OLCI and the destination edge device. It is expected that with WDM and availability of several wavelengths on a fiber strand and particularly with proper network engineering it is possible to find dedicated end-to-end wavelengths (or a concatenation of wavelengths) between source and destination edge devices [9, 10]. The process of effectively determining the available dedicated end-to-end wavelengths or appropriate concatenation of wavelengths is part of ongoing research.

6 Wavelength Allocation

The traffic measurement and wavelength assignment model is shown in Figure (9). User buffers are periodically observed. Based on observations and subsequent measurements, a number of wavelengths (n), $0 \leq n \leq N$ 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 unused at the OXCs. The wavelength assignment decision at an OXC can be made independently (autonomous) or in conjunction with other nodes in the network (integrated). OXC on a wavelength path can decide to release wavelengths as indicated by their measurement observation and an overall network cost/performance objective.

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 [11]:

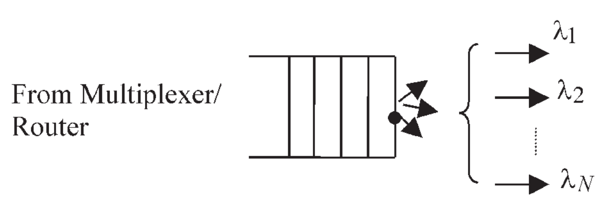

Figure (9): Wavelength Assignment Model.

$$
p_M = \begin{cases} p_0 \dfrac{(n\rho)^M}{M!} & \textit{for}\ M \leq n \\ \\ p_0 \dfrac{\rho^M n^n}{n!} & \textit{for}\ M \geq n \end{cases}
$$

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 $p_M \leq p^*$. Other QoS measures such as delay may also be used.

7 Conclusions

In summary, this paper presents a new mechanism in which heterogeneous packet and non-packet information can be transported in *Digital Containers* of preferably fixed size over optical links. Each Digital Container carries an identifier called the *Optical Logical Channel Identification (OLCI)* field, which represents the source and destination address of the edge devices to which the Digital Container is addressed. Each Container can carry multiple heterogeneous packets and/or non-packets addressed to the end users at the same destination edge device.

Using this approach, with the exception of occasional routing at the intermediate edge devices, which with proper design and engineering of the optical network can be avoided, and for extracting information from the Containers upon receipt at the destination edge devices, the processor intensive task of individual packet processing at the intermediate edge devices is avoided. Container processing at the edge device is limited to the process of delineation and possibly routing along with forwarding units of information within the Container to the individual end devices.

Theoretical consideration of this effort has concluded that the Digital Containers would be an ideal mechanism by which to provide heterogeneous traffic transport over optical networks, while providing dynamic support for new service provisioning. Scalability, without service degradation, for both services and users served seems assured. While all-optical networks are expected to be the norm in the future, we must be able to provide new services in today's hybrid network environment of electronic and optical network infrastructures. Current research efforts include gathering network performance data for the multimedia service delivery using this methodology.

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