Light-trails: A Novel Conceptual Framework for Conducting Optical Communications

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Abstract: We propose a solution for implementing a conceptual framework for catering to dynamic traffic in the optical domain. The solution called Light-trails coalesces a hardware platform and software protocol for realizing efficient optical communications from IP bursts to lightpaths. It is a paradigm shift from conventional optical communication modes, in supporting amongst others, very fast lightpath setup and tear down-burst communication and presenting a novel approach to bandwidth management and provisioning for dynamically configurable networks and a first solution to support multicasting, a key element for many of the central motivator services for optical capacity needs. Contrary to existing proposals for IP type communication, bursts etc., it also presents the first practically implementable solution to enable burst transport with mature and off-the-shelf technology and eased switching requirements

I   INTRODUCTION

Optical networks today have graduated into fine circuit based solutions. These all optical circuits each on a separate wavelength called lightpaths [1] represent the first major method for optical communication. The granularity provided between a source and destination node, is that of a complete wavelength. However, Internet traffic today is mostly IP centric. This traffic is characterized by its burstiness and provokes the need for bandwidth on demand kind of applications. It is often observed that the bandwidth requirement in today's network's is often dynamically varying and does not justify the need for allocating entire wavelengths for such bursty IP centric communication. There is no optical solution which utilizes efficiently the bandwidth offered by a single wavelength between multiple users. Opto-electronic solutions such as Gigabit Ethernet and Resilient Packet Rings (RPR) have been proposed for solving this sub-lambda issue of providing bandwidth on demand to end-users. Gigabit Ethernet is an end-to-end solution on a lightpath creating an information highway between a source and destination node. Gigabit Ethernet solution does not solve the issue for providing sub-lambda type traffic between a stream of users. It only provides a connection suitable for IP centric traffic between end-users, creating data flow that is oblivious to the intermediate nodes. RPR on the other hand provides for a solution that allows a stream of consecutive nodes to communicate in a downstream direction by effectively utilizing the capacity of an optical link. It does so by dropping and electronically processing the optical signal at each node and catering to local traffic on its way to the destination. However, RPR has some restrictions. The optical signal is dropped at every node, creating a need for high cost and high performance electronics at each network element. Further RPR is a slotted solution, creating issues of

synchronization leading to utilization problems and hence is not a perfect match for the burstiness of IP traffic. Moreover current versions of RPR have a speed restriction of 2.5 Gbps.

Optical burst switching (OBS) is a recent paradigm proposed for creating burst level communication at the optical layer. OBS in its native form is an excellent solution for providing a method for IP centric communication. However, for implementing such a solution, there exists a mismatch in the technology offered today, and that required by native OBS. For provisioning networks on a per-burst level there is an absolute need for high speed switches, leading to very low setup times, to create a practically allowable ratio of burst length to setup time. Lastly, there is an absence of a solution allowing lightpath or burst multicasting, a centerpiece for most of the "bandwidth killer applications" as envisioned today. The proposed Light-trail architecture [10] comes to resolve all these problems, using mature technology and an effective novel protocol.

II   LIGHT-TRAILS

To alleviate the problems in sustaining IP centric communication at the optical layer we propose the concept of light-trails. This concept consists of an architecture and a protocol that allows opening of an optical path between any chosen source and destination nodes, while allowing optical communication (access) to all the nodes en route to the destination. With the principle of access to the all optical path at any node, a light-trail offers to provide full uni-directional optical connectivity, while avoiding the need for dynamic, burst type, optical paths establishment.

A light-trail can provide within a single trail, $\binom{t}{2}$ number of connections without any need for optical switch reconfiguration. A system having light-trails architecture eliminates the need for fast optical switching at each node, yet permits fast provisioning for dynamic traffic needs.

In order to demonstrate the light-trails concept in its simplest form consider a 2-fiber ring of N nodes, with each fiber uni-directional. An arc of the ring comprising 't' nodes is a light-trail if there exists some wavelength λ_i such that an optical path is opened on λ_i and this path is

accessible to all the 't' nodes in the light-trail. In a light-trail $(N_1, ... N_t)$ node N_1, the first node in the light-trail is called the *convener node*, while the last node in the light-trail, node N_t is called the *end node*. In other words, a light-trail can be viewed as an optical bus between the convener and end nodes, with the characteristic that intermediate nodes can also access this bus, providing a method for uni-directional communication.

Shown in Fig. 1 is the proposed node configuration that enables the light-trails concept. For each of the two uni-directional fibers, is a full de-multiplex section that de-multiplexes a composite DWDM signal and feeds individual channels to a local access section. The local access section for each wavelength (channel), (Fig. 2) consists of two passive couplers separated by an optical shutter. The first coupler is called the drop coupler (DC) (for dropping the signal) while the second coupler is called the add-coupler (AC) (for adding a local signal). The optical shutter is a fast ON/OFF optical switch typically demonstrated currently by Mach Zehneder Interferometer technology on Lithium Niobate substrates [3]. Despite dynamically varying traffic demands, the ON/OFF switches need not be very fast, as a light-trail of 't' nodes

readily supports connection between $\begin{pmatrix} t \\ 2 \end{pmatrix}$ different

combinations of sources and destinations (within the light-trail) without any requirement for ON/OFF switching. If the optical shutter separating the two couplers is ON then the system represents a drop and continue function. On the other hand if the optical shutter is OFF then we can have wavelength reuse by virtue of spatial diversity. The network elements which demonstrate light-trails are built from available on-the-shelf technology.
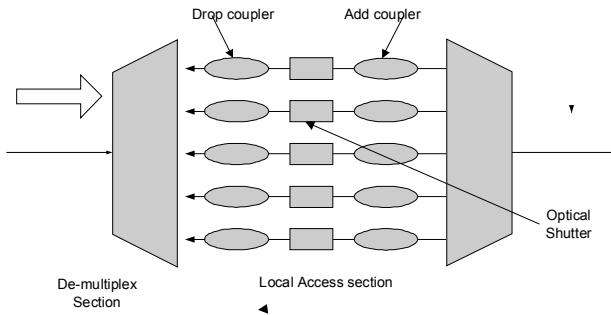

Fig. 1 Shows the uni-directional configuration of nodes for light-trails.

A light-trail is set up between two nodes, by configuring the optical shutters on the desired wavelength at the convener and end node (in the OFF position) as well as by configuring the optical shutters (in the ON position) at each of the intermediate nodes. Within a light-trail we assume communication to be unidirectional in the direction of convener node to end node.

In other words through this quintessence of light-trails we have demonstrated the method for optical multicasting.
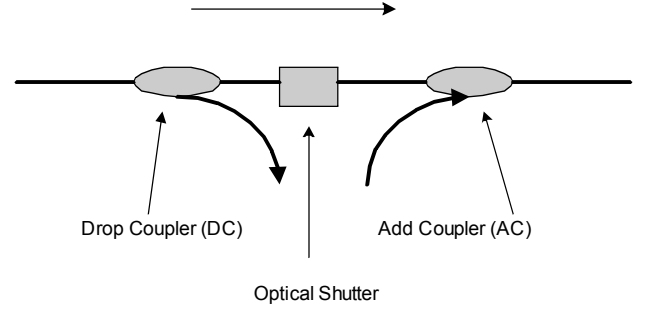

Fig. 2. Local access section of the Light-trail architecture. The top arrow represents the direction of communication.
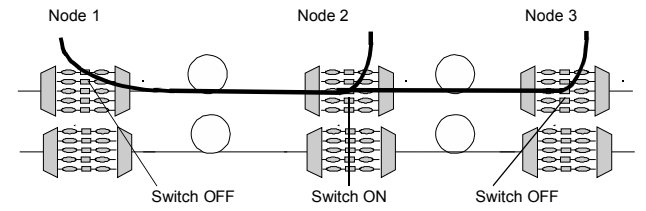

Fig. 3. Three nodes in a light-trail architecture.

For a bi-directional system (2-fiber optical ring) shown in Fig. 3 is the proposed configuration of the nodes that support light-trails. Note here the multicast nature of traffic from node 1 to nodes 2 and 3.

The Protocol

To establish light-trails and to provide optical connection establishments within light-trails we define the following protocol. The protocol has to establish light-trails and provide a signaling mechanism for ensuring conflict free communication in the opened optical path within a light-trail. For setting up light-trails as well as signaling purposes within light-trails we assume there exists an out of band communication channel called optical service channel (OSC). The OSC is dropped and processed at each node. The OSC also carries information about the resource (wavelength) availability in each link in the network as well as the light-trail table giving the status of the light-trails in the network.

The OSC is used to send control packets which carry information about the data that is to be sent on the light-trail. Control packets are assumed to be ahead of the data. This offset between the control packets and arriving data (lightpath/bursts) ensures conflict free communication. The offset time is a function of propagation delay from ingress to egress node as well as the control packet processing time at each node.

We define five kinds of control packets that are sent through the OSC for facilitating communication in light-trails:

Setup packets (SP): These are control packet that are used to set up light-trails initially. They contain the ingress, egress node information as well as the wavelength on which the light-trail is desired to be established. Setup packets are deciphered at each intermediate node en route to the destination and the intermediate nodes automatically (without any signaling are now part of this light-trail.

Communication control packets (CCP): These are the most abundantly used signaling packets used in the light-trails system. They are used to set up connections within a light-trail. CCPs are small in length (to justify their numerical strength) and carry information such as ingress node/egress node(s), light-trail number (a unique number which identifies the light-trail based on convener node, end node and wavelength used) and possible duration of desired connection.

Dimensioning packets (DP): These are packets used by the convener node to dimension light-trails for facilitating good utilization of the light-trails by allowing new nodes to be members, or eliminating nodes that are no longer active participants in the light-trail

Global Broadcast Packets (GBP): At regular intervals, on the OSC each light-trail sends GBPs throughout the network apprising all the nodes (and hence EMS's) of existence of themselves, their member nodes and their heuristics.

ACK packets: These are the most seldom used packets in light-trails. They are used when a light-trail is set up. They are sent by the end node and ratified by intermediate nodes to the convener node, indicating the acceptance of the request to set up a light-trail.

Light-trail database: The network management system (NMS) for light-trails contains a light-trails database: which is a plethora of information regarding the present light-trails in the network. This database is updated by GBPs and the database is assumed to be available to each node either locally or through a request scheme.

Local communication database: This is a single time sensitive pointer at each node, indicating whether the light-trail is occupied or not at that point through the node's local multiplex section. (Determines if data is flowing through the trail).

A. Setting up Light-trails:

For creating a light-trail between nodes N_1 and N_t assume N_t is in the downstream of N_1. Node N_1 selects a wavelength say λ_t and finds out through the light-trails database the availability of λ_t over all the links through to N_t. Upon availability of the wavelength in the desired path, node N_1 sends a control packet (SP) through the OSC requesting opening of this optical connection to N_t through the intermediate nodes $N_2, N_3, ... N_{t-1}$. Node N_t upon recieving the SP from N_1 replies through the OSC in the fiber (in the other direction) with an ACK. This ACK is validated by intermediate nodes also. If node N_t cannot allow the light-trail to be established, then it indicates with a NACK (a flag within the ACK packet). Nodes $N_2, N_3, ... N_{t-1}$ upon receiving the control packet (SP), switch their optical shutters on the selected wavelength in ON position while nodes N_1 and N_t keep the shutter in OFF position. We have created a

light-trail whose member nodes are $N_1, N_2, ... N_t$ such that there can be downstream communication between them.

B. Communication in Light-trails and setting up optical connections

If node N_j desires to communicate with node N_k, such that both are elements of a light-trail, and node N_k is downstream of node N_j, then communication can happen in the following way: To avoid conflict of usage by upstream nodes the initiating node N_j determines availability of the path by examining the local communication database, and hence finds out the occupancy of the light-trail at its own port (multiplex section). If no upstream node is using this light-trail for communication then it can initiate communication to node N_k by sending a control packet (CCP) of the data. Nodes $N_{j+1}, ... N_{k-1}, ...N_t$ are also now aware of this communication. Note that, after sending a control packet, node N_j does not have to care for time to configure switches or have to wait for any acknowledgements. As long as it does not obstruct communication from upstream nodes, it is guaranteed communication to downstream nodes. The destination node N_k detects the data through a transponder. Similarly if there are multiple destination nodes (as in case of multicasting) all the destination nodes can detect the data as a percent of the optical power is split through the multiplex section of each node locally.

C. Re-transmissions and Collision Avoidance:

It is easy to see that node N_j which is upstream of node N_q can access the optical path, even when N_q is transmitting information. If such does happen, then N_j requests for opening of an optical connection in the light-trail. Node N_q upon realizing the possibility of conflict holds back its data and allows the data from node N_j to pass through. In this event, the downstream node (N_q) may either send its data after the upstream node (N_j) has finished its data transmission or send the data on another light-trail. However for delay-sensitive applications, it may always not be possible to inhibit the local transmission. In that case, the downstream node (N_q) may switch its optical shutter (for that light-trail) in the OFF position and collect the data from the upstream node (N_j) (through its drop coupler). It may then either buffer this data or send it on another light-trail usually involving O-E-O from the initial light-trail to the new light-trail. In this process of re-transmission (either over time or over different light-trail) the incumbent node does not restraint its data flow into the light-trail.

D. Dimensioning light-trails: Expanding and Contracting

Light-trails are proposed to cater to bursty IP centric traffic demands. On certain occasions light-trails may require dimensioning (expanding or contracting) to meet certain kinds of applications. For example, if a particular optical connection grabs the bandwidth in the light-trail for a long time, making some downstream nodes oblivious spectators, then these nodes are wasting their ports and lowering possibility of wavelength reuse. Such cases

warrantee for pruning light-trails effectively. Similarly for efficient utilization of a under-utilized trail, nodes may be added to the trail as desired.

A node N_a upstream of node N_1 and not part of a trail $LT_1=\{ N_1, N_2, ..., N_t \}$, may request communication to a node in LT_1. The convener node by virtue of its dominant status may allow N_a to join the trail. It does so, it shifts the convener status to node N_a and the new trail $LT_{NEW}= \{N_a, N_{a+1}, ... N_1, ...N_t \}$ is formed and this information is broadcast through the network by GBP. The act of expanding a light-trail is similar to setting up a light-trail though we use dimensioning packets (DP) as control mechanisms for this purpose.

Similarly, over a period of time, if the end node, realizes that the end-node or a consecutive group of nodes including the end-node are not being recipients of information, it may in a reverse control packet (DP) to the convener request to relive itself (or the group) from the light-trail. In that case, the first node from the end node in the reverse direction which is still an active member of the light-trail now becomes the end-node of the light-trail and configures its shutter accordingly. Over large time periods light-trails can expand and contract depending on demands of traffic. On re-configuring a light-trail (expanding or contracting) the new light-trail information is broadcast throughout the entire network to facilitate nodes to learn about pre-set optical paths that can guarantee seamless communication of lightpaths as well as bursts.

III LIGHT-TRAIL EVALUATION

A. Provisioning time in Light-trails:

For IP centric burst type of communication on top of the advantages of light-trails, an additional consideration is the blocking probability due to the distributed nature of the system. Burst transport algorithms due to the constraints on switching speed, have relied on pre-allocation of resources to create an end-to-end optical path. JET[2] is a leading burst transport algorithm to facilitate pre-allocation of resources ahead in time and using an out of band approach. In light-trails because the optical connection does not need to be without delay penalty, something not available in conventional burst transport, because this would take prohibitive time as compared to the length of the burst. Shown in Fig. 5 is the provisioning time for light-trails and that for JET under similar considerations. For JET we assume the provisioning time to be a function of the hop length, switch configuration time and control packet processing time. Likewise for light-trails we assume only processing time of the control packet and the propagation delay. Optical bursts are generated by multiplexing different classes of traffic (namely voice and data). In the simulation study we assume Poisson and Pareto distributions for burst aggregation. Scheduling policy for bursts that are delay sensitive is shown in [5]. Line rate is assumed 1Gbps and bursts are typically 22 ms in length (average). Propagation delays are considered to be for 20 km links to emulate a typical metro area. Control packets are 20 kb

in length and we assume a 1 GHz. processor at each node that analyzes the dropped control packets. For rings (of sizes varying from 10~16 nodes) we also observe that the appropriate speed of control channel required is 51 Mb/s to avoid collision and to guarantee control packets to nodes as desired with a probability 0.999. We see a significant benefit in the provisioning times for light-trail communication. Quantitatively we see that even if a fast switch configuration time of 0. 1 ms is assumed for JET we still see a 61% decrease in provisioning time for single connection using light-trails. If we further assume that the light-trail is already set up and burst transport is the act of communication within a light-trail we observe further results (not quoted here) such that there is on an average an order of two advantage in provisioning as compared to the provisioning using JET. This validates the light-trails architecture as a method for providing high bandwidth on demand to end-users on a real time basis.
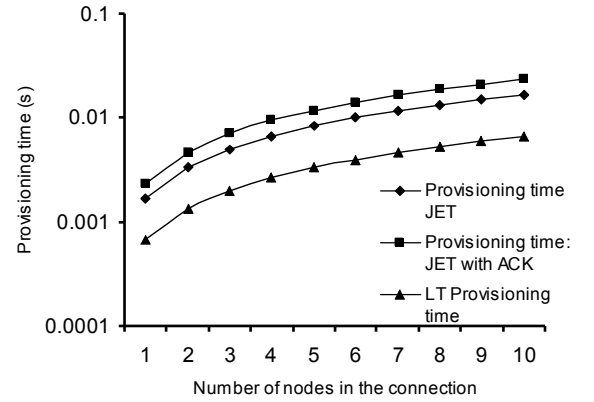

Fig.4 Comparison of provisioning times for conventional burst based communication algorithm JET and for Light-trails.

A. Benefit in number of wavelengths required:

A light-trails solution can cater very well to bursty IP centric traffic. As mentioned earlier current solutions which are proposed for IP centric traffic are RPR and Gigabit Ethernet. We conducted a simulation study to observe benefit of light-trails in terms of wavelength savings as compared to similar implementation using RPR and Gigabit Ethernet. We conduct a simulation of a 2-fiber optical ring, with number of nodes varying from 10~16. The number of wavelengths are assumed to be 40 in each fiber. We assume IP type bursty traffic in the system simulated by a Pareto distribution with Hurst parameter 0.9. Packets are aggregated at the node and are transmitted through the network. We measure the performance of RPR and Gigabit Ethernet and compare it to light-trails solution. For an RPR solution we assume fixed sized slots being propagated throughout the ring. A node on finding a slot empty may insert data proportional to the slot-size. In Gigabit Ethernet, for the same traffic arrival patterns we create end-to-end connections. We assume that the connection durations are exponentially distributed (also

same in RPR and light-trails). Unlike RPR which requires a single wavelength for communication between a group of nodes, we form a set of different connections on different wavelengths. In Fig. 5 we measure the number of wavelengths required against the utilization of the system. We calculate utilization as a function of burstiness in a linear way. Utilization is defined as the percentage of occupancy of the network link for a given blocking probability. In the simulation we calculate the number of wavelengths required for RPR, Gigabit Ethernet and light-trails at blocking probability 0.001. We observe that for every optical connection in a network, using Gigabit Ethernet pipes, we need one wavelength (lightpath) each. On the other hand we need much lesser number of wavelengths for RPR and light-trails. The number of wavelengths required for light-trails is lesser than for RPR showing a better performance of light-trails as compared to RPR for IP centric traffic. The degradation in RPR is because it is a slotted system, and slots are not created on a per demand basis. This means that slots are created without knowledge of whether they are required or not. In contrast for light-trails bandwidth is provisioned as required. This leads to tight bound on utilization. In Fig. 5 we observe the wavelength requirements the validation of research being done to migrate from circuit based (GigE) networks to packet based (light-trails) networks. In this regard we see light-trails as a solution with an architecture that is very conventional, yet a performance which facilitates packet based communication paving the way for an all IP communication core.
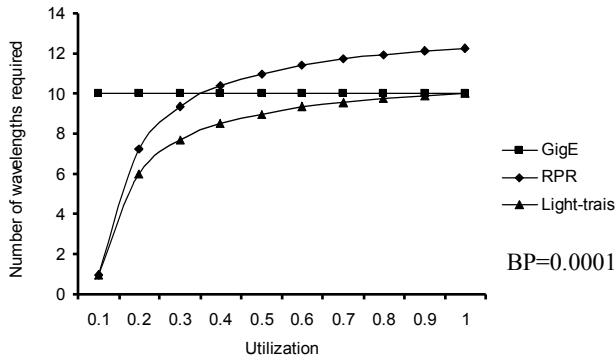

Fig. 5 Number of wavelengths required to implement RPR, Gigabit Ethernet and Light-trails as a function of network utilization for a burst admission probability of 0.001.

C. Burst blocking

Burst admission is an important issue for sustaining good quality and dynamic traffic. Burst blocking probability gives an idea of system performance for multimedia and IP centric networks. In Fig. 6 we compare burst blocking probability of light-trails solution to that of JET based solution. In JET [2], we assume no acknowledgements back to the ingress node for reservation of resources. Further a burst may be dropped if either there is conflict at one of the intermediate nodes for destination ports, or if there is overlap of bursts. Techniques such as burst segmentation have been proposed for minimizing

blocking probability in JET and found to be inadequate in the optical domain. Hence, we consider blocking as dropping of bursts at intermediate nodes for avoidance of possible conflicts. In contrast in light-trails blocking of bursts is the inability of ingress nodes to send bursts, into the light-trail due to time-conflict of the resource (channel) by upstream nodes. We note that once a burst is inserted into the light-trail by the ingress node, it is guaranteed to reach the destination. In Fig. 6. we show the blocking probability of JET and light-trails for different loads. Load is measured in Erlangs to emulate the stochastic behavior of the system. Blocking probability is calculated as in [8]. We observe from the onset that blocking probability of a burst in light-trail is lesser than that using JET. In the simulation model we assumed ring of 10~16 nodes and 40 wavelengths in each of the 2-uni-directional fibers. Burst aggregation, scheduling and lengths were as shown in previous sub-section. At 50 % load we observe 31.25 % drop in blocking probability for light-trails as compared to JET under similar conditions.
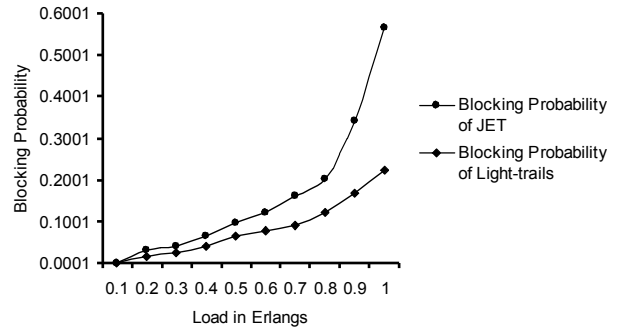

Fig. 6. Blocking probability of Light-trails and JET

IV   CONCLUSION

In this paper we have proposed the concept of light-trails which creates a framework for all IP centric communication in the optical domain. By creating multi-point accessible information highways we have shown that the basic limitation of optical multicasting in conventional optical communication through lightpaths can be circumvented by light-trails and also provides for a framework which eases the bounds on the ability of a network to facilitate dynamic traffic variations. By virtue of its architecture light-trails are also a natural candidate for burst transport, thereby relaxing the importance on fast switching which has so far prevented the implementation of burst communication. Light-trails represent a first method to allow fast provisioning in optical networks while using very mature and conventional technology.

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