Routing and Wavelength Assignment and Survivability of Optical Channels in Ultra-high Speed IP over DWDM Networks Under Constraints of Residual Dispersion and Nonlinear Effects

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Summary
Ultra-high speed 10Gb/s and 40 Gb/s optical Ethernet and/or SONET transmission carrying multi-wavelength channels as well as IP over WDM are emerging as the next generation optical networking. Under this ultra-high speed transmission and networking, the dispersion effects due to linear chromatic dispersion effects are critical. This paper investigates the impacts of residual dispersion effects on optically multiplexed channels to be routed over terrestrial or metropolitan all-optical dense wavelength networks. We propose a routing algorithm that integrates the layers of the networks, the physical trans-mission layer, the network wavelength channel management layer and the routers for connecting and routing of wavelength channels over physical lightpaths which are under constraints of wavelength availability, transmission capacity of the lightpath and the dispersion effects over the routed hops. An algorithm, the Hop and Bandwidth Integrated Routing (HBIR), that integrates both the bandwidth availability and the routing hops of the light path, is proposed for routing of lightpaths in a layered graph model which is structured with a wavelength assigned for each layered with the logical and physical links, and an IP layer. The routing is determined by processing the physical links and the logical links in different layers of the model graph. Optical channels with bit rate of 2.5 Gb/s can be dynamically routed without much effects from the residual dispersion. However for channels of operating bit rate of 40 Gb/s under dispersion effects suffers a low survivability rate with a blocking probability significantly increased as compared with the case of no such constraints. These studies are also carried out for the optical networks which are under the effects of nonlinear self phase modulation.

Keywords: *integrated routing; IP over WDM networks; network traffic; wavelength links*, nonlinear effects, dispersion, All-optical networks.

1. Introduction

Traditionally, Ethernet traffics are transported over other technologies, most likely SONET/SDH via Ethernet interfaces. The Ethernet traffics are then converted to SDH frames under the time-division multiplexing protocol. This is uneconomical as the Ethernet protocol is limited by the SONET/SDH frames while Ethernet is a packet-based technology. The limiting scenarios of Ethernet photonic networks operating under different transport technologies can be outlined: (i) Line rates of high speed SONET/SDH are 2.5/10.7/43 Gbit/s including forward error correction. This is clearly a limitation of the envisioned ultra-high bit rate, 100 Gbit/s, Ethernet. Thus a mismatching of transport bit rates. Thus to support 100 Gbit/s Ethernet over SONET/SDH, multiplexing of a 100 Gbit/s signal is required resulting higher cost. (ii) Data traffics are increasing tremendously and the transport of both voice and data traffics are essential. SONET/SDH is a TDM technology and is originally intended (and optimized) for voice traffic, internet protocol in Ethernet transport are the simple and best for carrying both data and voice as a packet-based technology; and (iii) SONET/SDH is normally operating in a ring environment with protection technique. Since Ethernet more flexible to the protection and cost-effective, e.g., shared-path protection, Internet Protocol (IP) is considered as a popular network layer technology, the IP traffic is increasing and gradually replacing for many different kinds of protocols, especially in the standardized 10 Gb/s Ethernet. The capacity can then be further enhanced with the employment of dense wavelength division multiplexing (DWDM) technique. Optical fiber transmission technique has now reached advanced stage of ultra-high speed and ultra-long haul with 40 Gb/s and even 100 Gb/s synchronous digital hierarchy (SDH), or SONET or Ethernet. Thus transmitting IP data packets directly over WDM optical network, the IP over WDM technology, is considered to be important for optical networking.

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Next generation telecommunication network employing IP over optical networks is quickly emerging not only in the backbone but also in metro and access networks. Fiber optics has revolutionized the telecommunication networking technology by offering enormous network capacity to sustain the next generation Internet growth. IP provides the only convergence layer in a global and ubiquitous Internet. So integrating IP and WDM to transport IP traffic over WDM enabled optical networks efficiently and effectively is an urgent yet important task. However in the routing at the ultra-high speed network there are several remaining issues to be resolved: (i) routing of wavelength with minimum blocking; (ii) mitigation of impairment due to dispersion (chromatic and polarization mode) and nonlinear effects; (iii) employment of advanced modulation formats for effective transmission to combat the limits of these impairments; (iv) all optical generation and wavelength conversion for passive automatic optical routing.

IP over DWDM can be modeled by either layer graph or peer linkage models. The link state information, routing and signaling protocol in IP layer is independent of those of WDM layer. In layer model the IP and WDM layers are related relate to each other as the client-server model, with IP layer being the client of WDM layer. IP routers send lightpath establishment or release requests to WDM layer via User Network Interfaces (UNI). In *peer model*, a uniform control plane is used for both IP and WDM layers, IP and WDM layers relate to each other in a peer-to-peer relationship. The link state information, routing and signaling protocol are shared between both layers. An *augmented model* combines both overlay and peer models. In order for all these models to operate effectively an ultra-fast photonic router is necessary. We thus propose an all-optical router in this paper. An algorithm, the Hop and Bandwidth Integrated Routing (HBIR), is proposed for all-optical routing of lightpaths in the peer model of the IP over WDM networks.

In DWDM the bit rate is now commonly operational at 10 Gb/s or higher. At these ultra-high speeds the pulse broadening of signals in single mode optical fiber is due to the dispersion effects which are contributed by the chromatic dispersion, nonlinear phase effects and polarization mode dispersion of the fundamental mode field propagating through fibers. These effects are worst due to their accumulation when the optical signals have to be traveling across different hops in metro networks. The dispersion effects are due to the different propagation velocities of the spectral components of modulated optical signals due to the waveguide and material properties. These dispersion effects become very critical when the bit rates reach above 10 Gb/s which is the standard Ethernet for next generation networks.

In this paper we model the routing traffics of IP over D-WDM (dense WDM) under these constraints with algorithms based on the layer graph technique and the shortest path selection. With the issues of routing and assignment of wavelength channels over the paths of all optical networks, especially the 10Gb/s and 100 Gb/s Ethernet networks. Whenever the signals are too dispersive then 3R optical regeneration must be activated. Recently the issues of transmission constraints have been rigorously address in Ref [1(a)]. However under the optical network infrastructure with several million of kms of standard single mode optical fibers (SSMF) or even advanced optical fibers, e.g. non-zero dispersion shifted fiber – NZDSF, at the transmission rate 100 Gb/s the residual dispersion effects are critical. Furthermore the nature of different hops of the data pulse sequence makes the dispersion effects variable from one light path to the others.

Furthermore the nonlinear Kerr or self phase modulation effects [17] play a significant role in the distortion of optical channels operating at high speed, particularly at 10 Gb/s and above. We thus report the survivability via the blocking probability of the channels in an optical network using standard single mode fibers and receiver sensitivity at appropriate bit rate.

This paper is thus organized as follows: Section 2 gives a brief scenario of the all-optical networks which we consider and model our traffic engineering problems for ultra-high speed Internet networks and the routing technology that enable ultra-fast all-optical cross connecting of wavelength channels. Section 3 develops the routing algorithms for routing based on layered graph representing the physical networks and simulation results of the traffic performance in term of blocking probability versus the traffic loads. Finally conclusions and some aspects of future works are given.

2. DWDM Networks and Ultra-high Speed Ethernet

2.1 General all-optical network structures

In IP over WDM networks, Optical Cross-Connects (OXCs) is connected together by optical fibers which form a wavelength router optical layer [1(b)], IP routers are attached with OXCs through optical transceivers. The optical layer provides lightpaths for transmission of information data between IP routers. Each lightpath uses the same wavelengths on the whole of optical fiber connections that they pass for OXCs without wavelength conversion, the *wavelength continuity constraint,* the number of hops forms a variable transmission distance of a channel from the source to the sinks of the networks, the *dispersion constraints,* . Different from OXCs, IP routers process data streams electronically with the support of

Multiprotocol Label Switching technology (MPLS). Through transceivers, IP traffic can be transmitted over light-paths by Label Switch Paths (LSPs). When one lightpath is not used by any LSP, it is released and all wavelengths that are used for that lightpath are recovered. Figure 1 shows an example of such IP/WDM networks in which there are several optical cross connects (OXC).The structures of the OXC are shown in Figure 2 in which the optical amplifier and wavelength converters are used to provide very fast routing to assigned wavelength output ports of the array wave guide demultiplexers. Under this network structure the routing of lightpaths can be assumed to be instantaneous and no optical buffers would be required. Three models are proposed for IP over WDM networks: *overlay model*, *peer model* and *augmented model*. These models differ by control plane and management plane of IP layer and WDM layer [1], [2]. In the *overlay model*, the control and management plane of two layers are virtually separate. The link state information, routing and signaling protocol in IP layer is independent of those of WDM layer. IP and WDM layers relate to each other as the client-server model, with IP layer being the client of WDM layer. IP routers send lightpath establishment or release requests to WDM layer via User Network Interfaces (UNI). In *peer model*, a uniform control plane is used for both IP and WDM layers, IP and WDM layers relate to each other in a peer-to-peer relationship. The link state information, routing and signaling protocol are shared between both layers. An *augmented model* combines both overlay and peer models.

To transmit of IP traffic over WDM optical networks effectively, optimizing the routing mechanisms is necessary that depends on network models. In this paper, the routing mechanism in IP over WDM networks is proposed using *peer model*. Further an integrated routing algorithm termed as *HBIR (Hop and Bandwidth Integrated Routing)* to achieve an improvement of the blocking probability is also proposed. The objective of HBIR is minimizing the blocking probability of connection establishment requests in the networks. To solve this problem, we model IP/WDM network into layered graph [3], and solve the problem on this platform. The next sections of paper are organized as follows: Section 2.2 analyzes routing mechanisms in IP/WDM network and presents simulation results. Section 2.3, the method of modeling IP/WDM networks into layered graph is described. The HBIR algorithm is then demonstrated in Section 2.4 under the scenarios of wavelength routing and bandwidth allocations. The simulation results and routing performance with the blocking probability against traffic loads for both cases are given in the Section 3.

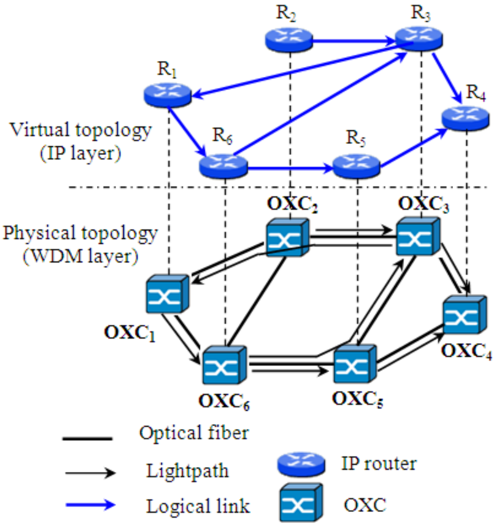


Figure 1 A typical structure of IP over WDM network for 10G and 100G Ethernet with OXC connecting all nodes and add/drop sites as shown in Figure 2.

2.2 Routing of IP over DWDM all-optical Networks

There are two kinds of routing mechanism used in the IP over WDM networks. That is *lightpaths routing* by algorithms of RWA (*Routing and Wavelength Assignment*) and *IP traffic routing over that lightpaths* by routing protocols of IP layer. The connection establishment request in IP/WDM network can be routed by sequential routing approach (SRA) or integrated routing approach (IRA) [4]. With SRA, the request is routed on the existing lightpaths first, i.e. routed on the logical topology of the IP layer. If it is not successful, new lightpaths are then established on the physical topology of WDM optical layer. If the establishment of new lightpaths is not successful, then this request is refused.

With IRA, the logical and physical links is concurrently considered during the selection of route for request. Based on *cost function* of links, the routing algorithm determines whether to pass a connection request on the logical links (existing lightpaths), physical links (establish new lightpaths) or both logical links and physical links.

The wavelength routing can be extremely fast on the photonic layer with the assistance of a wavelength router which consists of optical wavelength converter in the semiconductor optical amplifier (SOA) with control signal setting up the routing from the RWA plane. The micro electro-mechanical switch (MEMS) is then set up under the control of the network management layer well before the coming wavelength, switches the wavelength to a designated output port as shown in Figure 2. To the best of our knowledge this proposed wavelength router is presented here for the first time. The demultiplexer, usually a bank of array waveguides (AWGs) separate and assign wavelength channels to specific output ports of the demultiplexer. Thus a wavelength converter is used to convert a wavelength channel to a specific wavelength port that the network wishes to route to a specific path. Therefore, the wavelength router proposed here would significantly improve the throughput of the traffic and the RWA can be assumed to be in the least traffic congestion due to hard wired problems. However the residual dispersion and dispersion due to the difference of the group velocity of the polarized modes of the fiber remains a major obstacle to be resolved and not considered in this paper. Figure 3 illustrates the ORA and IRA. It is assumed that there is a connection request from node 1 to node 4. If ORA is used then the route is either $Path_1$ or $Path_2$. This approach has several weaknesses. First, the path found in ORA may be very long, hence suffering residual dispersion in the fiber propagation and consuming large amount of network resources. It also enhances the blocking probability of requests. Second, if it establishes new lightpath over WDM layer ($Path_2$), then this lightpath may have to pass over many optical hops. This problem may be overcome by using *wavelength conversion* at intermediate nodes but an expensive solution. To avoid these weaknesses, IRA is used as the path found in IRA is $Path_3$ containing both logical and physical links.

In recent years, there have been many routing algorithms according to the principle of IRA which are proposed for IP over WDM networks. M. Kodialam *et al.* [5] has proposed two integrated routing algorithms called MOCA (*Maximum Open Capacity Routing Algorithm*) and IMH (*Integrated Min-Hop Routing*). With MOCA, the path of LSP is selected so that the residual capacity is maximized. On the other hand, under the IMH, all links in network (both logical and physical links) are considered with the same degree of priority when it assigns a path for LSP request, the weight of all the links are identical and set to one unit. Their simulation results [5] show that MOCA performs much better, in term of blocking probability, than IMH. However the MOCA suffers a high complexity in setting up the routing. The main advantage of IMH algorithm is its simplicity for implementation, but it can cause high blocking probability because the cost of links does not consider other features and parameters of the logical link such as number of hops, residual bandwidth of lightpaths.

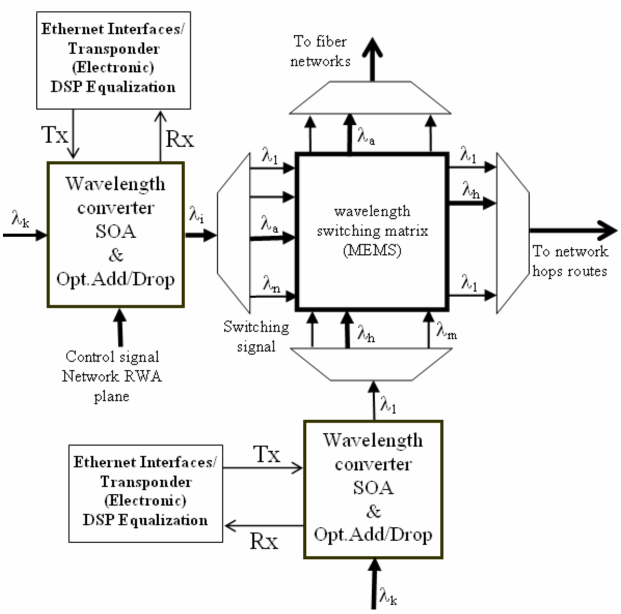


Figure 2: Detailed structure of optical nodes for ultra-high speed optical Ethernet. Wavelength conversion and routing by an SOA and demultiplexer and switching matrix for routing a specific wavelength to a designated output port for further routing

Assi *et al.* [6] has then introduced the residual bandwidth parameter of the lightpath into the *cost function* of a logical link in two algorithms: LLR (*Least Loaded Routing*) and MLR (*Most Loaded Routing*). The objective of LLR is to evenly distribute the load amongst the logical links, the LSP request is routed with higher priority over the logical links with a larger residual bandwidth. On the contrary, MLR attempts to route the traffic over the most loaded path. LLR and MLR are not considered to be restricted by the constraint of either the hops or the number of lightpaths in the *cost function* of logical links. Therefore, the LSP requests can route over the long reach lightpaths, thus consuming much resources of the network. Thus naturally it affects the blocking probability of the coming requests.

In the next section, we propose an integrated routing algorithm, the *Hop and Bandwidth Integrated Routing* (HBIR*)* incorporating the physical constraints due to wavelength availability, the chromatic dispersion effects and availability of all optical regeneration for networking due to bandwidth limitation with and without optical regeneration. For LSP, the HBIR simultaneously considers two parameters, the residual bandwidth and the hops number of lightpaths in the cost function of logical links. We solve this problem by modeling the IP/WDM as a layered-graph [7, 8]. Thus effectively we assign a layer for each wavelength channels and the routing is an integration and logical determination of the routing routes for optical channels.

Based on the link state information of network, the cost of the edges in the layered graph would be updated when a LSP request is routed over the network, hence significant improvement of routing can be achieved.

The cost function plays a major part on the blocking probability and thus we further investigate this function by proposing different scenario in which the bandwidth allocations are required for routing and assignment of the wavelength channels. This scenario is quite critical for effective transfer of information data that may occupy only a smaller bandwidth/capacity available in a wavelength channel. Thus another cost function is proposed with the traffic loads associated with the feasible bandwidth, thus it is proven that the blocking probability against the traffic load can be achieve to demonstrate the effectiveness of this cost function in the HBIR algorithm.

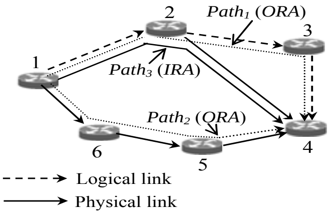


Figure 3 Routing using lightwave paths ORA and IRA

3. Layered Graph Model and Routing Algorithms

3.1 Layered Graph Model for IP Over DWDM

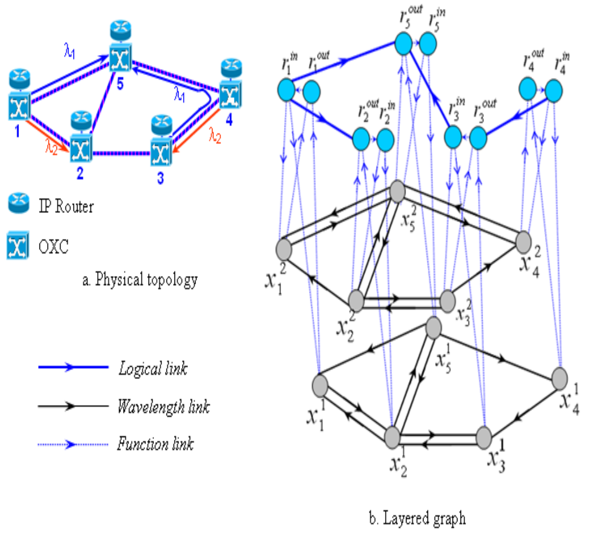
A layered graph model has been proposed in [9] to solve the routing and wavelength assignment problems (RWA) in WDM networks. In this section, we expand the layered graph model for networks using multi-wavelength channels and IP packets [1, 10, 11, 12, 13]. An IP over WDM network can be defined as a graph *G*(*N*,*E*), where *N* is the set of nodes which include the optical cross connects (OXCs) and IP routers. Let *E* is the set of bidirectional optical fiber links, each of which contains *w* wavelength channels and accumulated link distance L_a. Layered graph $G_L(N_L, E_L)$ is a directed graph which can be obtained from *G*(*N*,*E*) as follows:

- For each $OXC_i \in N$ in *G*, expand to *W* function sub-nodes denoted by $x_i^w(w=\overline{1..W})$. If there is an edge $e_{ij} \in E$ in *G* that connects between *i* and *j*, then use *W* directed edges denoted by $e_{ij}^w \in E_L$ in G_L to connect from x_i^w to $x_j^w(w=\overline{1..W})$ and *W* directed edges denoted by $e_{ji}^w \in E_L$ in G_L to connect from x_j^w to $x_i^w(w=\overline{1..W})$. All the edges are now assigned as *wavelength links.*
- For each IP router $R_i \in N$ in *G* which is attached to OXC_i, expand to two function sub-nodes denoted by r_i^{in} and r_i^{out} , using *W* directed edges to connect from node r_i^{in} to nodes $x_i^w(w=\overline{1..W})$, *W* directed edges to connect from nodes $x_i^w(w=\overline{1..W})$ to node r_i^{out} and a directed edge to connect from r_i^{out} to r_i^{out} . All these edges are now assigned as *function links.*
- If number of lightpaths available for connection from R_i to R_j is not zero then use one directed edge denoted by l_{ij} for connection from R_i to R_j. This edge is assigned as a *logical link.*
- When there is a new lightpath l_{ij} established from R_i to R_j, *the* use wavelength *w,* remove *wavelength links* e_k^w currently used for lightpath l_{ij}. Else, if there is a lightpath it is released and then *wavelength links* stored correlatively.

A well-known parameter to govern the effects of chromatic dispersion imposing on the transmission length of an optical system is known as the dispersion length L_D. Conventionally, the dispersion length L_D corresponds to the distance after which a pulse has broadened by one bit interval [14]. For high capacity long-haul transmission employing external modulation with the on-off keying (OOK) non-return-to-zero (NRZ) modulation formats, the dispersion limit can be estimated and given as [14, 15]

$$L_D = \frac{10^5}{D.B^2} \tag{1}$$

where B is the bit rate (Gb/s), D is the dispersion factor (ps/nm km) and L_D is in km. Eq.(1) provides a reasonable approximation even though the accurate computation of this limit depends the modulation format, the pulse shaping and the optical receiver design. It can be seen from this equation that the severity of the effects caused by the fiber chromatic dispersion on externally modulated optical signals is inversely proportional to the square of the bit rate. Thus, for 10 Gb/s OC-192 optical transmission on a standard single mode fiber (SSMF) medium which has a dispersion of about ±17 ps/nm.km, the dispersion length L_D has a value of approximately 60 km, that is corresponding to a residual dispersion of about ±1000 ps/nm and less than 4 km or equivalently to about ±60 ps/nm in the case of 40Gb/s OC-768 optical systems and less than 1 km for 100 Gb/s Ethernet. We assume that a residual dispersion of about 2% of the distance linking between the nodes. Thus the equivalent length of the distance of a channel between one to other node of the network must satisfy condition (1) so that error free can be achieved.



a. Physical topology

b. Layered graph

Figure 4 Layered graph model for multi-wavelength channels as layered graphs and IP layer.

An equalizer can also be integrated in the Ethernet transceiver that would equalize the received signals provided that the signals are still in the recoverable range. We set the L_E is about 2% of the dispersion length allowable for dispersion. The total transmission link distance between nodes must satisfy

$$L_D < L_T < L_E \tag{2}$$

Figure 4 shows an example of layered graph model of IP over WDM network whose physical topology is shown in Figure 4(a). Assuming that one optical fiber uses two wavelengths then *Figure 4*(b) represents the layered graph for this case. If the IP over WDM network is translated into layered graph, the routing problem in IP over WDM network becomes a shortest path problem in the layered graph. Thus the key issue is how to determine the cost function of all links in this layered graph.

3.2 Integrated Routing Algorithm HBIR

To implement the algorithm HBIR, we first transform the IP over WDM network into layered graph as discussed in Section 3. The *cost function* of all links can then be determined. *Dijkstra algorithm* is used *to* find lowest cost path in this layered graph.

3.2.1 Wavelength- and Logical- Links Based Cost Function

In a layered graph, the cost of a function link can be determined by setting $\varepsilon \to 0^+$. So the route selection only depends on the cost of *wavelength links* and *logical links*. The cost function of *wavelength* links (c_{ij}^{w}) can thus be determined as follow:

$$c(e_{ij}^{w}) = \begin{cases} * c_{ij}^{1}, \ \ if\ wavelength\ w\ in\ the\ link\ from\ i\ to\ j\ is\ occupied \\ and\ the\ traveled\ distance < L_D\ and\ 3R\ NOT\ available \\ * c_{ij}^{2}, \ if\ wavelength\ w\ in\ the\ link\ from\ i\ to\ j\ is\ not\ occupied \\ and\ the\ traveled\ distance < L_D\ and\ 3R\ NOT\ available \\ * c_{ij}^{3}, \ if\ wavelength\ w\ in\ the\ link\ from\ i\ to\ j\ is\ not\ occupied \\ and\ the\ traveled\ distance < L_D\ and \\ 3R\ NOT\ equalization\ available \\ * + \infty,\ otherwise \end{cases} \tag{3}$$

This cost function in (3) is thus dependent on several parameters, such as the lightpath length, channel signal dispersion and attenuation of the fiber propagation. By denoting l_{ij} as the distance between the ith node to the jth node, the cost function for all logical connections can be formulated. We now propose the *feasible capacity* of a logical link as the feasible capacity of a logical connection l_{ij}. Let $b_{av}(l_{ij}))$ is the summation of all the available bandwidth capacity of the optical wavelength channels (lightpaths) required the logical route satisfying the conditions that the requested capacity of the LSP is narrower than the available bandwidth. This condition must simultaneously be subject to the dispersion budget condition that is the lightpath propagation distance must be shorter than the maximum length limited by the dispersion length L_D given in (1). 3R demotes whether there is an optical regeneration attached to the node.

Therefore, depending on the requested capacity of a specific LSP the feasible capacity of a logical connection would alter. Let now examine the case of an optical network shown in Figure 5. At the scenario there are three lightpaths occupying the logical link l_{12} from node R_1 to node R_2 with an available capacity and the lengths of the lightpaths of the wavelength channels as indicated in Figure 5.

Assuming that there is a request to establish *LSP(1, 2, b)* that means LSP from 1 to 2 with a capacity b. With the dispersion factor of 17 ps/nm/km of SSMF as the lightwave guided medium, we can examine the following scenarios:

(i) b=2.5 Gb/s $\Rightarrow L_D \approx$ 941.2 Km, then all the lightpaths would satisfy the capacity condition and the chromatic dispersion limit given as $L_D \Rightarrow b_{av}(l_{12}) = 4.0 + 12.0 + 18.5 = 34.5$ Gb/s.

(ii) b= 10.7 Gb/s$\Rightarrow L_D \approx$ 51.38 Km. Thus LP_1 satisfy the dispersion limit L_D but not on the available capacity. However LP_3 can satisfy the capacity demand but not the dispersion distance limit. Only LP_2 can satisfy both conditions $\Rightarrow b_{av}(l_{12})$ = 12.0 Gb/s.

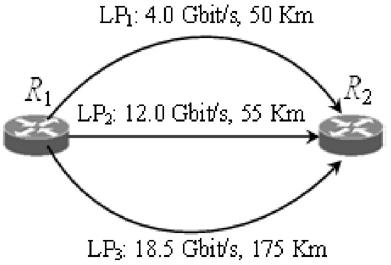


Figure 5: Schematic of a logical link consisting of three lightpaths associated with the line rate and link distance.

The cost function for the logical link l_{ij} can thus be determined based on $b_{av}(l_{ij})$ as follows:

$$c(l_{ij}) = \begin{cases} \underset{m=1..n}{\underline{Min}}\{L(m)\} + \dfrac{b}{b_{av}(l_{ij})}, & if\ b_{av}(l_{ij}) > 0 \\ +\infty, & if\ otherwise \end{cases} \qquad (4)$$

where n is the number of the lightpaths of the logical connection l_{ij} satisfying the capacity demand and the dispersion limit distance L_D, $L(m)$ is the length of the m^{th} lightpath and b is the requested capacity of the LSP.

3.2.2 The Algorithm

The input conditions to be set for the model and status of the output, the routing, can be defined as follows:

Setting Network Input Conditions: An IP over WDM network can be modeled into the layered graph $G_L(N_L, E_L)$. The establishment request is assigned as LSP (s, d, b), with s, source node, d the destination node and b the requested bandwidth of LSP ($0 < b \leq b_{lp}$), with b_{lp} is the maximum capacity of a lightpath.

Output status: A route from s to d having a capacity of b bandwidth units, or the request is refused if the establishment is not successful.

The algorithm can be described with the input conditions and status of the output in the following steps:

Step 1: Based on the requested capacity of the LSP, determine L_D and b_{av} of all the logical connections based on (1), form the cost functions of all the logical connections given in (4).

Step 2: Run Dijkstra algorithm in G_L to find the shortest cost path P_{sd} from r_s^{in} to r_d^{out}. Determine the cost value Cost(P_{sd}) of path P_{sd}. If Cost(P_{sd}) = $+\infty$,→ *go to step 7. Else, continue.*

Step 3: Determine the wavelength links in $P_{sd.}$ If $P_{sd.}$ Which do not pass through the wavelength link → *go to step 6. Else, continue →.*

Step 4: Determine the propagation distance of all new lightpaths. IF there remains newly formed LP whose propagation distance > L_D then go to step 7. *Else, continue →.*

Step 5: Establish the new lightpaths over wavelength links re found at step 3, → update the cost for these wavelength links according to the function (3). *Continue →.*

Step 6: Establish LSP over P_{sd}. → updating the residual bandwidth of lightpaths used for this LSP. *End.*

Step 7: Refuse the request and terminate action. *End.*

In this algorithm, the complexity is primarily dependent on the Dijkstra algorithm at Step 2. The constructed layered graph includes $N*(W+2)$ nodes, hence the complexity of the HBIR algorithm is $O(N*(W+2)^2)$.

In order to evaluate the validity of the HBIR algorithm described above, a simulator is developed for an optical Ethernet network whose topology network is given in Figure 6a including the dispersion residual distances between network nodes. The residual distance means that the distance is dispersion compensated either under or over compensation by an equivalent distance in kilometers of the SSMF. The physical parameters of the network are: (i) Fibers are SSMF whose averaged chromatic dispersion factor is 17 ps/nm/km. (ii) B Gb/s demotes the data bit rate of the wavelength channels. Obviously the pulse broadening depends on the dispersion factor, the bit rate and the modulation technique that influences the signal spectrum and hence the interference of the spectral components of the optical signals. Three bit rates for Ethernet networks are assumed as 1, 2.5 and 10.7 Gb/s. (iii) Requested capacity of each LSP is uniformly distributed with the range (0,B]. The arrival time of the LSP requests is assumed to follow a Poisson distribution with an exponential occupying time for connection. The average time is 1 second; (iv) The number of wavelength channels available for transmission is 8 and all are located the C-band with appropriate channel spacing, normally 50 GHz. The channel spacing is sufficiently wide so that no nonlinear interaction occurs and the total average power of all channels is below the nonlinear self-phase modulation threshold, even for 40 Gb/s bit rate.

3.3 Simulation and discussions

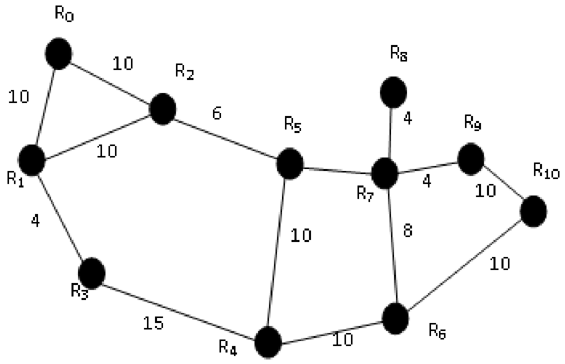


Figure 6: A typical optical Ethernet network with assigned residual dispersion distance in Kms between optical nodes.

We have developed a network simulation models based on layered graphs HBIR on OMNet++ 4.0b8 [16] under operating system Linux Red Hat's Fedora Core 9. The network structure is designed based on a three-simple module model as shown in Figure 7. Module *Gen_LSP* performs the functions of establishment of LSP. The LSP requests are evenly distributed based on natural law of equal opportunity of nodes within the networks. Each request is then represented in a file *Packet.msg*, consisting of address of the source, destination node, required capacity, occupation time of LSP and other fields o support the progressing period for the determination of the lightpath. The information package of the LSP is then sent down to module *Routing_IP/WDM* so as for the determination of the routing lightpath. As the HBIR is a mathematical algorithm for routing in IP over DWDM whose structure of nodes of equal access priority thus the module *Routing_IP/WDM* must contain information of both IP layer and WDM layer. The HBIR algorithm is therefore included in this module so as to establish the routing path of LSP. Once the routing path is found, LSP is sent to the next node so that the LSP can be finally established over the whole network. Module *Receiver* functions as the receiving end of the LSP package, once the package has arrived at its destination node thence the receiving information is erased. Otherwise it would be re-sent to module *Routing_IP/WDM* for further processing. *Figure 8* illustrates the processing steps on the topological mesh of *Figure 6* using 8 wavelength channels. In this case the physical topological structure can be transformed into 8 graphical layers for each wavelength channels plus one logical IP layer.

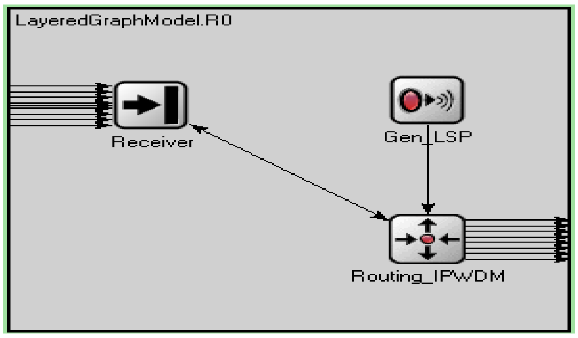


Figure 7 – Structure of network nodes under simulation using three modules.

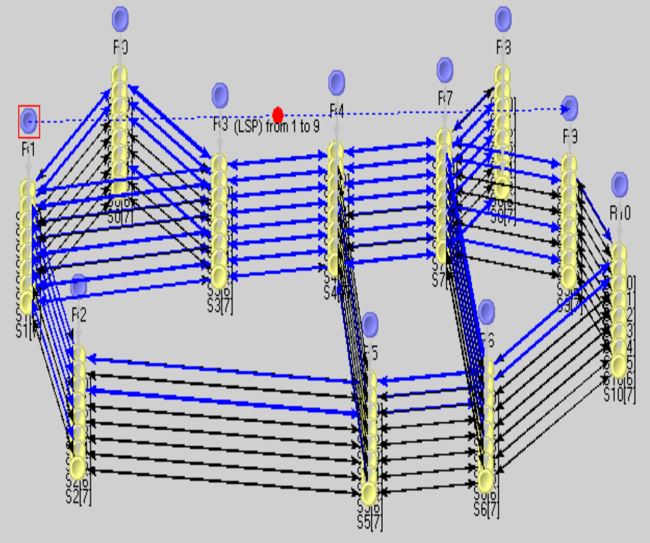


Figure 8 – Illustration of traffic processing over layered graph of a mesh topological mesh.

3.3.1 Survivability under Linear Dispersion Effects

Figure 9 shows the blocking probability of LSP for the cases that the allowable capacity for logical connection is 2.5 and 10.7 Gb/s, 20 Gb/s and 40 Gb/s with and without the constraints of dispersion effects. The blocking probability of networks with lightpath of bit rate 10.6 Gb/s is about 8 more percentile than that for 2.5 Gb/s for moderate traffic loads. However there is a dip and some fluctuation of this blocking probability for high traffic load. This could be due to the availability of the light paths. For the case of 2.5 Gb/s normally under long haul transmission the CD is not a major issue but we could see that in metro-networks there are blocking probability when the traffic load is moderate and similar to the 10.7 Gb/s bit rate case. For 40 Gb/s the blocking probability is very serious as expected and that even at very load traffic load the channels can be blocked at very low traffic load. That means that with SSMF as the principal fiber in metro-networks the networking of 40 Gb/s wavelength channels faces terrible difficulty unless electronic compensation or advanced modulation formats such as OFDM (orthogonal frequency division multiplexing) or differential phase modulation [15] are used together with electronic equalization. 20 Gb/s line rates network would perform without much problems in SSMF networks.

In summary, at 40 Gb/s the blocking probability is significantly different between the two scenarios. It is severely affected when the dispersion effects are taken into account. While at 2.5 Gb/s the impact is almost negligible. *Figure 10* illustrates the routing of the layered graphs of lightpaths under the dispersion effects. Distinct processing features can be observed with those of Figure 8.

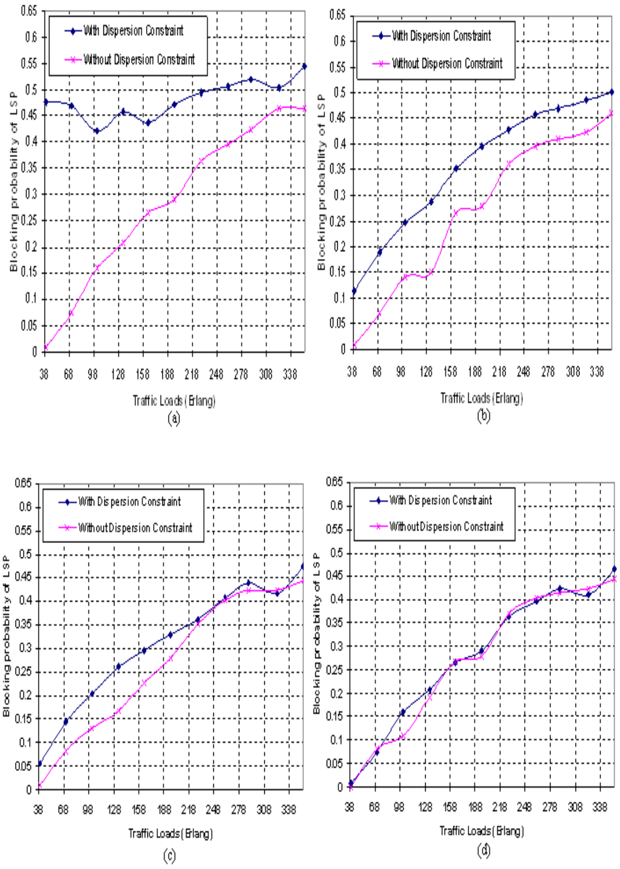


Figure 9 – Comparison of blocking probability of LSP under constraints of dispersion effects and without dispersion with different bit rates (a) 40Gb/s, (b) 20 Gb/s, (c) 10.7 Gb/s and (d) 2.5 Gb/s.

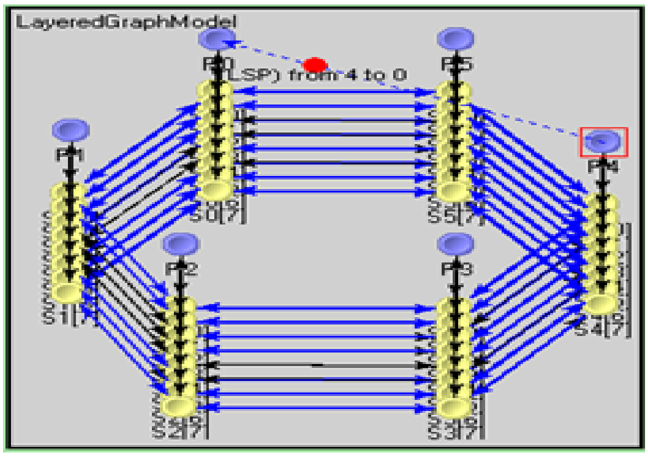


Figure 10 – Illustration of the processing of layered graph of mesh topology of network given in Figure 6 when lightpaths are under dispersion effects.

3.3.2 Blocking Probability Under Nonlinear Self Phase Modulation Effects

The setting of the limitation of the nonlinear self phase modulation (SPM) effects on the wavelength routing and blocking probability in the model in Omnet++ is implemented with (i) the maximum total average power of all wavelength channels, $P_{th\_NL} \leq 10$ dBm for standard single mode fibers (SSMF) with the fiber attenuation of 0.25 dB/km. (ii) the average power of each wavelength channel at the start of the transmission lightpath is 0.5 mW. The receiver sensitivity is assumed at -22 dBm for 20 Gb/s and -20 dBm for 40 Gb/s, appropriate level is also set for 10Gb/s and 2.5 Gb/s).

That means that we assume the optical networks IP over DWDM are operating in the linear limit so that the total average power level is below the threshold level of non linear SPM effects. Assuming that optical amplifiers are used wherever necessary, with the fiber attenuation, the receiver sensitivity and the power threshold limit and with -3dBm limit for each wavelength channel the residual transmission can be set at 68 Km and 76 Km for 40 Gb/s and 20 Gb/s bit rate respectively. The routing algorithm HBIR can now be limited to the nonlinear effects by (i) checking the number of wavelength and their total average power so that it is below the nonlinear threshold limit , $P_{th_NL} > 10$dBm. Blocking happens when this condition is not met and information of all wavelength channels is broadcast to all nodes. We term this as Algorithm 1.

The survivability of the wavelength channels is modeled for the network shown in Figure 11 with 16 wavelength channels in total. The distance is adjusted slightly shorter than those in Figure 6 in order to show some reasonable blocking probability. Figure 12 shows the dynamics of the wavelength routing in the network and assignment of edge nodes for all 16 wavelength channels.

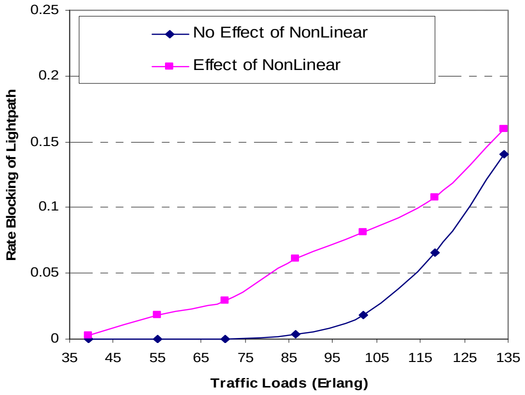


Figure 13 and Figure 14 show the blocking probability of channels with channel bit rate of 20 Gb/s and 40 Gb/s respectively.

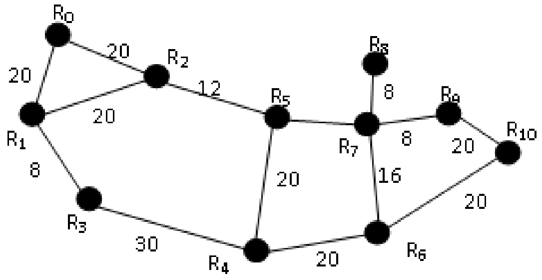


Figure 11 Network topology with the numbers assigned to each lightpath as the residual distance for study of channel survivability under nonlinear SPM effects.

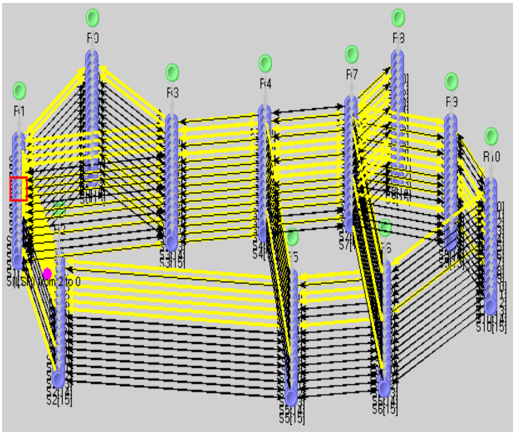


Figure 12: Illustration of wavelength routing under Omnett++ simulation using HBIR algorithm.

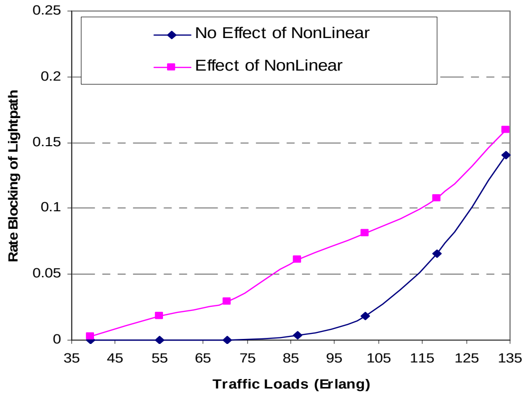


Figure 13: Blocking probability of 20 Gb/s channels in 16 wavelength DWDM optical networks under SPM effects and under no effects (Algorithm 1).

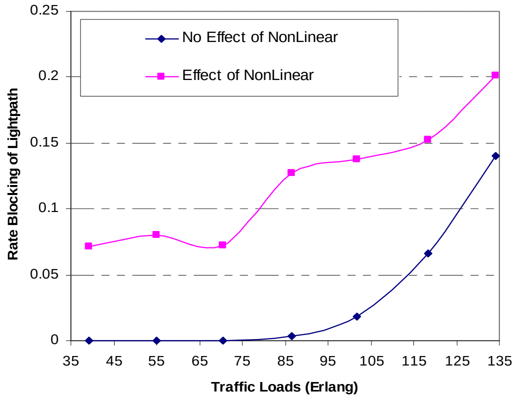


Figure 14: Blocking probability of 40 Gb/s channels in 16 wavelength DWDM optical networks under SPM effects and under no effects (Algorithm 1).

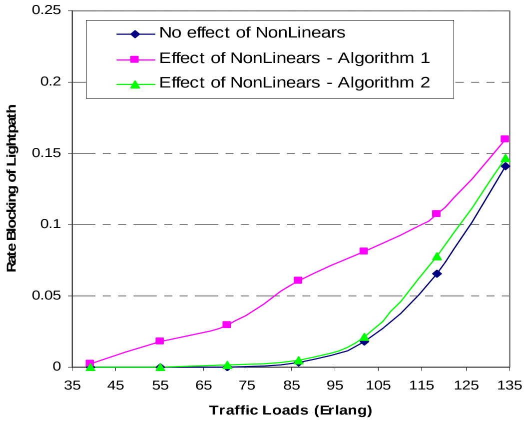


Figure 15: Blocking probability of 20 Gb/s channels in 16 wavelength DWDM optical networks under SPM effects and under no effects (Algorithm 2). Blocking under Algorithm 1 is also included.

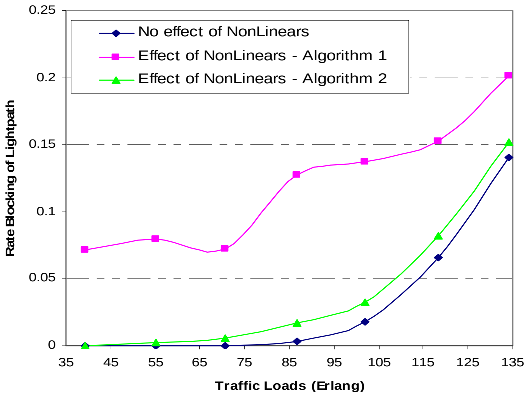


Figure 16: Blocking probability of 40 Gb/s channels in 16 wavelength DWDM optical networks operating at 40 Gb/s under SPM effects and under no effects (Algorithm 2). Blocking under Algorithm 1 is also included.

We thus can observe that the nonlinear SPM effects severely affect the routing of the channels. The blocking probability increases significantly when the SPM effect incorporated in the lightpaths, particularly when the traffic load is high. In order to overcome this limitation we propose to adjust the average power of a wavelength at the output of an OXC, that is the input of a lightpath so that it still satisfies to condition of the receiver sensitivity and the nonlinear threshold of all wavelength channels in that lightpath. We term this proposal as algorithm 2. This adjustment depends, naturally on the length of the lightpath. This would significantly improve the blocking probability of the routing channels as shown in Figure 15 and Figure 16 using Algorithm 2 for 20 Gb/s and 40 Gb/s respectively.

4. Conclusions

Traffic performance in ultra-high speed optical networks has been modeled and simulated with the physical constraints of dispersion limits of the lightpaths as well as the wavelength availability and channel capacity. Cost functions are developed to assign to each lightpath subject to the transmission distance limit and logic link capacity. The algorithm is developed based on the layered graph over which the network traffic performance is deduced. Line rates of 2.5 Gb/s and 10.7 Gb/s for lightpaths are studied in a typical configuration of metro-all-optical DWDM networks with eight wavelength channels. It is shown that a blocking probability of about 8% more for line rates 10.7 Gb/s as compared to 2.5 Gb/s case when the traffic load is sufficiently low, but fluctuating when the load is moderately high. 20 Gb/s and 40 Gb/s metro networks are also simulated and the 20 G lightpaths would perform with some penalty in the blocking probability but the 40G would face much difficulty even at low traffic loads. This is much expected when SSMF is the principle transmission medium in all network connections.

We have demonstrated an efficient algorithm, the Hop and Bandwidth Integrated Routing (HBIR), for all-optical routing of lightpaths in the *peer model* of IP over WDM networks. The proposed all-optical router facilitates and speeds up the routing in DWDM networks. They can be controlled and switched at very fast speed via the switching of the wavelength converter. Furthermore we have also studied the survivability of wavelength channels when the nonlinear SPM effects are incorporated in the lightpath and method to overcome these effects to reduce the blocking probability of the channels.

Further works should include the effects of noises and the electronic equalization for all optical networks operating in the ultra-high speed region up to 100Gb/s and 160Gb/s. The constraints of the routing at these extremely high speed are very stringent and complex cost functions must be developed.

The link distance should have been assigned with dispersion compensation using dispersion compensating fibers or fiber Bragg Gratings and optical amplifiers that contribute to the noises at the receiver end of users' terminals. This constraint should be modeled with an additional component in the cost function. The insertion loss of the OXCs must also be included. The limits of electronic equalizers should also be accounted for the maximum limit of hops allowable in the networks.

References

[1] (a) M. Batayneh, D. A. Schupke, M. Hoffmann, A. Kirstädter, and B. Mukherjee (2008), "Optical Network Design for a Multiline-Rate Carrier-Grade Ethernet Under Transmission-Range Constraints", IEEE J. Lighw Tech., Vol. 26, No. 1, Jan. 1, pp.121-130. (b) T. Ye *et al.*, (2004), "On-line Integrated Routing in Dynamic Multi-fiber IP/WDM Networks", *IEEE J. Sel. Areas Comm.,* Vol.22, No.9, pp.1681-1691.

[2] Y. Koizumi, S. Arakawa and M. Murata (2005), "On the Integration of IP Routing and Wavelength Routing in IP over WDM Networks", *SPIE APOC,* pp. 20-29

[3] S. Dixit (2003), IP over WDM - Building the Next Generation Optical Internet, John Wiley & Sons Pub, NY 2003.

[4] Q. Zheng and G. Mohan, (2003), "Dynamic protection using integrated-routing in IP over WDM networks, *Comp. Net.,* Vol. 43, pp.289-305

[5] M. Kodialam and T. V. Lakshman, (2001), "Integrated Dynamic IP and wavelength routing in IP over WDM networks", *IEEE INFOCOM,* pp. 258-366.

[6] C. Assi *et al.*, (2002), "Integrated Routing Algorithms for Sub-Wavelength Connections in IP over WDM Networks", *Photonic Net. Comm.,* Vol. 4, pp. 377-390.

[7] Q. Zheng and G. Mohan, (2003), "Dynamic protection using integrated-routing in IP over WDM networks, *Comp. Net.,* Vol. 43, pp.289-305.

[8] T. Ye *et al.*, (2005), "SLEA: A Novel Scheme for Routing in Overlay IP/WDM Networks", IEEE *J. Lightw. Tech.,* Vol. 23, No.10, pp. 2934-2944.

[9] S. Dixit, "IP over WDM - Building the Next Generation Optical Internet", John Wiley & Sons Pub., N.Y. 2003.

[10] T. Ye *et al (2003),* "Study on Integrated Routing in IP over WDM Networks", *Opt. Netw. Comm.,* Vol. 5285, pp. 404-408.

[11] C. Assi *et al.,* (2002), "Integrated Routing Algorithms for Sub-Wavelength Connections in IP over WDM Networks", *Photonic Net. Comm.,* Vol.4, pp. 377-390.

[12] M. Kodialam and T. V. Lakshman, (2001), "Integrated Dynamic IP and wavelength routing in IP over WDM networks", *IEEE INFOCOM,* pp. 258-366

[13] W. Wei *et al.,* (2006), "Multi-layer Integrated Routing Algorithm for IP over WDM Networks", *J. Opt. Comm.,* Vol.27, pp.29-34, 2006.

[14] P.J. Winzer, R.-J. Essiambre, and S. Chandrasekhar (2003), "System impacts of digital electronic signal processing", 31st European Conference on Optical Communications, Workshop on Electronic Digital Signal Processing in Optical Networks.

[15] I. Kaminov, T. Koch (2002) "Optical Fiber Communications" vol. IIIa, Academic Press.

[16] http://www.omnetpp.org/, access date: December 2008.

[17] G.P. Agrawal, "Fiber optic communications systems", 3rd Ed., J. Wiley, N.Y., 2002.

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