Transport of Assigned Wavelength Channels Over Ultra-high Speed Ethernet All-Optical DWDM Networks Under Constraints of Fiber Chromatic and Polarization Mode Dispersion Effects

Le Nguyen Binh[+] and **Le Huu Binh** [++],

[+] Department of Electrical and Computer Systems Engineering, Monash University, Wellington Rd., Clayton Victoria 3800, Australia.
[++] Transmission and Switching Station, Hue Telecommunications Centre, Thua Thien Hue VNPT Group, Vietnam.
08 Hoang Hoa Tham St., Hue City, Vietnam.

Summary – High speed 10Gb/s and 40 Gb/s optical Ethernet and SONET or SDH transmission systems carrying multi-wavelength channels are considered as the backbone of the next generation optical metro-networking technological development. Under this ultra-high speed transmission and networking, dispersion effects due to linear chromatic and polarization differential mode group delays and nonlinear effects of the single mode optical fibers are critical. This paper reports the traffic transport characteristics of multi-wavelength-channel optical networks with the channel bit rate from 2.5 Gb/s to 40 Gb/s. A layer graph approach is proposed by partitioning the multi-wavelength multi-path networks into parallel logical layers assigned to each wavelength, the physical transmission layer, and a layer for channel management. Once the edge nodes of the network are established, a cost function is established for the routing and wavelength assignment that integrates the layers and the routers for connecting and routing of wavelength channels over the physical lightpaths. The wavelength transport paths are dynamically subject to wavelength availability, capacity of the lightpath and the dispersion limit imposed on selected routed hops.

Blocking probability of the network traffics are obtained for different high speed cases. Severed blocking is observed for networks operating at speed higher than 20 Gb/s in metropolitan area. Advanced modulation formats and electronic equalization are expected to be useful in these networking scenarios. The blocking probability is further increased when the polarization mode dispersion effects are taken into account. Optical channels with bit rate greater than 20 Gb/s may not be operational if adaptive dispersion compensation is not implemented.

***Keywords**: integrated routing; DWDM networks; network traffic; network graph.*

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. 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 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 Ethernet. Thus transmitting IP data packet directly over WDM optical network, the IP over WDM technology, is considered to be important for optical networking. 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

Manuscript received August 5, 2009
Manuscript revised August 20, 2009

dense wavelength division multiplexing (DWDM) to transport IP traffic over DWDM enabled optical networks efficiently and effectively is an urgent yet important task. However in the routing at these ultra-high speeds, 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 DWDM 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 DWDM layer via User Network Interfaces (UNI). In *peer model*, a uniform control plane is used for both IP and WDM layers, IP and DWDM 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 DWDM 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 for next generation optical Ethernet networks.

In this paper we model the routing traffics of IP over Dense WDM under the constraints of linear chromatic dispersion and PMD effects 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. Recently the issues of transmission constraints have been rigorously address in Ref [1]. 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. In addition the allocations of available bandwidth of a wavelength channel are critical for routing information. For example the delivered 622 Mb/s or 1 Gb/s integrated in 10.7 Gb/s should not occupy the whole 10.7 Gb/s capacity. Thus we have assumed in this paper a scenario in which the information data may not occupy the whole bandwidth of the capacity of the channel. The allocation of bandwidth to a particular wavelength channel is thus necessary and considered in this work.

Further we have also included the pulse broadening effects due to polarization mode dispersion (PMD) which is very critical for operating bit rate greater than 10 Gb/s. The blocking probability is increased accordingly and the traffic performance is studied under this additional impact.

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 describes the routing algorithms for routing based on layered graph representing the physical networks. Simulation results of the traffic performance in term of blocking probability versus the traffic loads when the network is under the impacts of chromatic dispersion and PMD effects. Finally conclusions and some aspects of works should be further developed.

2. DWDM all-optical Networks and Ultra-high Speed Transmission

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 [2], 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 consists of a switching matrix, semiconductor optical amplifier (SOA) employed as wavelength converters based on the cross phase modulation effects, 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 [2, 3]. 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.

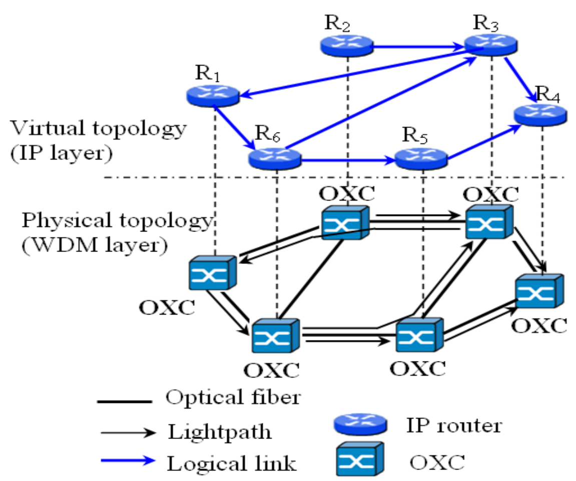

Figure 1 A typical structure of IP over WDM network for 10G and 100G Ethernet with optical cross connect (OXC) connecting all nodes and add/drop sites.

To transmit of IP traffic over WDM optical networks effectively, optimizing the routing mechanisms is necessary that depends on network models [9, 10]. 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 [8], and solve the problem on this platform.

The next few parts of this section address the following issues. Section 2.2 analyzes routing mechanisms in IP/DWDM network and presents some related research results. In Section 2.3, the method for modeling IP/WDM networks into layered graph for routing and control of channel transport is described. The algorithm is then demonstrated in Section 2.4 for wavelength routing and bandwidth allocations under the constraints of chromatic dispersion and polarization mode dispersion effects.

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, 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. 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 2 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.

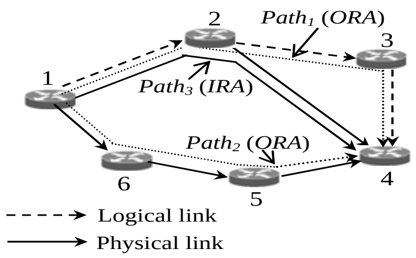

Figure 2 Routing using lightwave paths ORA and IRA

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.

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*) [6]. 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, an integrated routing algorithm, the *Hop and Bandwidth Integrated Routing* (HBIR*)* is proposed together with 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 [8, 9, 10]. 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.

3. Layered Graph Model and Routing Algorithms

3.1 Layered Graph Model for IP Over DWDM

Layered graph model has been proposed in [10] to solve the routing and wavelength assignment problem (RWA) in WDM networks. In this section, we expand the layered graph model for IP over WDM networks [2, 10]. In generic terms layered graph networking technique is that when the network is partitioned into layers then the routing and wavelength assignment becomes the problem of finding the shortest paths from the source to the targeted destination. The sub-problems in routing and wavelength problems can be solved simultaneously, that is if the short test passes through the i^{th} layer then the i^{th} wavelength can be assigned for this lightpath. The remaining essential problem is how to establish the cost function, or the determination of the weighting coefficient for the edges of the partitioned and layered graphs.

Now then, 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 called *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 called *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 termed 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 restored *wavelength links* correlatively.

3.2 Dispersion effects

3.2.1 Chromatic dispersion (CD) Effects

The effects of chromatic dispersion imposing on the transmission length of an optical system can be characterized by 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 [12]. For ultra-high speed optical transmission between nodes the transmission fibers are normally compensated with dispersion compensating fibers. So the dispersion length can be considered as the residual dispersion length of the light paths. Further 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 [12]

$$L_D = \frac{10^5}{D.B^2} \qquad (1)$$

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 at the terminal sites. 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 hierarchy on a standard single mode fiber (SSMF) medium whose dispersion factor of about ±17 ps/nm.km, the dispersion length L_D has a value of approximately 60 km. This is corresponding to a residual dispersion of about ±1000 ps/nm or equivalently to about ±60 ps/nm in the case of 40Gb/s OC-768 optical systems or a residual dispersion equivalent to 4 km of SSMF and less than 1 km for 100 Gb/s Ethernet. We assume that a residual dispersion of about 5% 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.

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

$$L_D < L_T < L_E \qquad (2)$$

Figure 3 shows an example of layered graph model of IP over WDM network whose physical topology is shown in Figure 3(a). Assuming that one optical fiber uses two wavelengths then *Figure 3*(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.

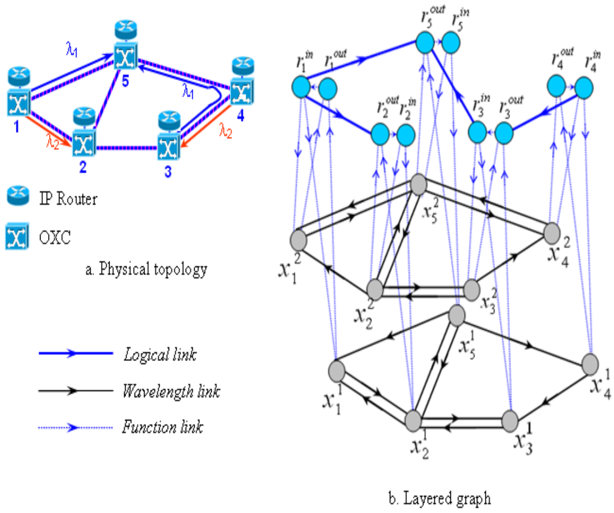

Figure 3 Layered graph model for IP over WDM network.

3.2.2 Polarization Mode Dispersion (PMD) Effects

In ultra-high speed optical networks, especially when the bit rate reaches 10 Gb/s and above, the effects of the difference of the propagation velocity of the polarized modes of the fundamental linearly polarized mode of single mode fibers become very important. This difference is randomly accumulated over the whole long distance of the hops of the optical networks as illustrated in Figure 4. Thus the lightwave signals arrived at the received end would be spread, hence pulse broadening. Therefore this effect must be taken into account in the study of the transport of optical channels over ultra-high speed optical networks. A special feature of this PMD effect in all-optical network is the variation of the length of the propagation path of a channel due to the number of different hops over which it has to be transported. In this paper we have taken this effect into account. The estimation of contribution of the PMD effect can be determined as:

$$\begin{aligned} \Delta\tau_{CD}(ps) &= 17 * 0.32 * L_{LSP} \\ \Delta\tau_{PMD}(ps) &= 0.5 * \sqrt{L_{LSP}} \end{aligned} \qquad (3)$$

where L_{LSP} is the total traveling lightpath over the distances connecting over the hops. This means that once the lightpath is determined the pulse spreading due to PMD is estimated. A decision is made to whether to transmit the optical channel or not. Note that the PMD effect is proportional to the square root of the propagation path. In this paper we have taken into account only the first order PMD effects, no higher order effects are considered. In the case that several optical wavelength-division-multiplexed channels are employed the second order PMD effect would be serious and should be included in the study of the transport of the channels over the entire all-optical networks. Similar to the case of compensating the CD effects, compensation of PMD effects can be installed by PMD at the receiving terminal by controlling the rotation of the polarized modes and propagation through a high birefringent fiber that slows down the fast mode and vice versa. However this compensation is limited by the maximum range of compensation. The pulse broadening due to PMD considered in this paper is the amount over this limit of compensation.

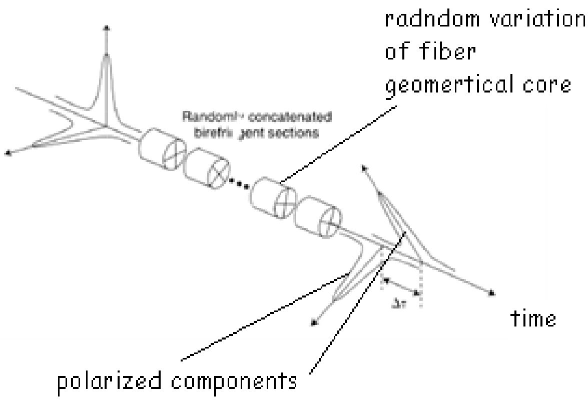

Figure 4: Illustration of polarization mode dispersion effects due to delay propagation time difference between the polarized modes of the linearly polarized mode of a single mode optical fiber.

3.3 Integrated Routing Algorithm HBIR

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

3.3.1 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:

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

(4)

This cost function (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 jth node, the cost function for all logical connections can be formulated. We can now propose the *feasible capacity* of a logical link as the 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 L_D and limit given by given by the PMD given in (1) and (3) respectively.

Therefore, depending on the requested capacity of a specific LSP the feasible capacity of a logical connection would alter. 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 the 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 + 8.5 = 24.5 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 LSP_3 can satisfy the capacity demand but not the dispersion distance limit. Only LSP_2 can satisfy both conditions $\Rightarrow b_{av}(l_{12})$ = 12.0 Gb/s.

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

$$c(l_{ij}) = \begin{cases} \underset{m=1..n}{Min}\{L(m)\} + \dfrac{b}{b_{av}(l_{ij})}, & \textit{if } b_{av}(l_{ij}) > 0 \\ +\infty, & \textit{if otherwise} \end{cases} \quad (5)$$

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.

3.3.2 Integrated Routing Algorithm HBIR

The input (source) and output (sink) into and from the network can be structured as follows:

Setting the Input: An IP over DWDM network is modeled into a 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 ($0 < b \le b_{lp}$), with b_{lp} is the maximum transmission capacity of a lightpath.

Output: Either the establishment of a route from s to d having a capacity of b bandwidth units is permitted, or the request is refused if all routing conditions are not met.

Therefore the algorithm can compose of 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}) = +∞,→ ***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)*.

The simulation model is implemented on OMNET++ platform [16]. The model is established in three phases as follows:

Phase 1: Set up a layer graph of the physical network and the IP layers by (i) Declaring N* [W+1] nodes; (ii) Establishing all links for wavelength channels: (iii) Establishing all logical links; and (iv) Establishing all Function links.

Phase 2: Procedures for establishing and liberation of LSP: (i) Establishing a module, Tx.cpp to detect demands for requests and generation of request signals; (ii) Each request is established ion the IP layer by a file, packet.msg whose fields consist of the address of source node, the sink node address, the requested bandwidth and the allowable time interval permissible on the network; and (iii) Modeling these fields using natural functions available in OMNET++.

Phase 3: Once Stages 1 and 2 are satisfied, establishment and liberation of a LSP can follow procedures given in Steps 1-6 of the algorithm as described above.

3.3.3 HBIR under PMD effects

The HBIR is to be modified for the case when the PMD is taken into account as follows:

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). Determine the allowable pulse broadening so that the total pulse broadening due to the polarization mode dispersion CD_PMD is not wider than 70% of the bit period of the LSP.

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 length of path P_{sd} (L_{LSP}). If $L_{LSP} > L_D$,→ *go to step 7. Else, continue.*

Step 3: Determine CD and PMD of route LSP. If CD + PMD > CD_PMD *go to step 7. Else, continue.*

Step 4: 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 5: Establish the new lightpaths over wavelength links are 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.*

3.4 Traffic performance

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 5 including the distances between network nodes. 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 is the bit rate of the data wavelength channels. 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; and
(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.

Figure 6 (a) 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. The blocking probability of networks with lightpath of bit rate 10.6 Gb/s is about 8 percentile higher than that for 2.5 Gb/s for moderate traffic loads. However there is a dip and some fluctuation of this blocking probability at 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 orthogonal frequency division multiplexing (OFDM) or differential phase modulation [15] are used together with electronic equalization. 20 Gb/s line rates metro-network would perform without much problems in SSMF metro-networks as indicated in Figure 6. Figure 6 (a)-(d) shows the traffic performance of the network under dispersion impact and without dispersion considerations. It shows clearly that for 2.5

Gb/s there no severe degradation of the traffic transport. This becomes higher when the bit rate is increased. The impacts of both the CD and PMD effects are detrimental on the blocking probability at 20 Gb/s and 40 Gb/s. It seems very likely that adaptive equalization must be required at the terminal nodes of optical networks operating at ultra-high speed or advanced modulation formats such as DQPSK, M-ary Star QAM should be employed to lower the symbol rates to combat the dispersion effects in the networks. Figure 7 illustrate a state of transport of a wavelength channel over the network using OMNeT++ simulation package [16].

This, indeed, pushes a good case for electronic equalization of the received signals at the terminal sites in metropolitan fiber networks and uses of advanced modulation formats and pulse forming, in particular the multi-level modulation techniques to combat the impact of dispersion in ultra-high speed optical networks.

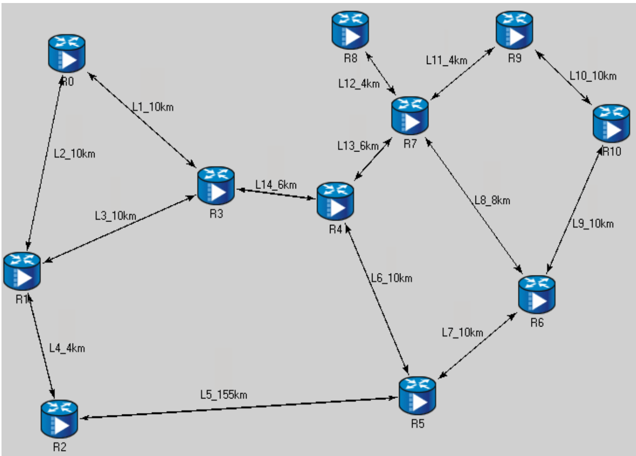

Figure 5 - A typical all-optical metro-network with assigned distance between optical nodes.

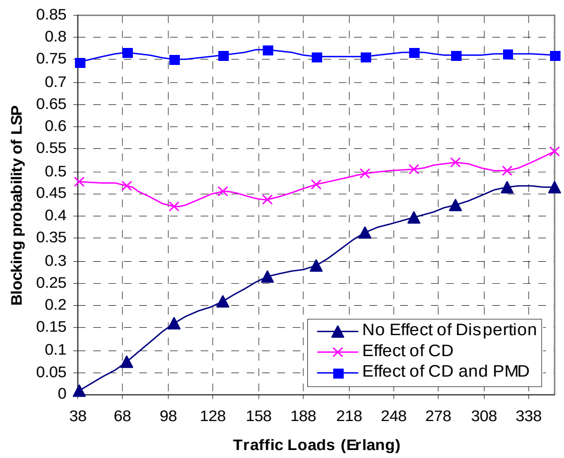

Fig. 6(a) 40 Gb/s bit rate

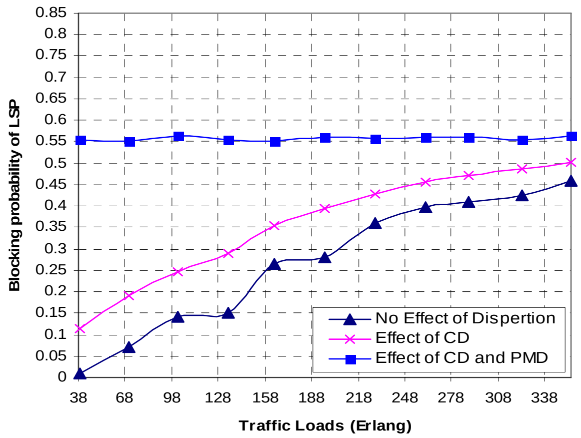

Fig. 6(b) 20 Gb/s bit rate

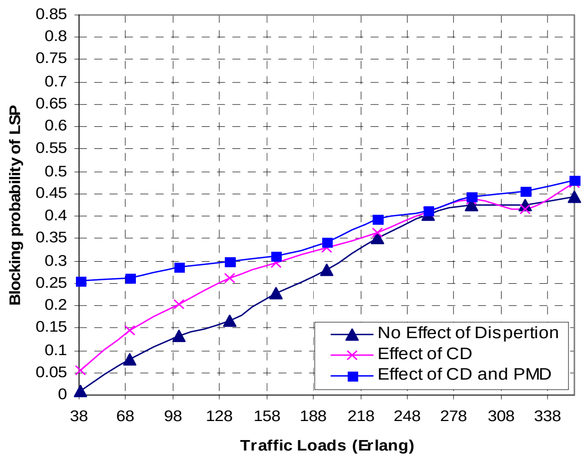

Fig. 6(c) 10 Gb/s bit rate

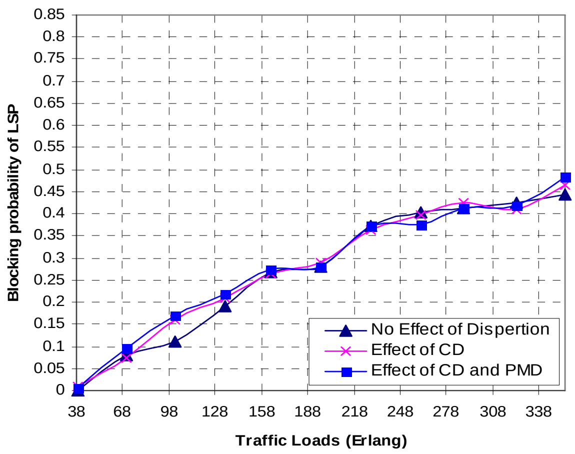

Fig. 6(d) 2.5 Gb/s bit rate

Figure 6 Traffic performance of optical Ethernet networks of

Figure 5: blocking probability versus traffic loads with parameter line rate of lightpath of 2.5 Gb/s, 10.7 Gb/s, 20 Gb/s and 40 Gb/s under without and with impacts of chromatic dispersion and PMD effects (a) 40 Gb/s under with and without dispersion impacts (b) 20 Gb/s (c) 10 Gb/s and (d) 2.5 Gb/s (current networking speed).

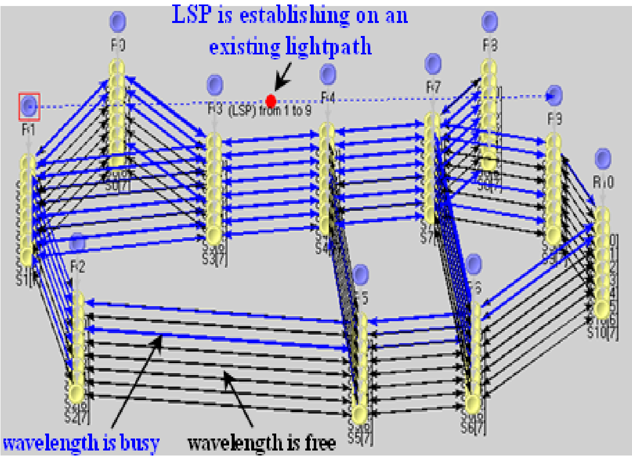

Figure 7 - Illustration of traffic processing over layered graph of a mesh topological mesh using OMNeT++.

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 40 G 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 facilitate and speed up the routing in DWDM networks. They can be controlled and switched at very fast speed via the switching of the wavelength converter.

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 100 Gb/s and 160 Gb/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.

The disadvantage of the proposed technique is the computing intensive computing resources which increase as a function of the nodes of the layered graphs and the total number of wavelength channels as $N*(W+1)$. Thus if the number of wavelength is 128 or 256 then the number of nodes for the network given above would be very high and it requires a significant increase of the computing resources. We are intensively developing alternative solutions and will report these findings in the near future.

Blocking probability of wavelength channels operating at or above bit rate of 20 Gb/s is severe and adaptive dispersion compensation must be place at the receiver as a pre- [15,16] or post equalizer [17] for combating the chromatic dispersion and PMD effects.

REFERENCES

[1] 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.

[2] 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.

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

[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] 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.

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

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

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

[11] 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.*

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

[13] http://www.omnetpp.org/, access date: June 2009.

[14] Le.N. Binh, Le H. Binh and Vo T. Tu, "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" *International Journal of Computer Sciences and Network Security*, Vol.9, No.2, 2009, pp. 49-60.

[15] S. Kieckbusch, S. Ferber, H. Rosenfeldt, R. Ludwig, C. Boerner, A. Ehrhardt, E. Brinkmeyer, H.-G. Weber, "Automatic PMD Compensator in a 160-Gb/s OTDM Transmission Over Deployed Fiber Using RZ-DPSK Modulation Format", IEEE *Journal of Lightwave Technology*, vol. 23, No.1, pp. 165-171 (2005)

[16] S. Kieckbusch, S. Ferber, H. Rosenfeldt, R. Ludwig, C. Boerner, A. Ehrhardt, E. Brinkmeyer, H.G. Weber, "Adaptive PMD compensator in 160Gb/s DPSK transmission over installed fiber", Proc. OFC, Los Angeles, California, USA (PDP31), (2004).

[17] L.N. Binh, "Digital Optical Communications", *CRC Press*, Bosca Raton, USA, 2008, Chapter 11.

Le Nguyen Binh received the degrees of B.E. (Hons) and PhD in Electronic Engineering and Integrated Photonics in 1975 and 1978 respectively, both from the University of Western Australia, Nedlands, Western Australia. In 1981 he joined in the Department of Electrical Engineering of Monash University after a three year period with CSIRO Australia as a research scientist developing parallel micro-computing systems. He was appointed to reader of Monash University in 1995. He has worked for and lead major research and development programs in the Department of Optical Communications of Siemens AG Central Research Laboratories in Munich and the Advanced Technology Centre of Nortel Networks in Harlow, U.K. He was a visiting professor in 2007-2008 and is currently an adjunct professor of the Faculty of Engineering of Christian Albretchs University of Kiel, Germany. Dr Binh has published more than 200 papers in leading journals and international conferences and three books, one on Photonic Signal Processing (2007) and the others on "Digital Optical Communications" (2008), and "Optical Fiber Communications Systems: Principles, Practices and MATLAB Simulink Models" (in press, 2009) all by the publishing house CRC Press of Taylors and Francis Group of Florida, USA. His fourth book scheduled for publication in January 2010 is "Ultra-fast Fiber Lasers" also by the same publisher. He is an associate editor of the International Journal of Optics and the Research Letters in Optics and the "Optics and Photonics" Series Editor for CRC Press. He is member of the Institute of Electrical and Electronic Engineers (USA) and the Optical Society of America, SPIE, Institution of Engineers and Technologist (UK). He has served on technical programs committee of numerous international conferences and as reviewer for several leading international journals and numerous Australian and international research grant committees. His current research interests are Tb/s optical transmission systems and networks, especially advanced modulation formats and associate electronic equalization methods, photonic signal processing, linear and nonlinear integrated photonics and multi-bound ultra-short soliton fiber lasers, quantum communications.

Le Huu Binh was born in Quang Tri, Vietnam on Jan 09, 1978. He obtained his B.Eng. (Telecom.) from Da Nang University of Polytechnics, Vietnam and the MSc (Info. Tech.) from Hue University of Sciences, Vietnam, in 2001 and 2007 respectively. He is currently a senior engineer with the Transmission and Switching Exchange of the Hue Telecommunications Centre, Thua Thien Hue of the Vietnam Posts and Telecommunications Group. His current research interests are optical fiber communication technology, especially IP/DWDM and packet/burst switch optical networking.