

Traffic Grooming Techniques in Optical Networks

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Abstract: With the increase of the number of wavelengths per fiber waveband switching has been proposed to decrease the number of switching ports in optical nodes. Another concept that of Light trails, allows the intermediate nodes along a lightpath to access the wavelength channel, aiming at the reduction of the number of wavelengths. Both techniques apply traffic grooming on different levels of the WDM network. In this paper, we combine them and compare the two switching techniques: waveband switching lightpath (WBS-LP) and waveband switching lighttrail (WBS-LT).

Auxiliary graph models (LP_AG/LT_AG) are proposed for WBS-LP/WBS-LT respectively. These two auxiliary graph models can exploit not only the wavelength resource in the fiber links but also the limited waveband ports resource inside the multi-granular optical cross connects (MG-OXC) nodes. The influence of network parameters, e.g. number of wavebands, ports and transceivers, is studied. The proposed algorithms are compared with shortest path (SP), least-weighted path (LW), and K-least-weighted path (KP) algorithms; numerical simulations show their better performance. For different algorithms, WBS-LT can have better blocking performance than WBS-LP especially when add/drop waveband ports are the critical resources.

Keywords: Routing and Wavelength Assignment, Waveband Switching, Multi-Granular Optical Cross Connect (MG-OXC), Light Trail networks, Auxiliary Graph

I. Introduction

Wavelength division multiplexing (WDM) is the most promising technology for next-generation networks. It effectively exploits the tremendous bandwidth in fibers by dividing the fiber bandwidth into a set of wavelengths [1]. With the advances of dense WDM (DWDM), a fiber can provide a large number of wavelength channels (e.g., 64 and 160) and each channel can operate at very high speed (10 Gbit/s and 40 Gbit/s). Optical technology does not only play the role in transmission but also in switching. By using optical cross connects (OXCs) in the network, a lightpath can be established from the source to the destination for a connection request in an optical network [2].

Generally, the ordinary OXC is composed by optical demultiplexer, optical switches and optical multiplexer in order to switch each wavelength individually in the nodes. However, with the increase of the number of wavelengths in the network, the number of ports at OXCs also rapidly rises, and increase the cost and difficulty associated with controlling such large cross-connects. Recently Waveband Switching (WBS) has been proposed for optical networks with large number of wavelengths [3-13]. The main idea of

WBS is to group several wavelengths together as a band, and switch the band using only one single port instead of several ports whenever possible. Therefore the size of optical cross-connects (OXCs) that traditionally switch at the wavelength level can be reduced because of the bundling of lightpaths into bands. This kind of OXCs which can switch not only wavelengths but also wavebands and even fibers is called Multi-Granular Optical Cross-Connect (MG-OXC). Different kinds of MG-OXC architecture have been proposed in [3-13]. [6] presents and compares two types of MG-OXCs: Single-layer and Multi-layer MG-OXCs. In a single-layer MG-OXC, the WBS function is realized by using one optical switch. In a multi-layer MG-OXC, different optical switches work at different levels, e.g. wavelength, waveband, fiber etc. The work in [7] studies how to design a scalable WBS network with the minimum number of extra switching points. WBS with limited wavelength conversion is studied in [3]. [4] shows that waveband transmission and switching technologies can be used in existing optical networks by field trials.

In a lightpath, no traffic is added or dropped in the intermediate nodes until it reaches the end. However, since a single connection will rarely utilize the full available capacity of a wavelength channel, lightpath principle leads to a low load on each wavelength. Recently a new concept called *light trails* was proposed to enable IP-centric communications at the optical layer [14-20]. A light trail is a unidirectional optical bus between the convener node and the end node. It is similar to a lightpath with one important difference that the intermediate nodes can also access this unidirectional bus, and the upstream node can send data to any of its downstream nodes without the need for optical switch reconfiguration. Every node receives the data from the upstream nodes, but only the corresponding destination node(s) will accept the data packets while other nodes will ignore them. Therefore this network can minimize the amount of active switching needed, reduce connection setup time and improve path utilization. Several connections can be established along a single light trail and then the ports used could be saved.

In this paper, we will study the combination of these two approaches: waveband switching and light trails. We will introduce dynamic WBS in light trail networks (WBS-LT) and compare it with traditional WBS in lightpath networks (WBS-LP). In order to efficiently set up lightpath and light trails in WBS optical networks, auxiliary graphs (AGs) will be proposed for WBS-LP and WBS-LT respectively. We show that our proposed algorithms achieve lower request blocking probabilities especially when the waveband ports are the critical resources.

This paper is organized as follows: in Section 2, the network model for WBS-LT is introduced and the MG-OXC node architecture for WBS-LT is presented and compared

with that for WBS-LP; in Section 3, methods for generating auxiliary graphs and algorithms for setting up lightpaths and light trails in WBS-LP and WBS-LT networks are proposed respectively; Section 4 compares the WBS-LP and WBS-LT for different situations by using extensive numerical simulation and then the work is concluded in Section 5.

II. Network model for WBS-LT

2.1 Waveband switching in light trail networks

In light trail networks, intermediate nodes can access the light trail by using optical couplers [14]. This is the main difference between lightpath and light trail networks, and will be kept between WBS-LP and WBS-LT networks. Therefore in WBS-LP networks wavelengths in a waveband or even a fiber can bypass the same intermediate node by using only one input/output waveband or fiber port. The wavelengths in the waveband and fiber do not need to be demultiplexed into wavelength level. While in WBS-LT networks, the light trail should be accessible to every intermediate node (maybe not all nodes transmit traffic at the same time, however one intermediate node with available transceivers should have the possibility to transmit traffic on the light trail by using an appropriate media access control (MAC) protocol), that means the light trail should be demultiplexed into wavelength level at every intermediate node.

2.2 Node architecture for WBS-LT

Similar to the multi-layer MG-OXC proposed for WBS-LP network in [6], Fig. 1 shows a generalized MG-OXC for WBS-LT networks. The MG-OXC is also composed of three optical switches, Fiber Cross Connect (FXC), Waveband Cross Connect (BXC) and Wavelength Cross Connect (WXC). The FXC has Z input and output ports for normal fiber inputs and outputs, while αZ ($\alpha \leq 1$) ports for add from and drop to waveband level. Waveband to Fiber (BTF) multiplexer and Fiber to Waveband (FTB) demultiplexer are used to connect FXC and BXC. There are Y input and output ports in BXC for normal waveband input and output, while βY ($\beta \leq 1$) ports for add from and drop to wavelength level. Waveband to Wavelength (BTW) demultiplexer and Wavelength to Waveband (WTB) multiplexer are used to connect BXC and WXC. Since any arbitrary waveband could be dropped to BTW demultiplexer and added from WTB multiplexer, Array Waveguide Grating (AWG) will be used for these BTW/WTB demultiplexer/multiplexer. Because the AWG has a periodic response in frequency, all the wavelengths in one waveband must lie within one free spectral range (FSR) [21].

Compared with the multi-layer node architecture of WBS-LP in [6], there are two main differences in that of WBS-LT:

- 1) In wavelength level, add/drop ports are not needed. Instead, in order to realize the light trail function, for each wavelength, an optical shutter is used for starting and ending a light trail. Optical couplers for each wavelength are used to realize the “drop and continue” function.
- 2) We consider that the nodes may not be fully equipped with transceivers, and two optical switches are added to

select tunable transceivers for adding and dropping signals and realizing “Tune-in” function [20].

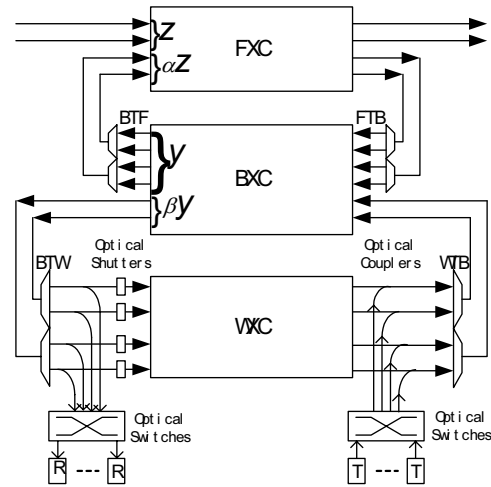


Fig.1 MG-OXC Node architecture for WBS-LT Networks

III. Algorithms description

As it is pointed out in [6], for single fiber systems, it is necessary to set $\alpha=1$ to allow any fiber to be demultiplexed to wavebands, otherwise, the blocking probability is too high. We will then focus on the value of β and study its influence on the performance.

For both WBS-LP and WBS-LT networks, auxiliary graphs are proposed respectively in order to exploit both the waveband port resources inside nodes and wavelength resources in fiber links. In section 3.1 the method of generating auxiliary graph for WBS-LP networks is introduced, and in section 3.2, the method of generating auxiliary graph for WBS-LT networks is introduced. The routing and wavelength assignment algorithms for both WBS-LP and WBS-LT is then introduced in Section 3.3

3.1 Auxiliary graph for WBS-LP networks

In WBS-LP networks, generally there are four kinds of ways to group wavelengths (lightpaths) into wavebands: end to end (ETE), source to intermediate (STI), intermediate to destination (ITD), and intermediate to intermediate (ITI) [5, 11]. In ETE waveband grouping, multiple wavelengths between the same source and destination nodes are grouped into a waveband. In STI, the wavelengths are first grouped in a waveband at the same source node and then disaggregated at intermediate nodes. Similarly, in ITD, wavelengths are grouped into wavebands at intermediate nodes and all the wavelengths are disaggregated at the same destination node. In ITI, wavelengths are aggregated and disaggregated at any intermediated nodes. Intuitively, ITI is the most flexible method for waveband switching. Therefore we propose an auxiliary graph for ITI waveband switching in WBS-LP networks (LP_AG).

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1: If (there is a fiber connecting one node pair in  $G_0$ ) then
    {Two unidirectional arcs with weight  $E_L$  are added from corresponding T to R in the neighboring nodes.}
2: For ( $n=1:N$ )
    If  $I(n)>0$  then /* there are free add waveband ports can be used. */
        {Unidirectional arcs with weight  $E_S$  are added from A to all the Ts within node  $n$ .}
    If  $O(n)>0$  then /* there are free drop waveband ports can be used. */
        {Unidirectional arcs with weight  $E_R$  are added from all the Rs to A within node  $n$ .}
        Unidirectional arcs with weight  $E_D$  are added from all the Rs to all the Ts within node  $n$ .
    }
3: For ( $x=1:X$ ) /* check existing lightpaths */
    If ( $\lambda_x \in B_m$ ) then /*the wavelength used by  $x^{\text{th}}$  lightpath is in the same waveband of  $\lambda$ .*/
        For ( $y=1:L_x$ )
            If ( $\lambda_x = \lambda$  &  $y < L_x$ ) then /*the wavelength has been used in these arcs*/
                {Remove the unidirectional arc from corresponding T in  $LP_x^y$  to R in neighboring node  $LP_x^{(y+1)}$ .}
            If ( $y=1$ ) then /* the first node of the lightpath */
                {A unidirectional arc with weight  $E_C$  from A to the corresponding output T is used to replace the one with  $E_S$  in  $LP_x^y$ , and remove all other arcs to the T.}
            If ( $y=L_x$ ) then /* the last node of the lightpath */
                {A unidirectional arc with weight  $E_G$  from the corresponding input R to A is used to replace the one with  $E_D$  in  $LP_x^y$ , and remove all other arcs from the R.}
            If ( $y \neq 1$  &  $y \neq L_x$ ) then /* the intermediate node of the lightpath */
                If ( $LP_x^y$  is demultiplexed into wavelength level) then
                    {A unidirectional arc with weight  $E_S$  from A to the corresponding output T is used to replace the one with  $E_S$  in  $LP_x^y$ , and remove all other arcs to this T.}
                    {A unidirectional arc with weight  $E_G$  from the corresponding input R to A is used to replace the one with  $E_D$  in  $LP_x^y$ , and remove all other arcs from this R.}
                Else /* the lightpath is passing through  $LP_x^y$  in waveband level */
                    {A unidirectional arc with weight  $E_S$  from the corresponding input R to the corresponding output T is used to replace the one with  $E_S$  in  $LP_x^y$ , and remove other arcs from the R and other arcs to the T.}
            }
        }
4: A unidirectional arc is added from the virtual source node S to A in the real source node.
   A unidirectional arc is added from A in the real destination node to the virtual destination node D.

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Fig. 2 The method to generate the auxiliary graph for WBS-LP networks

The physical network can be represented by $G_0=(V_0, E_0)$, where V_0 and E_0 are the set of nodes and fiber links. Assume there are W wavelengths can be used in the network and these wavelengths are uniformly divided into B wavebands. According to the current status of the network, for one lightpath establishment request, an auxiliary graph $G=(V, E)$ is generated for each wavelength (λ). Four types of vertices are defined in the auxiliary graph in order to abstract the nodes in the original network.

Transmitting vertex (T): abstracts a transmitting port on a node and is in waveband level. The T can connect to a remote R (see below) on a neighboring node if the wavelength λ is free in the fibers. The T can be connected to other Rs within the same node. The T can also be connected to the accessing vertex A (see below) within the same node according to add/drop waveband ports. The number of Ts in each node equals to the node degree.

Receiving vertex (R): abstracts a receiving port on a node and is in waveband level. The R can be connected to a remote T on a neighboring node if the wavelength λ is free in the fibers. The R can connect to other Ts within the same node. The R can also connect to the accessing vertex A (see below) within the same node according to add/drop waveband ports. The number of Rs in each node also equals to the node degree.

Accessing vertex (A): abstracts the accessing point on a node and is in wavelength level. The accessing vertex A can

be connected to the Ts/Rs within the same node according to add/drop waveband ports. The number of A in each node is 1.

End vertex (EX): represents the virtual source (S) and destination (D) node in the auxiliary graph.

We use the following notations: $I(n)$ and $O(n)$ ($1 \leq n \leq N$, $V_0/N=N$): the number of free add (from WXC to BXC) and drop (from BXC to WXC) waveband ports in node n . Assume there are X lightpaths being established in the network. The wavelength used for the x^{th} ($1 \leq x \leq X$) lightpath is λ_x , and the number of nodes of this lightpath is L_x . The node in the x^{th} lightpath is labeled as LP_x^y ($1 \leq x \leq X$, $1 \leq y \leq L_x$). For each wavelength λ in the network, assume λ belongs to waveband B_m , the auxiliary graph for wavelength λ is generated by using the method shown in Fig. 2.

In Fig.2, Step 1 and Step 2 initialize the network state without considering the existing lightpaths in the network. Step 1 sets wavelength channels free at all fiber links. Step 2 sets waveband ports free in all the nodes. If there are existing lightpaths in the network, the network status, including the wavelength occupied in the fiber links and waveband ports used in the nodes, is updated in Step 3. In Step 4, virtual source and destination nodes are connected to the accessing vertices of the real ones.

In the auxiliary graph, the arcs with weight E_L represent the wavelength resources in the fibers. If there is an arc between

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1: If (there is a fiber connecting one node pair in  $G_0$ ) then
   {Two unidirectional arcs with weight  $E_L$  are added from corresponding T to R in the neighboring nodes.}
2: For ( $n=1:N$ )
   {If  $I(n)>0$  then /* there are free add waveband ports can be used. */
   {Unidirectional arcs with weight  $E_B$  are added from A to all the Ts within node n.}
   If  $O(n)>0$  then /* there are free drop waveband ports can be used. */
   {Unidirectional arcs with weight  $E_B$  are added from all the Rs to A within node n.}
   }
3: For ( $x=1:X$ ) /* check existing light trails */
   {If ( $\lambda_x \in B_m$ ) then /*the wavelength used by  $x^{\text{th}}$  light trails is in the same waveband of  $\lambda$ . */
   {For ( $y=1:L_x$ )
   {If ( $\lambda_x == \lambda$  &  $y < L_x$ ) then /*the wavelength has been used in these arcs*/
   {Remove the unidirectional arc from corresponding T in  $LT_x^y$  to R in neighboring node  $LT_x^{(y+1)}$ .}
   If ( $y=1$ ) then /* the first node of the light trail*/
   {A unidirectional arc with weight  $E_G$  from A to the corresponding output T is used to replace the one with  $E_B$  in  $LT_x^y$ .}
   If ( $y=L_x$ ) then /* the last node of the light trail*/
   {A unidirectional arc with weight  $E_G$  from the corresponding input R to A is used to replace the one with  $E_B$  in  $LT_x^{L_x}$ .}
   If ( $y \neq 1$  &  $y \neq L_x$ ) then /* the intermediate node of the light trail*/
   {A unidirectional arc with weight  $E_G$  from A to the corresponding output T is used to replace the one with  $E_B$  in  $LT_x^y$ .
   A unidirectional arc with weight  $E_G$  from the corresponding input R to A is used to replace the one with  $E_B$  in  $LT_x^y$ .}
   }
   }
   }
4: A unidirectional arc is added from the virtual source node S to A in the real source node.
   A unidirectional arc is added from A in the real destination node to the virtual destination node D.

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Fig. 3 The method to generate the auxiliary graph for WBS-LT networks

R and T in different nodes, it means the signals can be transmitted from one node to its neighboring node on this fiber since wavelength λ is free. The arcs with weight E_G represent connections between used waveband ports. It means these waveband ports have already been configured for other wavelengths (lightpaths) in the same waveband, and the signals can be transmitted on them without configuration. The arcs with weight E_B represent potential connections between free waveband ports. These waveband ports can be configured for the new connection request. The arcs with weight E_B and E_G represent the waveband ports resources in the nodes. By finding the least-weighted route across the auxiliary graph from the virtual source node S to the virtual destination node D, a route for the new lightpath can be found. Different values of arc weights can lead to different routing strategies. For example, if we set $E_G \ll E_L \ll E_B$, then the least-weighted route will try to find the route using the least number of new waveband ports.

3.2 Auxiliary graph for WBS-LT networks

Similar to that for WBS-LP networks, an auxiliary graph model is also proposed for setting up light trails in WBS-LT networks (LT_AG). We defined the same types of vertices in the auxiliary graph:

Transmitting vertex (T): The T can connect to a remote R on a neighboring node if the wavelength λ is free in the fibers. The T can also be connected to the accessing vertex A within the same node. However, compared with that in LP_AG, The T can not be connected to other Rs within the same node.

This is because the waveband ports need to be demultiplexed to wavelength level.

Receiving vertex (R): The R can be connected to a remote T on a neighboring node if the wavelength λ is free in the fibers. The R can also connect to the accessing vertex A. Compared with that in LP_AG, The R can not connect to other Ts within the same node.

Accessing vertex (A) and End vertex (EX) are the same as those in LP_AG.

Let $I(n)$ and $O(n)$ ($1 \leq n \leq N$, $V_0 \neq N$) still represent the number of free add (from WXC to BXC) and drop (from BXC to WXC) waveband ports in the node n . Assume there are X light trails in the network. The wavelength used for the x^{th} ($1 \leq x \leq X$) light trail is λ_x , and the number of nodes of this light trail is L_x . The node in the x^{th} light trail is labeled as LT_x^y ($1 \leq x \leq X$, $1 \leq y \leq L_x$). For each wavelength λ in the network, assume λ belongs to waveband B_m , the auxiliary graph for wavelength λ is generated by using the method shown in Fig. 3.

There are also four steps in Fig. 3. Step 1 sets wavelength channels free at all fiber links. Step 2 sets waveband add/drop ports free in all the nodes. In Step 3, the network status is updated by checking existing light trails. Finally, virtual source and destination nodes are connected to accessing vertices of the real ones.

In LT_AG the arcs with weight E_L , E_G and E_B have the same meaning as those in LP_AG. A route for the new light

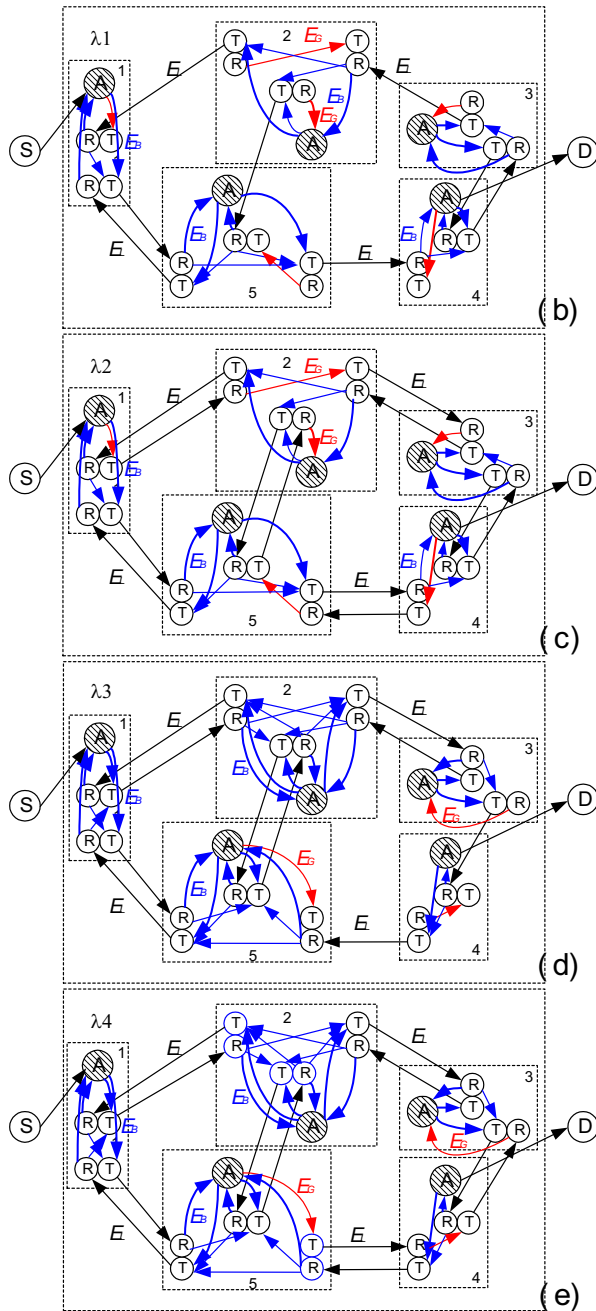
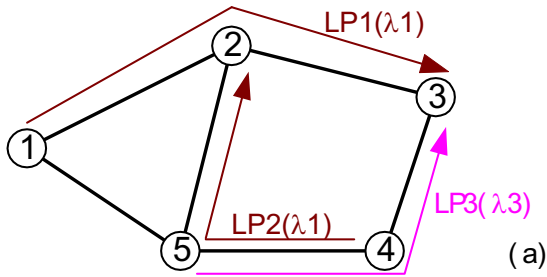


Fig. 4 An example to generate the auxiliary graphs for WBS-LP Networks

trail can be selected by finding the least-weighted route across the auxiliary graph from S to D.

Compared with the method in Fig. 2, it can be found that in Fig.3, inside one node Rs and Ts can only be connected to A, and there are no arcs between Rs and Ts. This is because light trail needs to be demultiplexed into wavelength level in every intermediate node. While in the WBS-LP network, the lightpath can pass through one node without demultiplexing into wavelength level, which is reflected by arcs between Rs and Ts inside one node.

Fig.4 and Fig. 5 show examples to generate auxiliary graphs for different wavelengths in WBS-LP and WBS-LT networks respectively. Fig.4 (a) shows the physical network of WBS-LP, in which 3 lightpaths have already been established. There are 4 wavelengths in the network, and λ_1, λ_2 belong to waveband B_1 , λ_3, λ_4 belong to waveband B_2 . For a new connection request from node 1 to node 4, a new lightpath needs to be established. Fig.4 (b)-(e) shows the auxiliary graphs generated for λ_1 to λ_4 respectively. Assume that the weights of the arcs are $E_G \ll E_L \ll E_B$, it can be found that in Fig. 4(b) the least-weighted route for λ_1 is 1-5-4, and no existing waveband ports can be used. In Fig. 4 (c), the least-weighted route is 1-2-3-4 for λ_2 and it first shares the existing waveband ports with $LP1$ along 1-2-3 and new waveband ports are used in 3 and 4. In Fig. 4 (d), the least-weighted route is also 1-2-3-4 for λ_3 , and new waveband ports need to be used in all these nodes. In Fig. 4 (e), the least-weighted route is still 1-2-3-4 for λ_4 , and no existing waveband ports can be used. Comparing all these four available routes, the route 1-2-3-4 in λ_2 will be selected to setup the new light path since it has the least weight.

For comparison, assume there are also 3 light trails (along the same routes of LPs in Fig.4 (a)) in the physical network of WBS-LT, as shown in Fig.5 (a). A new light trail also needs to be established for a new connection request from node 1 to node 4 (we do not consider traffic grooming between light trails like that in [20]). Fig.5 (b)-(e) shows the auxiliary graphs generated for λ_1 - λ_4 .

In Fig. 5(b) the least-weighted route is 1-5-4 and no existing waveband ports can be shared. In Fig. 5 (c), the least-weighted route is 1-2-3-4 for λ_2 and it first shares the existing waveband ports with $LP1$ and then uses new waveband ports in node 3 and 4. In Fig. 5 (d), the least-weighted route is also 1-2-3-4 for λ_3 , and new waveband ports need to be used in all these nodes. In Fig. 5(e), the least-weighted route is 1-5-4 for λ_4 , and it first uses new waveband ports in node 1 and 5, and then shares waveband ports with $LT3$ in node 5 and 4. Comparing all these four available routes, the route 1-5-4 in λ_4 will be chosen to setup the new light trail.

3.3 Dynamic algorithms for waveband switching in optical networks

The steps for setup lightpaths/light trails in WBS-LP/WBS-LT networks are the same. The new lightpath/light trail is established by using the auxiliary graph models proposed above (LP_AG/LT_AG). Each time for a request to establish a connection $Req(s, d, C)$, where s, d are the source and

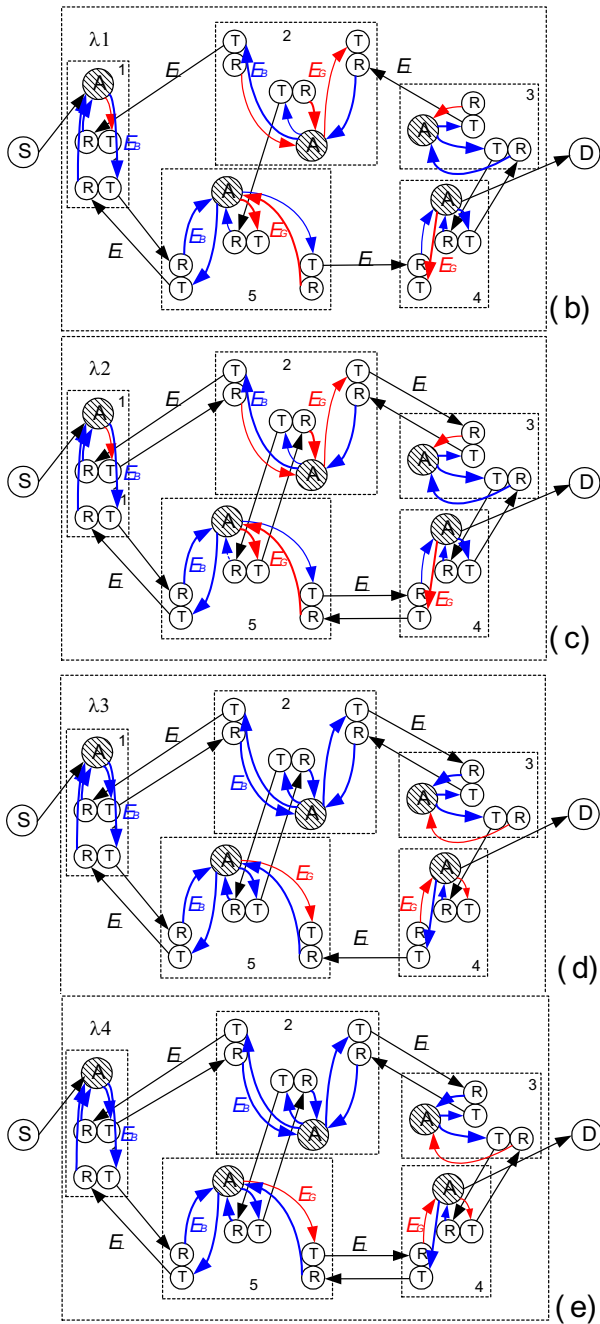
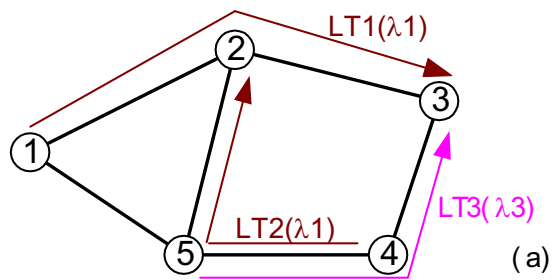


Fig. 5 An example to generate the auxiliary graphs for WBS-LT Networks

destination nodes, respectively, and C is the traffic requirement, the sequence of steps to establish it is the following:

Step 1: try to establish the connection on a single existing lightpath/light trail. (In WBS-LP, check each exiting lightpath with residual capacity not smaller than C , if s and d are the same, then this connection can be established in this existing lightpath, go to *Step 3*; while in the WBS-LT, check each existing light trail with residual capacity not smaller than C , if s and d are both in one light trail, s is the upstream node of d , and there are transceivers that can be used for this connection, then this connection can be established on this single light trail, go to *Step 3*. Otherwise go to *Step 2*).

Step 2: try to establish the connection by setting up a new lightpath/light trail. If there are free transceivers at both the source and destination nodes, then for each wavelength generate the auxiliary graph (LP_AG/LT_AG), and then find the least-weighted route in each auxiliary graph. Choose the one with the least value to set up the new lightpath/light trail. If succeed, go to *Step 3*. Otherwise go to *Step 4*.

Step 3: update the residual capacity of the lightpath/light trail used and the number of residual transceivers. Wait for another request.

Step 4: the connection request can not be established by residual network resources, and it will be discarded. Wait for another request.

If the new request is to release a connection, then update the residual capacity of the lightpath/light trail used and the number of free transceivers in the nodes. If one lightpath/light trail does not carry any traffic, then remove it from the network and release the wavelength resources used in the fibers and the port resources used in the nodes.

Let N and M be the number of nodes and the maximum node degree in the network $G_0=(V_0, E_0)$ respectively. Then we can get $|V|=O(NM)$, and the worst complexity of this algorithm is the complexity of Dijkstra's algorithm $O(W|V|^2)$ since W wavelengths need to be examined.

IV. Numerical Results

The NSFNET with 14 nodes and 21 links has been chosen for the simulation studies. Assume each link is bi-directional with a fiber in each direction. A node with a higher node-degree is equipped with more transceivers, e.g. a node with m links is equipped with mw ($1 \leq w \leq W$) tunable transceivers. There are $W=16$ wavelengths in each fiber with the wavelength capacity $P=4$. All the wavelengths are divided into B bands. The generation of connection requests for the whole network is governed by a Poisson process, and a connection is held for a negative-exponentially distributed time with a mean of unity after being established. Connection requests are uniformly distributed between all the node pairs. The traffic requirements of the connection requests are uniformly distributed as order of $1/P$. First 10,000 connection requests are used for network warm-up; blocking probabilities are estimated by subsequent 100,000 requests.

We compare WBS-LP and WBS-LT networks for different algorithms. In the proposed algorithms (LP_AG/LT_AG), we assume the weights of the arcs are $E_G \ll E_L \ll E_B$, which can find the route using the lowest number of new waveband ports. In WBS-LP networks, we also study the following algorithms for setting up a new lightpath:

- 1) LP_SP: In this algorithm, first the shortest hop path will be found for the s and d node pair and then each wavelength will be checked in order to find the one in common with other existing lightpaths in the same band as much as possible.
- 2) LP_LW: In this algorithm, the least-weighted path (here weight means the number of wavelengths occupied in the fibers) will be found for the s and d node pair and then each wavelength will be checked in order to find the one in common with other existing lightpaths in the same band as much as possible.
- 3) LP_KP: In this algorithm, K least-weighted paths will be found for the s and d node pair. Each wavelength in each of the K paths will be checked, and the wavelength and the path in common with other existing lightpaths in the same band as much as possible will be selected.

In the WBS-LT network, similar to that in WBS-LP, the following algorithms are studied for setting up a new light rail:

- a) LT_SP: In this algorithm, the shortest path will also be used for the light trail setup and each wavelength will be checked in order to find the one use as few new add/drop waveband ports as possible.
- b) LT_LW: In this algorithm, the least weight (LW) path will also be used for each light trail setup and each wavelength will be checked in order to find the one use as few new add/drop waveband ports as possible.
- c) LT_KP: In this algorithm, K least-weight paths will be checked sequentially for each light trail setup request and for each one of the K paths, all the wavelengths will be checked, and then the route and the wavelength use the least number of new add/drop waveband ports will be selected.

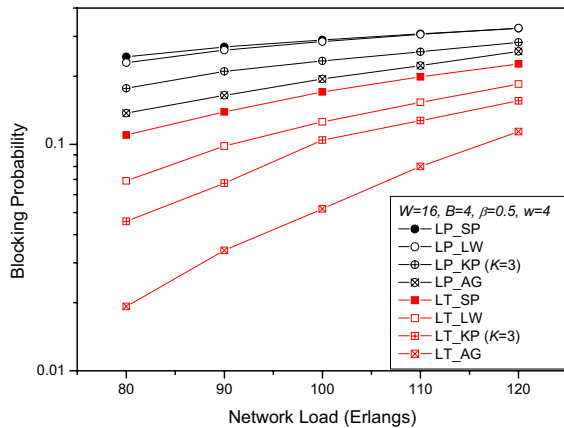


Fig. 6 Blocking Probability vs. Network Load

Fig. 6 shows the relationship between the network blocking probability and the network load for different algorithms, when the number of wavebands is $B=4$, the number of transceivers in the nodes and the add/drop waveband ports are limited ($w=4$ and $\beta=0.5$). It can be found that in this case the WBS_LP network has much worse blocking performance than the WBS_LT network. Under the same condition, the best result of WBS-LP network can not be better than the worst one of WBS-LT network. This is because the light trail principle leads to connections sharing the capacity in light trails and then saving transceivers and waveband ports.

In these two networks: Shortest Path (SP) algorithm always has the worst performance since it always uses the same route to setup lightpath/light trail for the same source and destination. Least-Weight (LW) algorithm is better than SP because it can find alternative routes to setup lightpath/light trail for the node pairs. While KP ($K=3$) algorithm is again better these two algorithms since K routes can be examined and the network resource can be explored. Among all the algorithms, the proposed algorithms LP_AG and LT_AG always have the best blocking performance. This is because in both algorithms, they can explore not only the wavelength resources in the fibers but also the port resources in the nodes and always tries to find the route and the wavelength using the least number new add/drop waveband ports and then can save these resources for later connection request.

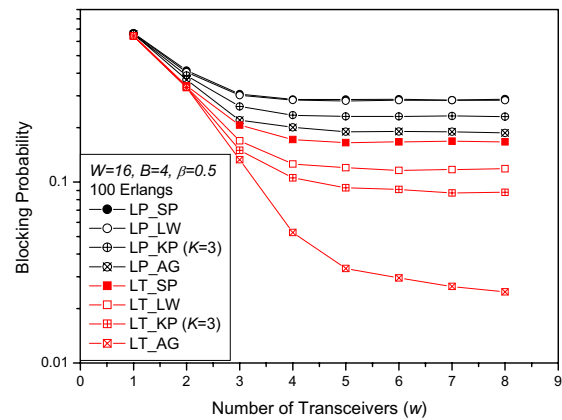


Fig. 7 Blocking Probability vs. Number of Transceivers

Fig. 7 shows the relationship between the network blocking probability and the number of transceivers in the nodes for different algorithms, when the network load is 100 Erlangs and $B=4$, $\beta=0.5$. It is obvious that with the increase of the number of transceivers in the nodes, the blocking probability for different algorithms will decrease. For all the algorithms, when w is smaller than 4, the blocking probability decreases very quickly with the increase of w , and it means the network blocking probability is mainly due to the shortage of transceivers. When w is larger than 4, the blocking probability almost keeps the same (except the proposed LT_AG algorithm) and that means now transceivers are not the critical part, the blocking probability comes from the non-

efficiently using other network resources, like waveband ports and wavelengths. It can be found that WBS_LT has better blocking performance than WBS_LP for difference algorithms. In both WBS_LT and WBS_LP, KP algorithm is better than LW and SP, while LW is better than SP. When the LP_AG/LT_AG algorithms are used, the blocking probabilities are always the lowest for different number of transceivers. That means the proposed algorithms can efficiently use the network resources.

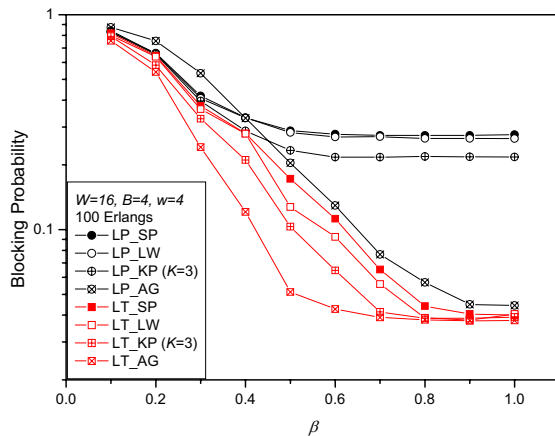


Fig. 8 Blocking Probability vs. β

Fig. 8 shows the relationship between the network blocking probability and the percentage of add/drop to normal waveband ports β , when the network load is 100 Erlangs, and $B=4$, $w=4$. It can be found that in the WBS_LP network, for LP_SP, LP_LW and LP_KP, with the increase of β , first the blocking probability decreases very quickly and then levels down after β is larger than 0.5. However, for LP_AG, the blocking probability keeps decreasing until β is larger than 0.9. When β is smaller than 0.5, LP_AG is worse than other algorithms, however when β is larger than 0.5, LP_AG has much better performance than other three algorithms in WBS_LP. For different β , WBS_LT network still has better blocking performance than WBS_LP. In the WBS_LT network, it can be found that LT_AG algorithm has much better performance than other algorithms especially when β is moderate. That means the AG algorithm can efficiently explore the waveband ports resources. When β is large than 0.9, LP_AG and all the algorithms in WBS_LT have similar performance since now the blocking probability is mainly due to the shortage of transceivers in the nodes.

The relationship between blocking probability and the number of wavebands in the network for different algorithms is shown in Fig. 9. The 16 wavelengths are uniformly divided into 2, 4, 8 wavebands. It can be found that the blocking probability decreases with the increase of the number of wavebands B . Under the same condition, WBS-LT is better than WBS-LP. The proposed algorithms LP_AG and LT_AG are better than other algorithms.

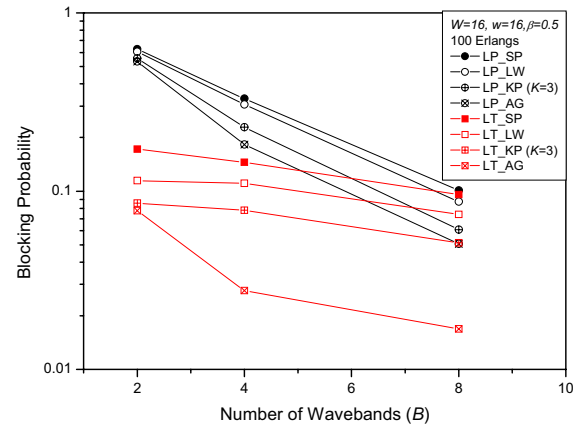


Fig. 9 Blocking Probability vs. number of wavebands (B)

V. Conclusion

In this paper we have studied waveband switching in both lightpath and light trail networks. In order to effectively setup lightpaths and light trails in optical networks, two auxiliary graph models have been proposed for WBS-LP and WBS-LT respectively. The auxiliary graph models can effectively exploit not only the wavelength resources in fiber links but also the limited number of waveband ports resource in MG-OXC. Compared with waveband switching in lightpath networks, the light trail principle leads to connections sharing the capacity in light trails and then saving transceivers and waveband ports. By numerical simulation, it can be found that the WBS_LT network has better blocking performance than the WBS_LP network for different RWA algorithms. The proposed algorithms LP_AG and LT_AG can find the route using the least number of new waveband ports and therefore have better performance than other algorithms: SP, LW, and KP.

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