Full Dedicated Optical Path Protection in the WDM Mesh Networks without Wavelength Conversion

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***Abstract*-In this paper, a WDM mesh network is planned and designed by two methods so that to satisfy all its demands and each connection has to be protected with the dedicated way by both nodes. In the first method, each connection uses the free available wavelength after the maximum busy wavelength (higher index) of each optical link from full complementary working and protection lightpaths. In the second method, each connection uses the first free (lowest index) available wavelength of each optical link from full complementary working and protection lightpaths.**

Keywords -WDM networks; dedicated protection.

I. INTRODUCTION

Optical networks using Wavelength Division Multiplex (WDM) make use of the enormous bandwidth of an optical fiber. WDM divides the tremendous bandwidth (~50THz) of a single mode optical fiber in to many non overlapping wavelengths (or wavelength channels with bandwidth 1-10 Gbps or more) which can operate simultaneously, with the fundamental requirement that each of these channels operate at different wavelengths. WDM basically is frequency division multiplexing in the optical range where the carrier frequencies are referred as wavelengths. These high capacity WDM optical mesh networks that based on optical technologies, provide routing, grooming and restoration at the wavelength level as well as wavelength based services.

In this paper, all network parameters are known and the WDM mesh network is planned and designed so that to satisfy all its demands using the shortest path algorithm and each connection has to be protected with the dedicated way and based on the spare capacity which is allocated as a "dedicated" resource for sole use of the connection. The assignment of the suitable wavelengths for each connection is done using a) the free available wavelength after the maximum busy (higher index) wavelength of each optical link from full complementary working and protection lightpaths, b) the first free **(**lower index**)** available wavelength of each optical link from full complementary working and protection lightpaths and c) the benefits of the second method versus the first one also shown when wavelength conversion is not used as well as the performance improvement when the wavelength conversion is used. The demand tables are large and they are not showed.

This paper is broken down in the following sections. Section II describes the related works. Section III describes the problem and provides a solution, the method synoptic description, an example and the discussion and proposals. Section IV draws conclusions and finally ends with the references.

II. RELATED WORKS

Research has been done [1]-[13] in relation to the methods and the problems associated with planning, protection and restoration of optical networks. A modelling and analysis was performed by H. Kobayashi [1]. Advanced software engineering course is showed by F. L. Bauer et al. [2]. There are several approaches to ensure fibre network survivability, as described by T. Wu [3] and A. Bononi [4]. V. E. Benes [5] analyzes Mathematical Theory of Connecting Networks and Telephone Traffic. In [6], B. Ramamurthy et al. write about Wavelength Conversion in WDM Networking. In [7], J. Emirghani et al. offer an overview of the enabling technologies and extend the treatment to the network application of the wavelength converters. In [8], C. Xiaowen et al. demonstrate that their paper network architecture can significantly save the number of wavelength converters, yet achieving excellent blocking performance. In [9], M. O'Mahony et al. begin with an overview on the future of optical networking. A historical look at the emergence of optical networking is first taken, followed by a discussion on the drivers

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pushing for a new and pervasive network, which is based on photonics and can satisfy the needs of a broadening base of residential, business and scientific users. J. Zhang et al. [10] present that, for fault management in optical WDM mesh networks end to end path protection, is an attractive scheme to serve customers' connections. In [11], the modelling methods and simulation tools are described and used for the analysis of a new integrated restoration scheme operating at multilayer networks. In [12], T. Ingham et al. deal with the modelling and simulation effectively help and validate the design of various components constituting the service delivery platform. In [13], J. Burbank deals with the modelling and simulation and gives practical advices for network designers and developers.

III. THE PROBLEM AND ITS SOLUTION

A. The problem

The network topology and other parameters are known as WDM and optical fibre capacity, the number of node pairs and the node pairs that the demands (requests for connection) must be satisfied and the m:N (1:7) WDM and optical fibre shared protection protocol. So, this network is characterized as multifibre network by working and protection fibres per link (multifibre link) and edges of two opposite direction links. The WDM mesh network is planned and designed so that to satisfy all its demands using the shortest path algorithm and each connection has to be protected with the dedicated way and based on the spare capacity which is allocated as a "dedicated" resource for sole use of the connection. The assignment of the suitable wavelengths for each connection is done using a) the free available wavelength after the maximum busy (higher index) wavelength of each optical link from full complementary working and protection lightpaths, b) the first free **(**lower index**)** available wavelength of each optical link from full complementary working and protection lightpaths and c) the benefits of the second method versus the first one also showed when wavelength conversion is not used as well as the performance improvement when the wavelength conversion is used. The demand tables are large and they are not showed.Table I with symbols is showed below. The network has identical nodes. Each node can be assumed to have two functionalities: first, a lightpath or connection request generation/termination capability and, second, a wavelength routing capability. This essentially means that a node can either act as the source/destination node of a lightpath or as wavelength routing node. On the network nodes are installed the Optical Cross Connects (OXCs). The Wavelength Division Multiplex- Optical Cross Connect (WDM - OXC) has multiplex and demultiplex systems that convert the aggregated optical signal to simple optical signals and vice versa. A lightpath is an optical channel from source to destination to provide a connection between these nodes and using a same free wavelength on all of the fiber links in the path.

TABLE I. THE SYMBOLS

Symbol	Comments
q	The node set element number
p	The edge set element number
G(V,E)	The network graph
V(G)	The network node set
E(G)	The network edge set
2p	The number of links
n	The number of source – destination nodes pairs of the network
(S_n,D_n)	The order pairs of the node pairs
Xn	A column matrix (nx1) with elements the connection group size of the corresponding source-destination node pairs and corresponds to the successful requests for connection.
n(i)	The total number of the connection groups that passes through the fiber (i) and means that each fiber has different number of connection groups pass through it
k	The number of the wavelengths channels on each fiber that is the WDM system capacity
Yw	The column matrixes (2px1) with the working wavelengths of network links.
Aw	Matrix (2p x n) which shows the network active links that pass working lightpaths
$aw_{i,j}$	Element of the matrix Aw and takes the value one if the node pair (j) passes all its primary connections from the fiber (i) and zero (0) if no passes
Adp	Matrix (2p x n) which shows the network active links that pass protection lightpaths
$adp_{i,j}$	Element of the matrix Adp and takes the value one if the node pair (j) passes all its backup connections from the fiber (i) and zero (0) if no passes
Ydp	The column matrixes (2px1) with the dedicated protection wavelengths of network links
A	Matrix (2p x n) which shows the network active links that pass lightpaths
$a_{i,j}$	Element of the matrix A and takes the value one if the node pair (j) passes all its connections from the fiber (i) and zero (0) if no passes
λmax,i	The maximum (highest index) busy wavelength of each optical link
m	The shared protection WDM and optical fiber systems of each link
N	The WDM and optical fiber systems of each link
Tw	The total working WDM and fiber systems
Tp	The total protection WDM and fiber systems

This is called wavelength continuity constraint. An optical channel passing through a cross-connect node may be routed from an input fiber to an output fiber on the same wavelength. It is assumed that no different wavelengths are assigned on all links along the route if nodes have not wavelength conversion capabilities. It means that the initial wavelength which carries the traffic does not shift to other wavelengths by intermediate nodes of the lightpath. The networks with this capability are called "Networks without wavelength conversion". If nodes have wavelength conversion different wavelengths can assign on all links along the route for each lightpath. It means that the initial wavelength which carries the traffic can shift to other wavelengths by intermediate nodes of the lightpath. The networks with this capability are called "Networks with wavelength conversion". For this example, the connection group size of each node pair is set to the number two (2).

B. The formulation

To make the problem computationally feasible, the problem is generally divided into subproblems, the working lightpath assignment and the backup lightpath assignment. But the lightpath assignment is different for each method. At the first method, the free available wavelength after the maximum busy (higher index) one on all of the links is assigned and at the second one, the first free (lower index) available wavelength on all of the links is assigned (if wavelength conversion is not used these wavelengths must keep along each lightpath but if wavelength conversion is used it is not valid). So each different assignment method produces different needs for optical fibers. So the maximum (higher index) occupied wavelength of the first method for each fiber is greater than the second one (lower index). So the critical factor is the number of wavelengths required to satisfy the network demands.

The solution of the planning and designing problem is based on the following equations.

$$Yw = Aw * Xn \tag{1}$$

Aw is a matrix that shows the active optical fiber network links (*2p*) from which the (*n)* working connection groups pass so its dimension is (2p x n), Y_w the column matrix (2p x 1) which has elements the working busy capacity of each optical fiber network link and Xn the column matrix (n x 1) which has elements the connection group size of each node pair. The total working wavelengths for all links (*TYw*) are given below but the total working wavelengths of each link is the term in the bracket.

$$TYw = \sum_{i=1}^{2p} \left[\sum_{j=1}^{n} A_{w\,i,j} * X_j \right] \tag{2}$$

The knowledge of each node pair demands which are its requests for connection and their shortest full disjoint dedicated protection lightpaths create the necessary wavelengths for their satisfaction for each link.

$$Ydp = Adp * Xn \tag{3}$$

Adp is a matrix that shows the active optical fiber network links (*2p*) from which the (*n)* protection connection groups pass so its dimension is (2p x n), Y_{dp} the column matrix (2p x 1) which has elements the protection busy capacity of each optical fiber network link. The total dedicated protection wavelengths for all links (*TYdp*) are given below but the total dedicated protection wavelengths of each link is the term in the bracket.

$$TYdp = \sum_{i=1}^{2p} \left[\sum_{j=1}^{n} A_{dp\,i,j} * X_j \right] \tag{4}$$

$$A = A_w U A_{dp} \tag{5}$$

The unity of the matrixes A_w and A_{dp} gives the matrix A in which there are common active links for working and protection lightpaths.

The total wavelengths are the following

$$TY = TYw + TYdp \tag{6}$$

The maximum (higher index) busy wavelength of each optical link is λmax,i. The maximum (higher index) busy wavelength of all optical links is λmax and λmax= maximum ($\lambda max,_1$, $\lambda max,_2$, …, $\lambda max,_{2p}$).

The total working WDM and fiber systems given by

$$T_w = \sum_{i=1}^{2p} \left\lceil \frac{\lambda max,i}{k} \right\rceil \tag{7}$$

The total protection WDM and fiber systems given by

$$T_p = \sum_{i=1}^{2p} \frac{m}{N} \left\lceil \frac{\lambda max,i}{k} \right\rceil \tag{8}$$

The parentheses mean the rounding. When the protection network is not used the term which multiplied with (m/N) is neglected and the available resources are less. The equation (8) means that multiplying the number of the necessary working WDM and optical fiber systems of each link with the m:N ratio creates the necessary protection WDM and optical fiber systems. The m:N=1:7 shared protection WDM and optical fiber systems of each link means that the maximum number of working WDM and optical fiber systems that sharing a protection WDM and optical fiber system is seven. It is a practical way to reduce the cost of the protection network. The roundup is always done for the larger integer. If there are not protections WDM and fiber systems the equation (8) is zero.

The total WDM and optical fiber systems are

$$T = T_w + T_p \tag{9}$$

The wavelength protection ratio for dedicated protection is written below

$$PR_d = \frac{TY_{dp}}{TY_w} \tag{10}$$

C. Synoptic description of the methods

Two methods are used in this paper. These methods have two parts, the first part or the planning and designing part that means network without failure and the second part or network with failure. The algorithm of allocation path and routing uses a more traditional approach which is the shortest path algorithm. The synoptic description of these methods is showed in the table II. On the failure free network phase, the third step (wavelength allocation step) is the more critical and it is different to each method. The network has not nodes with wavelength conversion. The working connection starts from the source node and progresses through the network occupying a wavelength on each optical fibre and switch to another fibre on the *same* wavelength by OXC, according to its shortest working optical path up to arrive at the destination node. Simultaneously, the protection lightpath of the connection starts from the source node and progresses through the network occupying a wavelength on each optical fibre and switch to another fibre on the *same* wavelength by OXC, so another full disjoint protection optical path is obtained. So the full dedicated protection for this connection is obtained. The difference between "without wavelength conversion" and "with wavelength conversion" is the occupied wavelength of the link after switching that is the "same" with the wavelength if input, for the case of "without" and "anyone" for the case "with".

The assignment problem of both algorithms can be used by both cases (nodes without or with wavelength conversion) suitably modified. The assignment problem of each algorithm is working as follows to keep the capability of nodes without conversion. For the first algorithm, each node pair uses the free available wavelength after the maximum busy (higher index) one which is the same for all optical links of the working path of the connection and the same is done for the protection lightpath of the connection. The first algorithm is adapted in the problem of nodes without wavelength conversion. In this scheme, all wavelengths are numbered. The searching for available wavelengths is done after the maximum busy wavelength and a higher numbered wavelength is considered. The first available wavelength is then selected. This scheme is requires no global information. The assignment problem for the second algorithm is as follows. For the second algorithm, for each node pair the *first* same (lower index) free available wavelength of all optical links of the working path of the connection is assigned and the same is done for the protection lightpath of the connection for the same node pair. If there is any such wavelength for all optical links, the connection is done by them. If no, the first algorithm is done. The second algorithm is the First Fit one adapted in the problem of nodes without wavelength conversion. In this scheme, all wavelengths are numbered. When searching for available wavelengths, a lower numbered wavelength is considered before a higher numbered wavelength. The first available wavelength is then selected. This scheme is requires no global information. The second algorithm is used for the problem of nodes with wavelength conversion.

When a failure occurs and an optical link cut, the working and protection WDM and fiber systems of this link are also cut and the network topology changes and protection lightpaths pass the traffic. Table II presents the synoptic description of the methods. Its worst case time complexity of each method depends of the network topology and the total number of connections. *It is $O(t*q^2)$ where t the total number of the connections*. The second method needs about 11 100th of the second (0.11 seconds) time to consume but the corresponded first protection method needs only 5 100th of the second (0.05 seconds). The time difference of these protection methods is small but the first method is faster than the second one.

In graph theory, the shortest path algorithm finds the shortest path between two given vertices in an undirected graph G= (V, E).The shortest path connects the two vertices and its length is minimum.

TABLE II. THE SYNOPTIC PRESENTATION OF THE METHODS

FIRST PART
First step. Network parameters reading
(q, p, V(G), E(G), G(V,E), 2,2p, k)
Second step. Connection selections
(n, (S_n,D_n), Xn,)
Failure-free Network Phase
Third step. Wavelength allocation
(Routing and wavelength assignment method)
Forth step. Results
(Yw, Ydp, (λmax,i) ,(Tw,i,) Tw, (Tp,i), Tp)
SECOND PART
With failure Network Phase
Fifth step. Network parameter modifications
(cut link, q, p, V(G'), E'(G'), G'(V,E'), 2,2p-1, k)
Sixth step. Traffic is passing by Protection lightpath
(Protection method)
Seventh step. New Results
(Y'w, Y'dp, (λ'max,i), (Tw,i), T'w, (Tp,i), T'p)

D. Example

It is assumed that the topology of the network is presented by the graph G(V,E). This mesh topology is used because it is a simple, palpable and it is easy to expand to any mesh topology. The vertex set has q=8 elements which are V= $\{v_1, v_2, v_3, v_4, v_5, v_6, v_7, v_8\}$ and the edge set has p=12 elements which are E = $\{e_1, e_2, e_3,\ldots, e_8, e_9, e_{10}, e_{11}, e_{12}\}$. Each edge has two optical links of opposite directions with their fibers for each direction. The connections of each node pair form connection groups according to its shortest path and transverse the network. Figure 1 presents the mesh topology.

Network planning and designing is flexible to meet the needs of the network. The capacity of WDM optical fiber system takes values of 8, 16 and 32 OCh (wavelengths). The number of node pairs is n=8*(8-1) =56. The source destination demands are not showed because their tables are large. The m:N WDM and optical fiber system shared protection is 1:7, which is a practical way to reduce the protection network. No further calculations and results are presented for the network planning and designing because their tables are very large and their meaning to solve the protection problem is small. The symbolism V_1,V_2,V_3 is usually used as follows on optical path layer (OCh layer). If the nodes have no wavelength conversion capability, it means that the wavelength of the input port wavelength is used at the output port. So a connection wavelength of the optical link <V_1, V_2> routes at the same wavelength one to the optical link <V_2, V_3> by WDM-OXC of node V_2 and thus, it is written V_1, V_2, V_3. If the nodes have wavelength conversion capability means that the wavelength of the input port wavelength is the same or different at the output port. The dedicated protection is done during the planning and designing steps allocating to each connection two links full disjoint lightpaths between the source and the destination node, one for the working lightpath and the other for the protection lightpath. If a failure occurs, the infrastructure will change and the protection lightpath passes the traffic. The capacity of the WDM system is 8,16 and 32 optical channels and each node pair has two connections. The total working wavelengths are 200 and the total protection wavelengths are 304, for each case of table 4. So the total busy wavelengths are 504. The wavelength protection ratio is 1.52. The <V_1, V_2> is assumed as a cut link. The table III shows the node pairs connections that pass through the cut link. The bold lightpaths are cut.

For the assignment (nodes without wavelength conversion), the tables which show the procedures and the results of each algorithm are large, so I don't show them. The connection of each node pair forms a connection group and by the both working and protection lightpaths proceed from source node to its destination node and by allocating a common free wavelength on all of the fiber links in the working lightpath and one corresponded in the protection lightpath. The entire bandwidth available on each lightpath (working or protection) is allocated to this connection during its holding time and the corresponded wavelengths cannot be allocated to any other connection. When a connection is terminated, the associated lightpaths are torn down and the wavelengths become free once again on all links along the routes. All connection group sizes are equal to two (2). The second algorithm has $\lambda_{max,i}$ wavelength for each link which is lower or equal than the corresponded of the first one and it means that equation (9) gives smaller or equal number WDM systems for the second algorithm versus first one. The difference of the performance is ought to the maximum wavelength index difference of two algorithms. The lightpath length is an important factor that effects on performance. The table IV shows the performance of each case as number of WDM and fiber systems. The performance of first algorithm is showed in the table IV(x). The performance of second algorithm if can find lower index free wavelengths for lightpaths with only one hop length, is showed in the table IV(1). The performance of second algorithm if can find lower index free wavelengths for lightpaths with only one and two hop length, is showed in the table IV(2). The performance of second algorithm if can find lower index free wavelengths for lightpaths with only one, two and three hop length, is showed in the table IV(3). The performance of second algorithm if can find lower index free wavelengths for lightpaths with only one, two, three and four hop length, is showed in the table IV(4). The performance of second algorithm if can find lower index free wavelengths for lightpaths with only one, two, three, four and five hop length, is showed in the table IV(5).Table IV(y) shows the improvement of performance if the second algorithm is used *with wavelength conversion*.

TABLE III. THE NODE PAIR CONNECTIONS THAT PASS THROUGH THE CUT LINK

A /A	Node Pair	Working Lightpath	Protection Lightpath
1	[V_1,V_2]	**V_1,V_2**	V_1,V_3,V_2
2	[V_1,V_3]	V_1,V_3	**V_1,V_2,V_3**
3	[V_1,V_5]	**V_1,V_2,V_5**	V_1,V_3,V_6 ,V_5
4	[V_1,V_6]	V_1,V_3,V_6	**V_1,V_2,V_5,V_6**
5	[V_1,V_7]	**V_1,V_2,V_5 ,V_7**	V_1,V_3,V_6,V_7
6	[V_1,V_8]	V_1,V_3,V_6,V_8	**V_1,V_2,V_5,V_7,V_8**
7	[V_3,V_2]	V_3,V_2	**V_3,V_1,V_2**
8	[V_4,V_2]	**V_4,V_1,V_2**	V_4,V_3,V_2
9	[V_4,V_5]	**V_4,V_1,V_2,V_5**	V_4,V_3,V_6,V_5
10	[V_4,V_6]	V_4,V_3,V_6	**V_4,V_1,V_2 ,V_5,V_6**
11	[V_4,V_7]	V_4,V_3,V_6,V_7	**V_4,V_1,V_2 ,V_5,V_7**
12	[V_4,V_8]	V_4,V_3,V_6,V_8	**V_4,V_1,V_2,V_5,V_7, V_8**

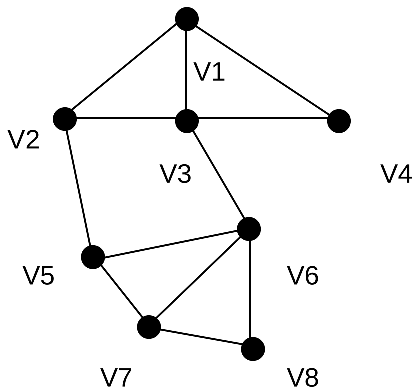

Figure 1.The mesh topology of the network

E. Discussion and Proposals

Protection strategies are critical for optical mesh networks. Although dedicated path protection mechanisms are simple and fast, they use 100% or more redundant capacity. Protection is the primary mechanism to deal with a failure and it is faster but no flexible. Spare wavelengths on the routes are dedicated or shared across working path demands that have no spans in common. It is not need to know the exact location of the failure because it is capable of protecting against multiple simultaneous failures on suitable working lightpaths. This protection method can give to the network surveillance after single failure as optical link cuts, node failures, wavelength scratches and multiple failures on working connection lightpaths. It is also uses the coherent protection of the mesh network. If the network is planned and designed to satisfy all its needs with protection paths, it means that no blocking probabilities should be calculated. The algorithm of the assignment is critical because it could be saved significant number of WDM and fiber systems and to do the network design less expensive. The second assignment algorithm has better performance than the first one (table IV, case (5) versus case (x)) because for each optical link its λmax is less or equal than the corresponded of the first one and produces smaller number of WDM and fibre systems. The other cases (1),(2),(3) and (4) give the transition to case (5). The wavelength conversion improves more the performance because reduced number of WDM and fiber systems is required, table IV(y). Its disadvantage is the usage of wavelength converters that are expensive. In a mesh network with wavelength conversion capability, each output port of the optical switch is associated with a dedicated wavelength converter. So it is able to convert all the input wavelengths to any other wavelengths without any limitation. This wavelength conversion method is called complete one. The number of converters is equal to the number of the fiber links multiplied by the number of wavelengths per fiber. So the number of converters will be large and the cost of such architecture can be high. The converters can be incorporated in the OXCs. The second algorithm of assignment is a variety of the First Fit. First Fit chooses the available wavelength with the lowest index. This is adjusted for both problems (nodes without and with wavelength conversion). When the capacity of WDM systems increases the number of these systems may be same, table IV, cases IV(4), IV(5) and IV(y) but their occupation percentage is different.

TABLE IV. THE COMPARISON OF THE PERFORMANCE

Up to Lightpath length	**WDM systems Capacity, 8λ**	**WDM systems Capacity, 16λ**	**WDM systems Capacity, 32λ**
x	224	124	83
1	208	115	75
2	143	85	61
3	124	78	54
4	118	72	48
5	118	72	48
y	92	64	48

IV. CONCLUSIONS

In this paper, the problem of using the shortest path algorithm to plan and design a WDM mesh network with dedicated protection path is showed. The wavelength assignment problem is studied by two algorithms. The first one is looking for available wavelengths out of the busy wavelength space and the second one in the busy wavelength space. The second algorithm has significant benefits versus the first one because it uses fewer resources than the other one when a dedicated protection lightpath is used with the shortest path algorithm for both lightpaths. The first algorithm is faster than the second one. But the conclusion is that both approaches are suitable for the telecommunication traffic protection for fault management. The selection of the suitable method is based on wavelength availability of the failure site. The wavelength conversion method has also better performance than without wavelength conversion method but it is more expensive and the optimization is obtained if this problem is studied.

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