RELIABILITY EVALUATION OF WDM NETWORKS WITH LINK CAPACITY AND HOP CONSTRAINTS

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Abstract: A reliability evaluation module is presented for study of WDM network reliability. In this module, WDM networks are assumed to consist of three kinds of network elements - nodes, links and wavelength channel-related elements. And a network performance index – network 'function value', was introduced here as a quantitative representation of working-state of WDM network under certain link capacity and hop requirements. In addition, WDM networks here are assumed to be a survivable network, which can operate in a degradative manner against destruction and thus have multiple working-states instead of two opposite states. The reliability evaluation module was used to analyse the reliability of a WDM network with CERNET topology. Simulation results indicate that different link capacity requirement as well as different working-state requirements may lead to different reliability evaluation results, and the differences will enlarge very quickly with the increasing of network element failure rates. This implies that the study of WDM network reliability should be performed under multiple working-states assumption and the addition of the new network element kind - a wavelength channel-related element is necessary.

1 INTRODUCTION

The restoration techniques used in large-scale network systems make it possible for networks to survive in a degradative manner against destruction. Therefore the assumption that network systems have only two opposite working-states is not justifiable any more. It was suggested in our former paper (Fan Hehong et. al, 2005) that large-scale network systems should be regarded as having multiple working-states. Such idea has appeared in some other studies recently, in which large complex systems like network are deemed as multi-failure-state systems (Julia V. Bukowski, William M. Goble., 2001), or having additional working states, e.g. failure sectioning state (Enrico Carpaneto et. al, 2002). Thus a network performance index is needed for the classification of working states. Whereas not only network connectivity (Kent Fitzgerald et. al, 2003), (AboElFotoh et. al, 2001) but also network performance Ali M. Rushdi (1998). is important for communication, a composite performance and reliability measure for network, i.e. performability (J. F. Meyer, 1980), (B. R. Haverkort, I. G. Niemegeers, 1992), is worthwhile to examine. Thereby, an index, function value, representing the percentage of network meeting certain Qos requirement is introduced in this paper. For WDM networks, PLR (packet loss ratio) and delay are two fundamental Qos indexes and has tight relationship with link capacity and hop separately. So network function value are calculated with link capacity and hop constraints.

Considering that there exist such kind of elements in WDM network whose failure affect neither the nodes nor the entire links but certain wavelength channels in the links, such as transponders in OLTs (optical line terminals), a new kind of network element is added to the traditional elements (nodes and links) of network reliability evaluation module, namely wavelength channel-related elements. In this way, links in WDM network may be up or totally down or only shrink in capacity. The necessity of this addition is reinforced by the fact that WDM network protection/restoration schemes may operate in different layers, such as in optical multiplex section (OMS) layer, which restores the entire group of lightpaths on a link, and the optical channel (OCh) layer, which restores only one lightpath at a time.

In the following parts, some knowledge for reliability of multiple working-states object

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(MWSO) as well as the reliability evaluation module for WDM networks was introduced in the second part. Then the algorithm of the network performability index – function value was described in the third part for the first time. In the fourth part the reliability of CERNET (China Education and Research Network) topology was studied as an example to demonstrate the use of this module. Finally, a conclusion will be drawn in the final part.

2 RELIABILITY EVALUATING OF MWSO

2.1 Network performability index - network function value

Performability index in different papers may be different, such as service availability, frame loss (V.Catania et. al, 1990), network delay and capacity (Alexander A.Hagin, 1994) etc. While communication network systems are used to ensure all the nodes in the network to normally communicate with each other, here the performability index - function-value, v_f, was defined as the percentage of node pairs in the network that can communicate with each other under certain performance requirement. And the performance requirement includes link capacity and maximum hop of connections. In other words, network function value represents the degree in which the network nodes as a whole can accomplish their required communication tasks.

2.2 State term cloud series (STCS) and reliability of MWSO

Whereas network function value of network can be regarded as a quantitative representation of network working states, it's not necessary for us to study network reliability according to each function value. In other words, working states of network can be classified to several states. As we can always use a series of linguistic terms, such as "very good", "fairly good", "medium", "bad", "worst" and words alike to describe all kinds of variables, working states of network can also be classified to several kinds like this. Relation between the qualitative description (working state) and the quantitative description (v_f) for working states can be explained explicitly by Linguistic Cloud Model (LCM) (Huang Haifeng et. al, 2001), (Li De-yi et. al, 2000). And a series of linguistic term cloud - state term cloud series (STCS) (Fan Hehong et. al, 2005), as showed in figure 1, demonstrate the qualitative description of a variable at the full length of its defined value area with reference to its quantitative values. With STCS we can scientifically differentiate the multiple working-states of network easily.

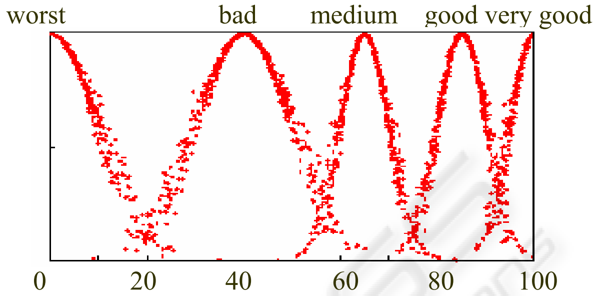

Figure 1: Diagram of STCS.

With respect to the reliability of MWSO, the parameters should be confined by not only stated conditions and time but also certain state linguistic term (SLT), w. Reliability of MWSO confined by term w is:

$$R_w(t) = P\{t \mid v_f > (x_{0,w} - b)\} \qquad (1)$$

Here $x_{0,w}$ refers to the expected value (information center) of word *w*, and *b* refers to the bandwidth of its membership cloud (fuzziness of the concept).

And the availability of MWSO, A_b, in time interval between *t*1 and *t*2, is defined as the time weighted function value percentage:

$$A_b = (\int_{t1}^{t2} v_f dt) / v_{f,\max} \cdot (t2 - t1) \qquad (2)$$

Additionally, for repairable MWSO, useful life under certain circumstances and repair rate was defined as the operating time before its availability of certain period length drops to an unacceptable value.

2.3 Mapping form WDM network elements to elements in the Reliability evaluation module

WDM networks are typically consisting of OXCs (optical crossconnects), OLTs (optical line terminals), OADMs (optical add/drop multiplexers), fibers and sometimes OAs (optical amplifiers)(Rajiv Ramaswami, Kumar Sivarajan). Furthermore, transponders and optical multiplexer/demultiplexers are two fundamental units that make up OLTs and OADMs of parallel architectures. As transponders operate on and affect certain wavelength channels in the link, they may be regarded as the channel-related elements, which affect only capacity of the related

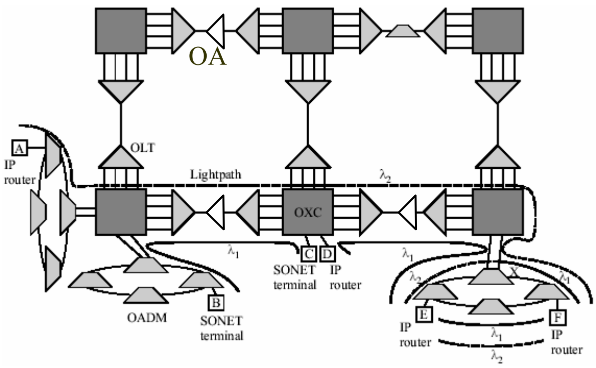

Figure 2: A WDM wavelength-routing network

link. While OXCs and multiplexer/demultiplexers in the OLTs and OADMs always handle all the wavelength channels in a link together, they can be considered as composing the nodes in the traditional network reliability module. Different from OADMs of parallel architectures, some OADMs are composed of wavelength selective units in series. This kind of OADM can be considered as being composed of node in serial with wavelength channel-related elements. In addition, the failure of fibers or fiber bundles and OAs will affect all the wavelength channels in it at the same time.

To sum up, the mapping from the WDM network elements to the elements in the reliability evaluation module can be implemented as follows: each conjunction node in the topology in backbone WDM networks, either OADM or made up of OXC and OLTs, can be deemed as composed of a node and channel-related elements in series; Fibers (or fiber bundles) and sometimes OAs consist the network links.

2.4 Reliability evaluation module for WDM network

Based on the reliability information of the nodes, links and channel-related elements (mainly transponders), reliability of WDM networks can be figured out by way of Mont Carlo simulation. The main steps to evaluate the reliability of networks are listed as follows:

1). Make use of the failure distribution function knowledge of the elements, by way of Mont Carlo method, to simulate function value, v_f, under certain link capacity and maximum connection hops requirement, and A_b of certain period length of the network system (by Eq. (2)) changing over time.

2). Repeat step 1 to obtain the distribution of the system's v_f and A_b at different time as well as average short period A_b and useful life distribution, confined by certain capacity and hop requirement and SLT of STCS.

3). Reliability confined by a SLT at t can be calculated by Eq. (1).

4). SLT to describe the system's running state and reliability level can be determined according to STCS.

3 ARITHMETIC OF NETWORK FUNCTION VALUE

Different from some former methods (K. K. Aggarwal, 1998) which begin with the minimum sets to calculate network capacity, we'll begin with the weighted adjacency matrix $A=[a_{ij}]_{m\times m}$, working-state vector of nodes $B=[b_1 b_2 \ldots b_m]$ and working-state matrix of channel-related elements $C=[c_{ij}]_{n\times k}$ in the network to calculate the function value, v_f, of the network. Here, the element a_{ij} in A represent the maximum capacity of the link directs from node i to node j. If there isn't a direct edge connects from node i to node j, the link capacity from link i to link j is regarded as 0. So the total link number is the number of non-zero elements in A. b_i (0 or 1) in B indicates whether the node i is up or down. c_{ij} in C refers to the channel j in link i. The total number of node and link are separately m and n while the maximum number of channel in each link is k. In this method we don't want to calculate the minimum sets as even the minimum path may have more hops than required.

Whereas undigraph can be transferred to digraph easily by replacing each directionless link with a couple of directional links in opposite direction, only the algorithm for digraph is given below:

Step 1: For each link i, calculate the available capacity, that is, to subtract the number of failure channels, $\sum_i c_{ij}$ in it from the maximum capacity.

Step 2: current adjacency matrix, $A_c=[a_{c\,ij}]$, can be reckoned by delete (or set zeros) columns and arrays in A according to the zeros in B.

Step 3: calculate the reachable matrix, R, under certain capacity requirement for the links within h hops of the remaining adjacency matrix, A_c:

The reachable matrix of l hops, $A_c^{(l)}=[a_c^{(l)}{}_{ij}]$, can be obtained from the reachable matrix of l-1 hops, $A_c^{(l-1)}=[a_c^{(l-1)}{}_{ij}]$, by

$$a_{cij}^{(l)} = \max(\min(a_{ci1}^{(l-1)}, a_{c1j}), \ldots, \min(a_{cim}^{(l-1)}, a_{cmj})) \quad (3)$$

Thus reachable matrix R can be work out by

$$r_{ij} = \max(a_{cij}, a_{cij}^{(2)}, \ldots, a_{cij}^{(l)}) \quad (4)$$

As any nodes in the network are not required to communicate with themselves, the diagonal of R is set to be zero for further calculation.

Setp4: Two kinds of $v_{f,system}$ are defined and used here. One kind is a normal one which is the amount of elements in R that are no less than the required capacity; and the other is a normalized one which denotes the percentage of maximum minimum link capacity of all the routes between node pairs in the network with reference to maximum minimum link capacity of all the routes between node pairs in the failure-free network:

$$\bar{v}_{f,system} = \sum_{ij} r_{ij} / m \times (m-1) \times k \quad (5)$$

It can be easily figured out that the maximum traditional function value and maximum normalized function value of an m-node WDM network with k channels in each link are separately $m \times (m-1)$ and 1.

4 APPLICATION OF THE EVALUATION MODULE

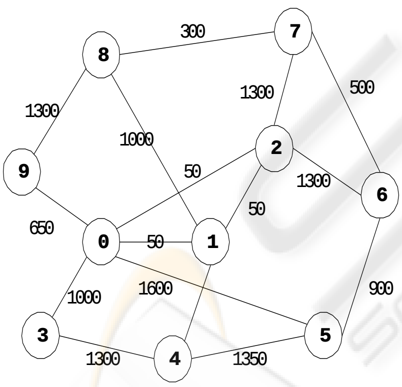

Figure 3: topology of 10-node CERNET

To demonstrate the reliability evaluation module, WDM network of CERNET topology is used here as an example. The elements are supposed to follow Weibull failure distribution in order to examine the system reliability parameters changing with failure rates rising. Figure 2 showed the topology of CERNET, and the nodes in the topology, either made up of OXC or OADM, are all assumed to consist of node and 2x16 parallel channel-related elements in series with connected link. The shape parameters and location parameters of the elements are assumed to be 3 and 0 separately. And the scale parameters of nodes, channel-related elements (transponders) and links are assumed to be 20000h, 50000h and 50000h, respectively. As operation of the nodes in the WDM networks need power supply, the reliability of such equipment is considered to be much lower than the passive element – fiber link. In addition, while nodes in WDM networks are larger and more complexly configured than transponder, scale parameters of transponders are also deemed as larger than those of nodes. MTTR here is assumed to be 2h. The simulation is repeated 100 times and the time step is 96h (4 days). Every node is assumed to have full wavelength conversion capability, so that traffic in some failed wavelength channels can be restored in other working or backup channels. The maximum hops between each node pairs are limited to 4.

The simulation results are showed in the following three figures. Fig (4) shows that while there is no perceptible difference between average availability between different link capacity demands when failure rates are rather low, the network availability under full channel requirements (16 channels) are lower than availability of all the other three conditions, and the distance between them become more and more larger with failure rates went higher. This is further proved by the figures listed in table 1, during which there is no difference between different capacity requirement at 47904h, and only 0.0002 in difference between capacity requirement of 16 channels and that of the other three at 95904h, while the difference arise to about 0.025 after another 47904h and finally reached 0.13 at 163104h; the slightly lower value of normalized availability than the availability under two lower channel number demands, and the same value of availability under 8 and 1 channel demands indicate that such kind of channel demand may be easy to meet and there're very little chance for only a few channels left under the element failure distribution assumptions given above.

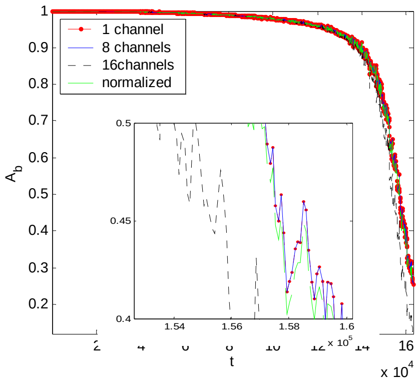

Figure 4: Average CERNET availability of 96h under different link capacity requirements changing with working time (and failure rates)

Table 1: Average CERNET availability of 96h under different link capacity requirements at four different working time (denote different failure rates)

Working time(h) / Capacity demand	47904	95904	143904	163104
1	0.9969	0.9802	0.8573	0.2550
8	0.9969	0.9802	0.8573	0.2550
16	0.9969	0.9800	0.8317	0.1199
normalized	0.9969	0.9802	0.8556	0.2441

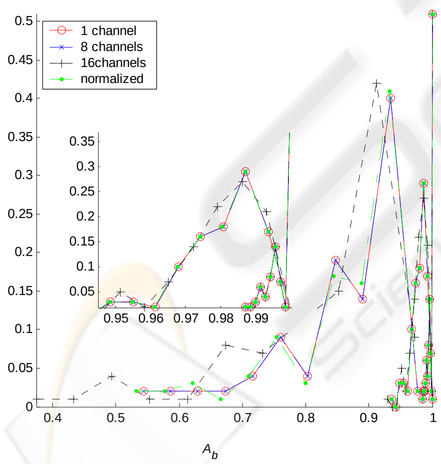

Figure 5: CERNET availability distribution of 96h changing with working time and failure rates. The three groups of lines from left to right are separately at working time of 47904h, 95904h and 143904h.

Figure 5 told us that when failure rates are rather low, the short period availability concentrated near 1, but as failure rates going up, the distribution of availability becomes widen, from 0.01 at 47904h, to 0.05 at 95904h, to about 0.6 at 143904h, which implies that the system begun to be unstable.

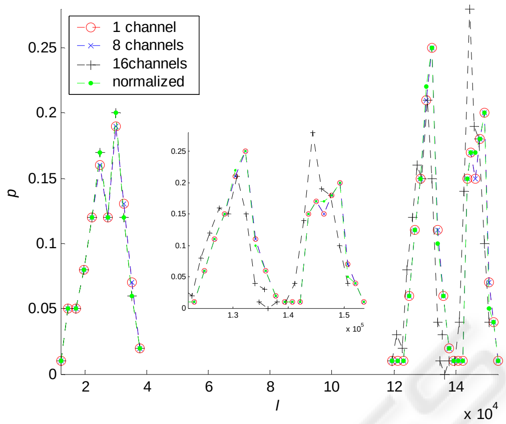

Figure 6: distribution of CERNET useful life under different capacity and SLT requirements. Performance requirement SLTs of the line groups from left to right be separately "perfect", "very good" and "good".

From figure 6 we can see that useful life become longer and longer with SLT of network performance become lower. What is more important is that although the distance of availability requirement between "perfect" (expected value is 1 and bandwidth 0) and "very good" (expected value is 1 and bandwidth 0.05) are very small, their useful life are far cry from similar: the average useful life of "very good" performance requirement are almost 5 times the length of "perfect", separately 1.30x105h and 0.26x105h. Which have a sharp contrast with it is that, although the distance of availability requirement between "good" (expected at 0.85) and "very good" are much larger than the former two, useful life of them hasn't that big difference. These results show that while reliability level and useful life increases with performability requirement decrease, the extent that useful life increases are not proportional to the decrease of performability requirement. Only a very small step down from the requirement of "perfect" will lead to a great longer useful life but further decrease of performability requirement will have much lower effect on lengthening useful life.

5 CONCLUSION

Simulation results indicated that different link capacity requirement for network may lead to different evaluation results, especially when failure rates are high and the differences enlarge very fast with the increasing of failure rate; different working-state requirements may lead to fairly different reliability evaluation results as well: the lower the performability requirement the higher the reliability level, and the lengthening of useful life are not proportional to the decrease of performability requirement - a small step down from the requirement of "perfect" (to "very good") will be enough to lengthen the network useful life remarkably.

All these results imply that study of network reliability should be performed under multiple working-states assumption and the addition of the new network element kind - wavelength channel-related elements for reliability analysis of WDM network is necessary.

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