Reduction of Hop-Count in Packet-Switched Networks using Wavelength Reconfiguration

S. N. Larsson*, S. Hubendick.
*Telia Research AB, S-123 86 Farsta, Sweden (stefan.n.larsson@telia.se), *also with Royal Institute of Technology.*

Keywords: Virtual Topology, Optical Cross-Connect, Network Reconfiguration, WDM.

Abstract: A method using packet flows to create a wavelength topology is shown to reduce the hop-count in a packet-switched network. The wavelength cross-connect function is achieved by opaque cross-connects, providing full wavelength conversion. Simulations on a 5-node, an 11-node and a 26-node network are done for different number of ports per node and wavelength channels per link.

1. INTRODUCTION

The use of optical layer functionality is still in its infancy. DWDM has since the mid-nineties been widely deployed by Telcos to overcome fibre exhaust. Apart from using WDM as a capacity booster, other optical layer functions are uncommon. The fact that optical layer functionality on the wavelength level is very simple and potentially cheap has however lead to increasing interest in optical network elements such as optical add/drop multiplexers (OADM) and optical cross-connects (OXC). While static OADMs are becoming deployed as a means of reducing network cost, /1/ the reason for using OXCs is presently mainly due to protection /2/ or reduction of personnel /3/. However, new optical layer functions using OXCs for traffic engineering (load balancing and redirection of traffic) and Class of Service are proposed /4,8/.

The original version of this chapter was revised: The copyright line was incorrect. This has been corrected. The Erratum to this chapter is available at DOI: 10.1007/978-0-387-35410-1_19

A. A. Stavdas (ed.), *New Trends in Optical Network Design and Modeling*

In order to implement the OXC a technology choice must be made. First, should the OXC work entirely in the optical domain, i.e. optically transparent, or is optical/electrical conversion allowed? If a transparent OXC is desired, common switch-technologies include opto-mechanical, thermo-optical (e.g. polymers), electro-optical (e.g. $LiNbO_3$) or acousto-optical. Of these, mainly the opto-mechanical has gained commercial interest, while new micro-mechanical switches (MEMS) are emerging as a strong candidate /5/. Transparent OXCs always impose some limitation on the optical network, e.g. maximum size or capacity. Opaque OXCs (including o/e conversion) can to a large extent relax size/capacity issues by using standard electrical regeneration. To assure flexible networking, the regeneration should be multi-rate and such circuits are commercially available today. Apart from being small in size, electrical switch-cores are cheap, can be made with a large number of ports and exhibit fast switching speeds (10's of ns). The drawback with electrical switch-cores is the limit on maximum bit-rate per port. 2.5 Gb/s is the limit of commercial products today.

In this paper, a method for using opaque OXCs to connect packet-switches in a dynamic way is proposed. The logical network topology[1] is adapted to the traffic demand by an optical network management system. The key questions in this study are:

1. how much can one benefit from having a re-configurable physical network when traffic demands change[2]
2. how this benefit depends on number of nodes, router ports and wavelengths per fibre.

The gain is measured as the reduction in number of router hops. A field trial evaluating the OXC implementation and optical layer functionality is described elsewhere /6/.

2. NODE AND NETWORK MODEL

Figure 1 shows the node model used. On top of the (opaque) OXC is the packet switch (e.g. IP-router) interfacing the OXC with a number of optical ports. The OXC is characterised by the number of input (=output) ports which is equal to the number of wavelength channels of all input links plus the number of add (=drop) switch-ports. With this OXC, wavelength conversion is performed in every node. In the following, the number of ports refers to the switch-ports and not all of the ports of the OXC.

[1] The virtual topology consisting of reconfigurable wavelength channels connecting the switches (or routers) via the OXCs.

[2] A similar study is presented in /9/ for a 14-node network.

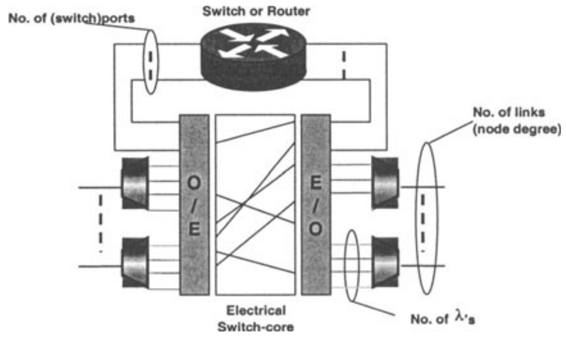

Figure 1 The node model

The physical network models are shown in figure 2. with b) originating from the COST239 project /7/.

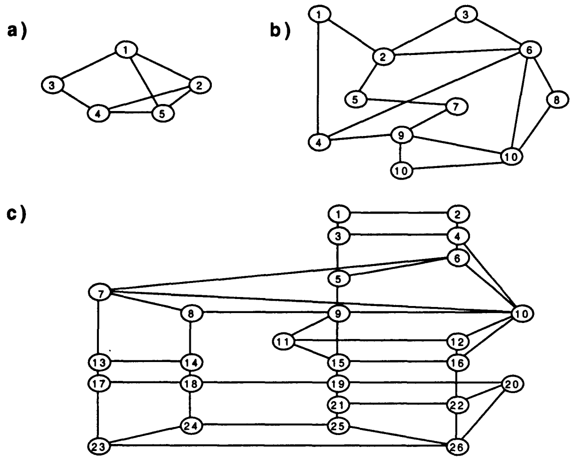

Figure 2 The physical network models. a) 5-node, b) 11-node and c) 26-node. Each node includes an OXC.

The average node degrees of the three networks a-c) are 2.80, 2.91 and 3.46 respectively. Thus, all networks used are meshed to varying degrees.

3. EXAMPLE

The simulated traffic demands are randomly generated as a uniformly distributed variable from 0 to 100 uni-directionally for each node pair. Table

1 shows an example for the 5-node network. (The demand from node i to node i is set to 0)

To\From	Node 1	Node2	Node3	Node 4	Node 5
Node 1	0	99	90	11	78
Node 2	88	0	8	92	57
Node 3	16	35	0	14	67
Node 4	45	21	2	0	88
Node 5	93	32	100	17	0

Table 1 Traffic demands by randomly generated number of packets.

The demands are then summed for each pair and ordered so that a list of demands is given. (E.g. the combined demand from node 4 to node 5 is 88+17=105.) The resulting list would be:

Demand #	Node nr.	Node nr.	# of packets
1	1	2	187
2	1	5	171
3	3	5	167
4	2	4	113
5	1	3	106
6	4	5	105
7	2	5	89
8	1	4	56
9	2	3	43
10	3	4	16

Table 2 Ordered list of traffic demands from table 1.

From this list the bi-directional wavelength connections in the network are made in sequence using the Dijkstra algorithm for shortest path calculation as described by the psuedo-code in figure 3.

```
OptimizeNet_Simple(physical_Net,Demands)
logical_NET ← null;
for k ← 1 to NumberOf(Demands)
 do  node_a,node_b ← Demands(k)
      if connected(NET,node_a,node_b) & exist_port(node_a)& exist_port(node_b)
       then sp ← connect_shortest_path(NET,node_a,node_b)
            add_path(logical_NET,sp)
check_full_connectivity(logical_NET)
return logical_NET
```

Figure 3 The pseudo-code of the proposed method.

Figure 4 show the physical and logical networks and the paths through the network when using table 2. Here, the number of ports per node is set to two. As a result demand 5 is excluded since node 1 used its ports for demands 1 and 2. However, bypass traffic through node 1 can still be handled if free WDM-channels are available. Demands 6-9 are also excluded due to the same reason. Thus five demands are satisfied, which equals half the number of nodes times the number of ports per node. This characterises the proposed method: the demands with largest traffic are assigned a wavelength channel until either the ports or WDM channels are depleted and the other demands must go through one or more additional switches (routers) to reach their destination.

The average number of hops is now given as the number of packets in table 2 times their respective number of hops divided by the total number of packets. Demands 1-4 and 10 are single-hop while the rest are two-hops. This gives: ((187+171+167+113+16)+(106+105+89+56+43)*2)/1053= <u>1.3789</u>

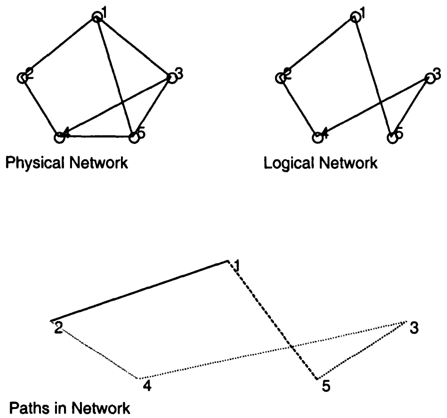

Figure 4 The five-node physical network and the logical network and paths resulting from table2.

A new random demand is shown in table 3.

To\From	Node 1	Node2	Node3	Node 4	Node 5
Node 1	0	63	93	8	15
Node 2	29	0	71	6	24
Node 3	77	32	0	6	24
Node 4	15	35	16	0	87
Node 5	62	26	71	24	0

Table 3 New randomly generated number of packets.

If now the average number of hops is calculated using the logical network of figure 4, the result for table 3 would be <u>1.5106</u> which is an increase of 9.6 % compared to the result when optimising the logical network from table 2.

Some list of demands result in logical networks that are not connected. E.g. if the demand list for the 5-node network, with 2 ports per node, started with 1-2, 1-4 and 2-4, the nodes 3 and 5 can only communicate with each other and the network is not connected. The algorithm in Figure 3 checks for such cases and if so, a re-start is made.

4. RESULTS

In all cases the number of ports per node is lower then the (number of nodes-1) in the network. Thus, full wavelength-connectivity in the networks can not be achieved and benefit from re-configuring the wavelength connections is possible (more than one wavelength channel per node pair is not considered). In the following, wavelength connections are referred to as "logical connections".

Starting with the 5-node network, average hop-count for 4 random demands was calculated resulting in 4 optimised logical networks. (The reason for choosing 4 demands is a compromise between readable graphs and the need for sufficient statistics). On these 4 optimised logical networks, average hop-count for the other demands (i.e. not the ones used for optimising the logical network) was calculated resulting in 4*(4-1)=12 values. The top graph of figure 5 show these results for 2 and 3 ports/node with 3 WDM-channels per link. Each star represents an optimised case and the solid line connects the two numbers of ports for that demand. The circles and dashed lines represent the non-optimised results. The bottom graph of figure 5 show the non-optimised results in percentage increase relative to the optimised case.

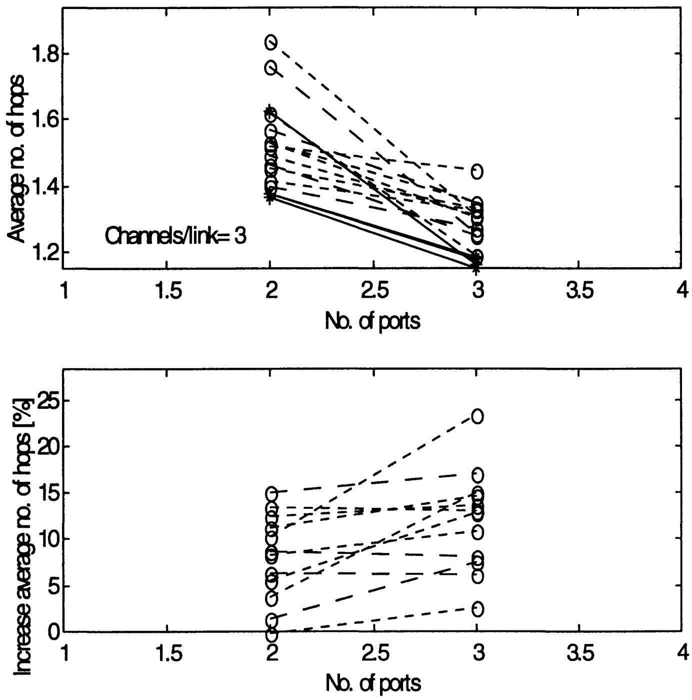

Figure 5 Average number of hops (top) and increase in average number of hops relative to the optimised case (bottom) for 4 demands. Stars are for optimised results and circles for non-optimised.

Another way of representing the result for optimised and non-optimised logical networks for different demand is by using histogram plots. Figure 6 show the number of packets vs. the number of hops for 4 demands. The left graph show the result for an optimised logical network (using demand 1) and the three others are for different demands applied to the logical network optimised according to demand 1.

The same calculations are made for the 11-node network with the results showing in figures 7,8 for 4 WDM-channels per link, figures 9,10 for 6 channels per link and figures 11,12 for 8 channels per link. To assure connected logical networks the minimum number of ports is 3.

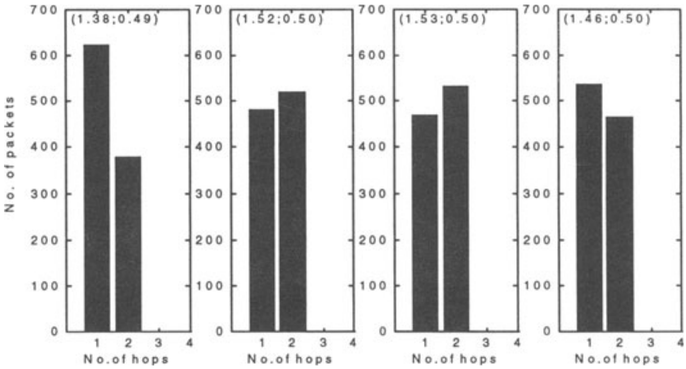

Figure 6 Number of hops vs number of packets for an optimised logical network (left) using one demand and for 3 other demands applied to that logical network (i.e. non-optimised). Ports=2 and WDM channels/link=3. The average and standard deviation are shown in each graph as (Av;Std).

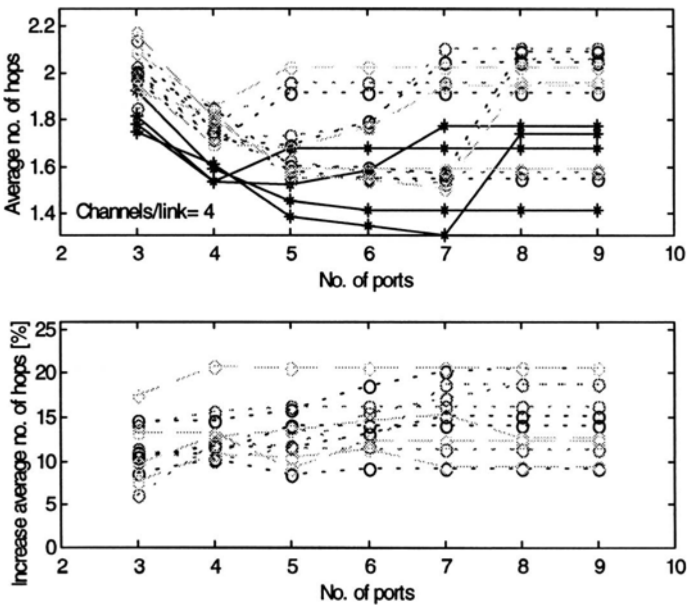

Figure 7 Same as figure 5 but for the 11-node network with 4 WDM-channels per link.

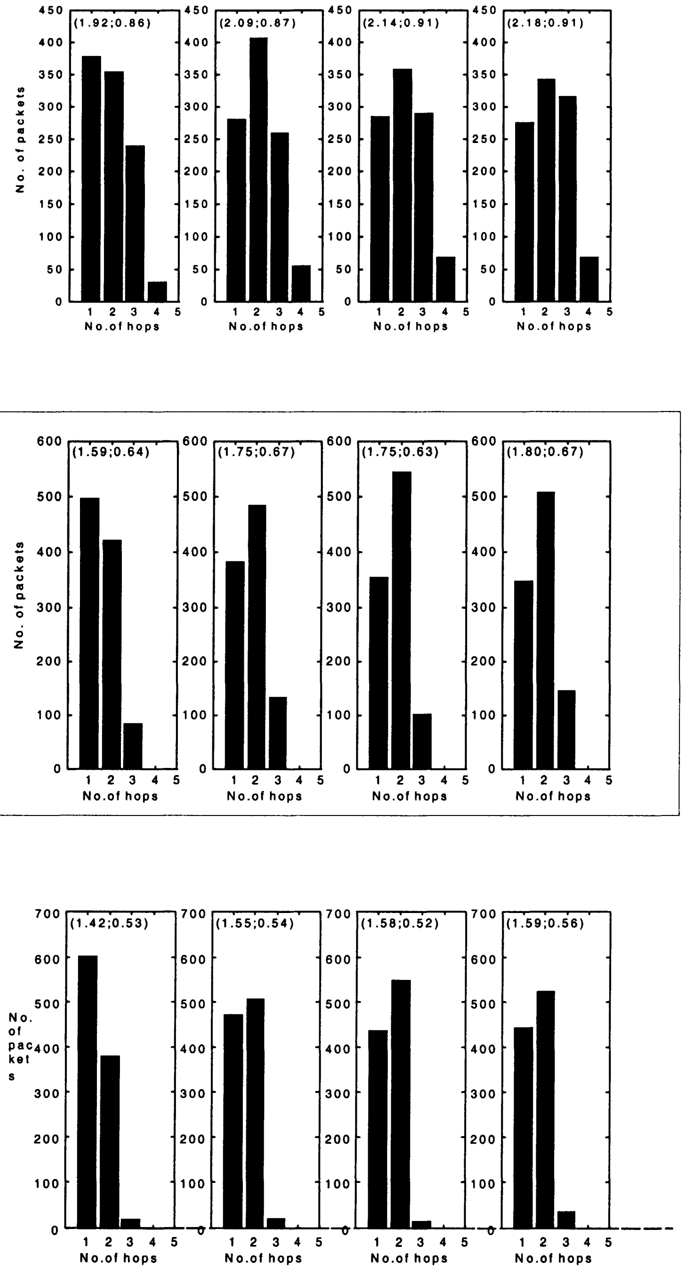

Figure 8 Same as figure 6 but for the 11-node network with 4 WDM-channels per link and 3 ports/node (top), 4 ports/node (middle) and 8 ports/node (bottom).

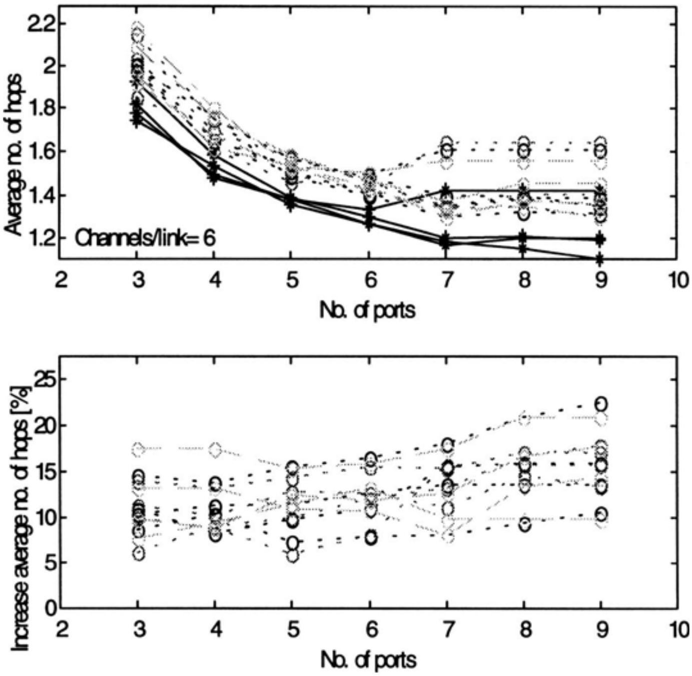

Figure 9 Same as figure 5 but for the 11-node network with 6 WDM-channels per link.

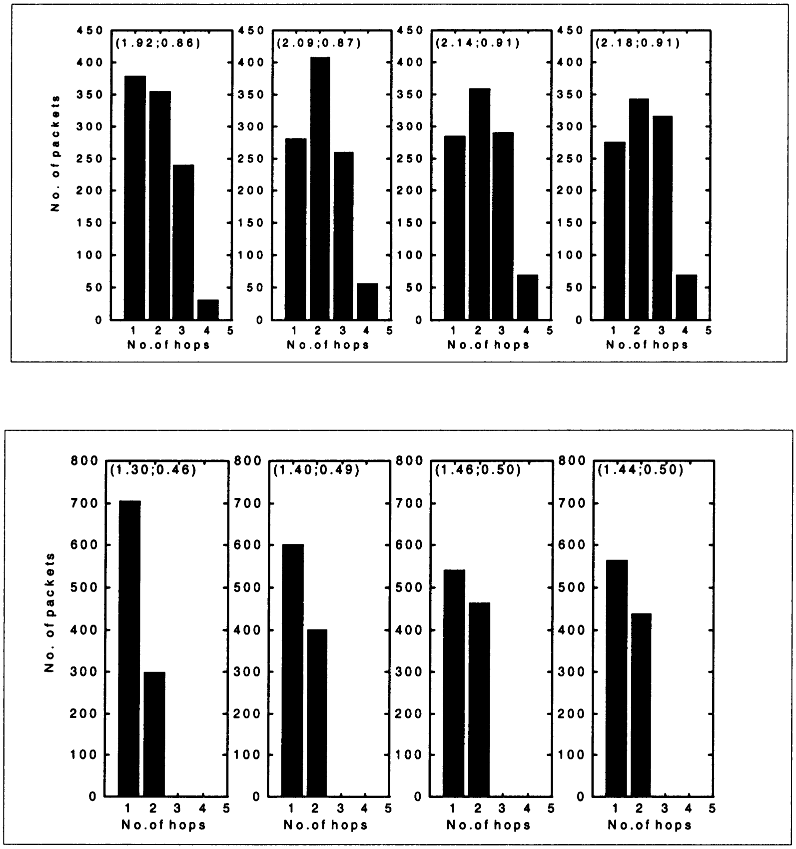

Figure 10 Same as figure 6 but for the 11-node network with 6 WDM-channels per link and 3 ports/node (top) and 6 ports/node (bottom).

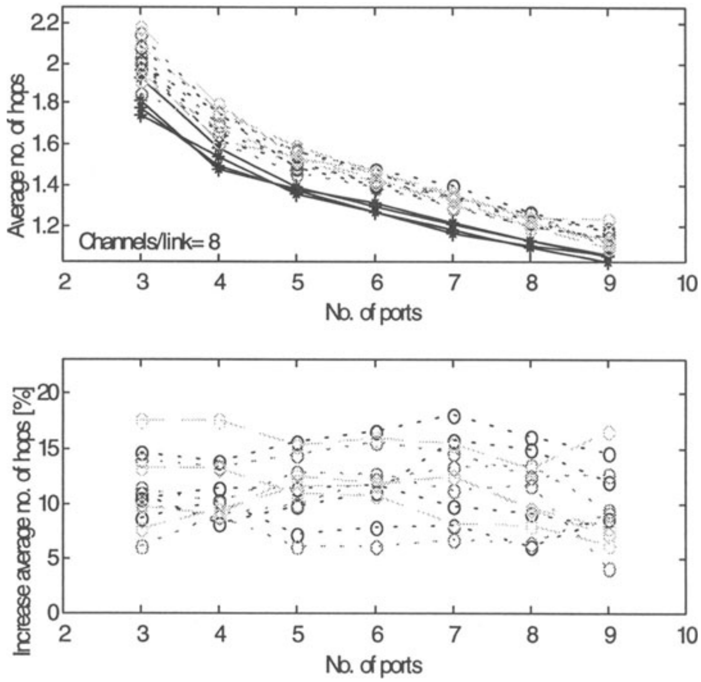

Figure 11 Same as figure 5 but for the 11-node network with 8 WDM-channels per link.

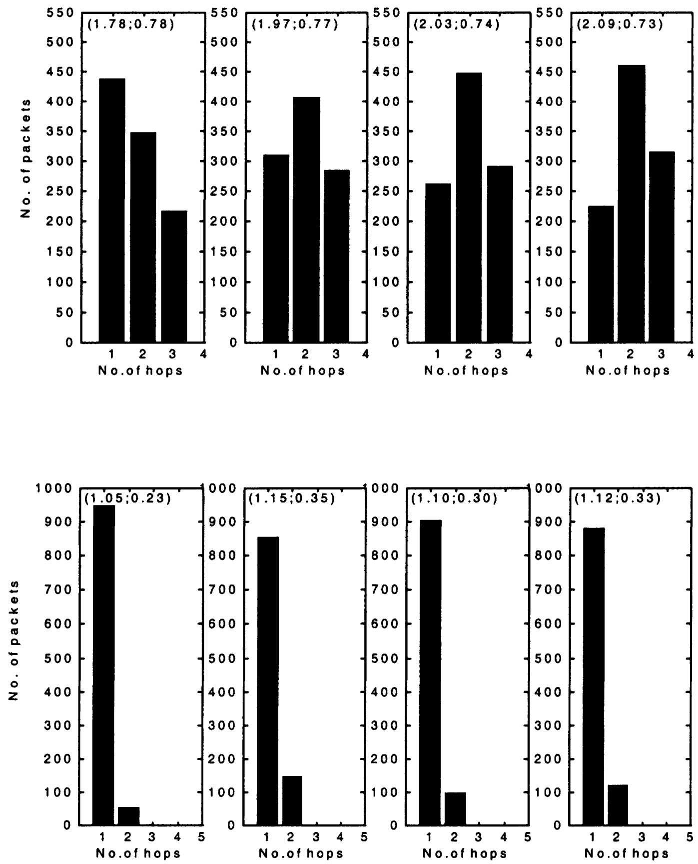

Figure 12 Same as figure 6 but for the 11-node network with 8 WDM-channels per link and 3 ports/node (top) and 9 ports/node (bottom).

As seen in figures 7,9,11, the percentage increase in average number of hops is very dependent on the characteristics of the demand but grows somewhat with the number of ports/node. The average number of hops decrease with the number of ports as expected until the number of ports approaches the number of channels per link, where an increase is evident. The reduced number of hops with more ports is also made clear by figures 8,10 and 12, as well as the benefit of optimising the logical network.

The same calculations are made for the 26-node network, with the results shown in figures 13, 14 for 8 WDM-channels per link, figures 15, 16 for 12 channels per link and figures 17, 18 for 16 channels per link. To assure connected logical networks the minimum number of ports is 4.

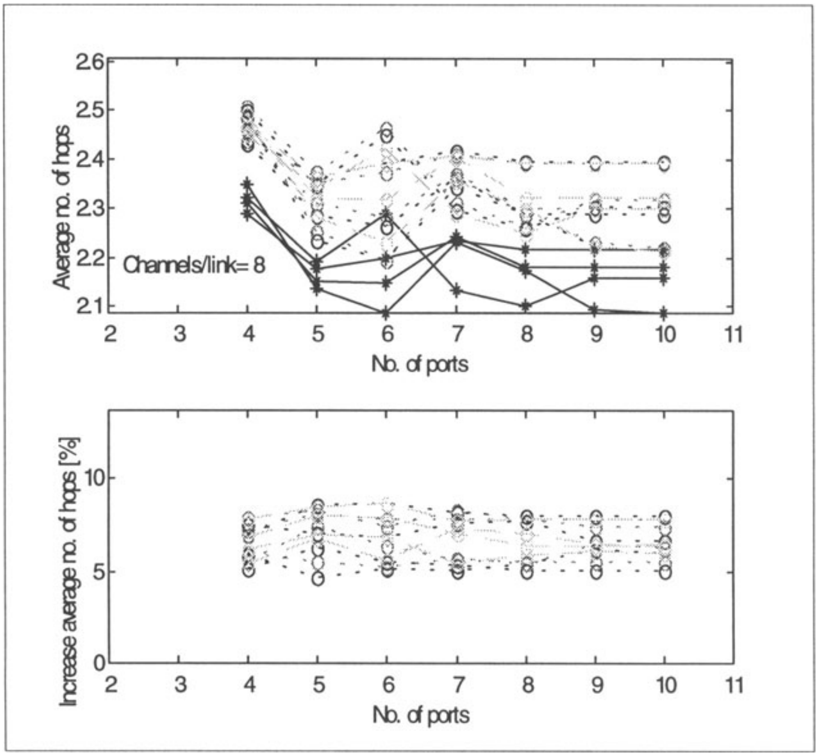

Figure 13 Same as figure 5 but for the 26-node network with 8 WDM-channels per link.

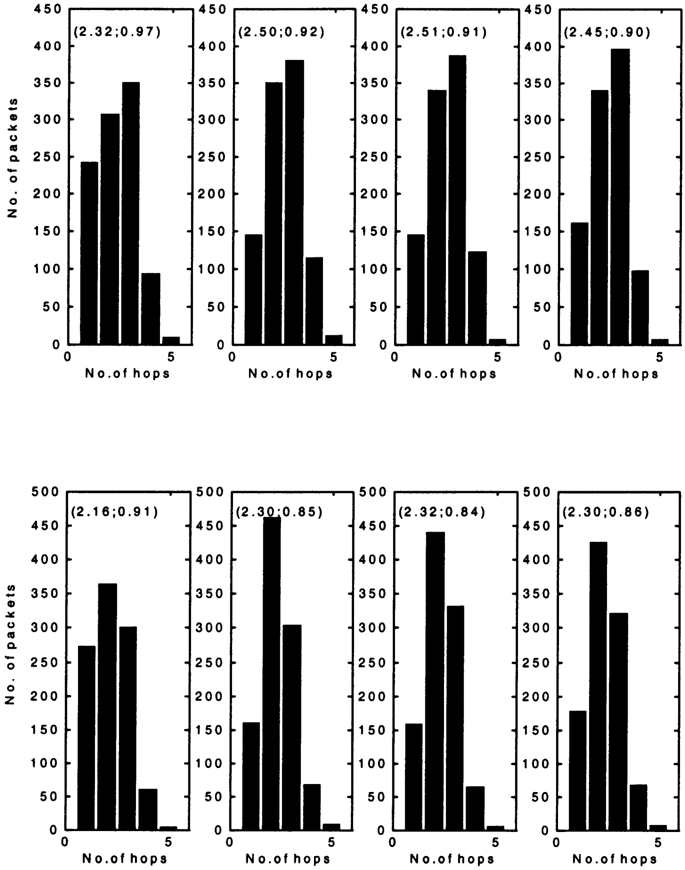

Figure 14 Same as figure 6 but for the 26-node network with 8 WDM-channels per link and 4 ports/node (top) and 10 ports/node (bottom).

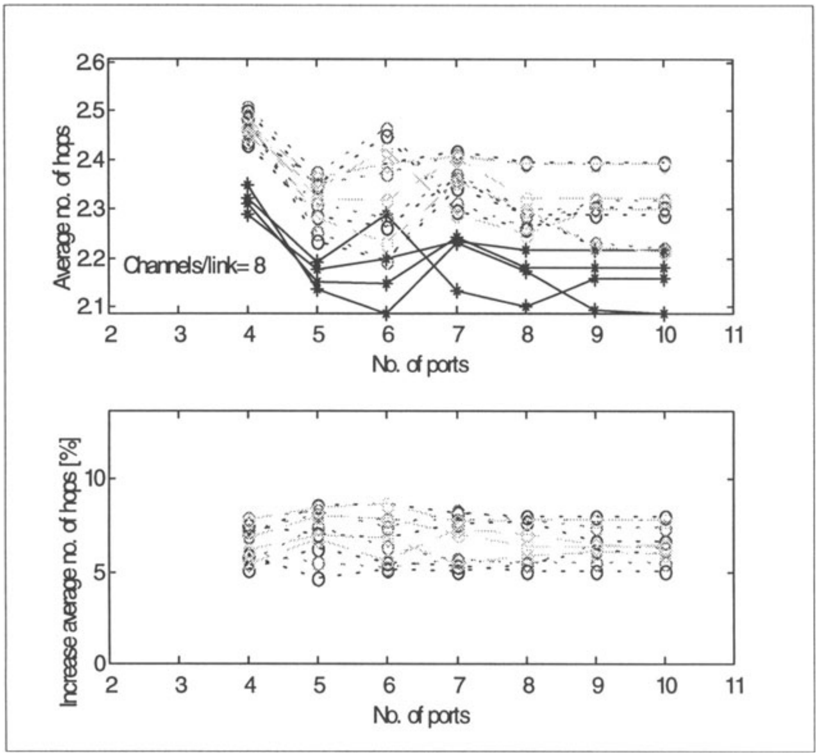

Figure 15 Same as figure 5 but for the 26-node network with 12 WDM-channels per link.

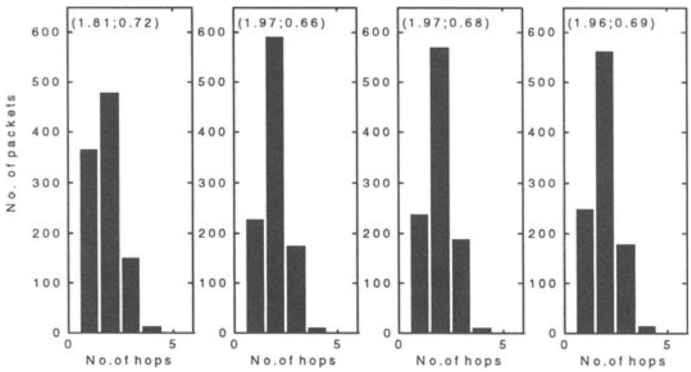

Figure 16 Same as figure 6 but for the 26-node network with 12 WDM-channels per link and 10 ports/node.

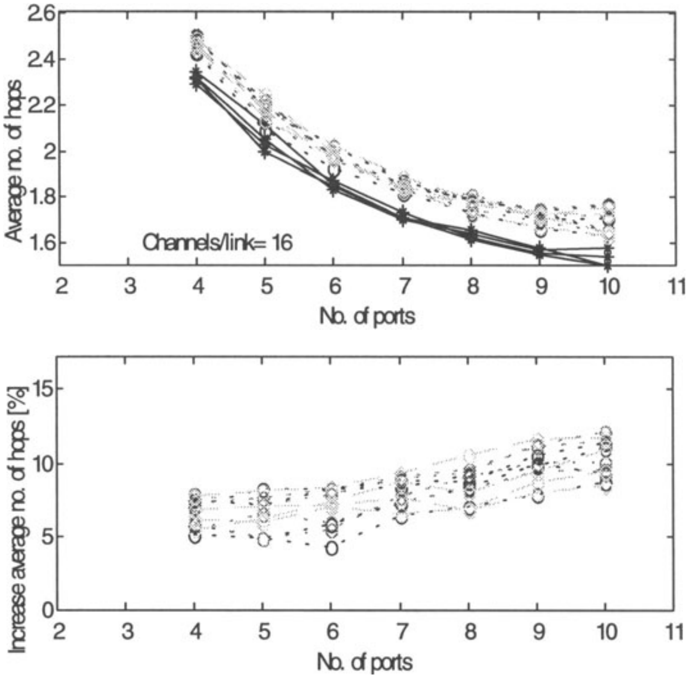

Figure 17 Same as figure 5 but for the 26-node network with 16 WDM-channels per link.

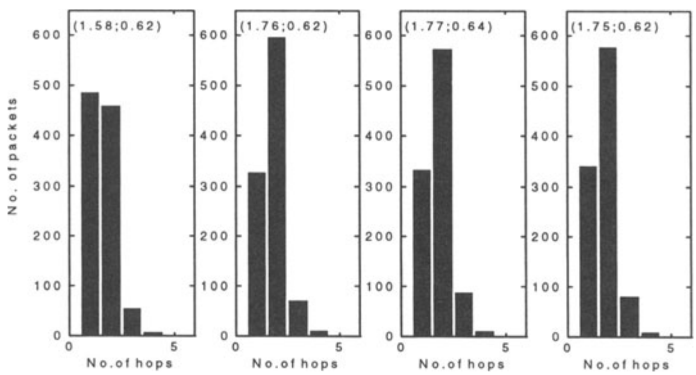

Figure 18 Same as figure 6 but for the 26-node network with 16 WDM-channels per link and 10 ports/node.

As for the 11-node network, the average number of hops decreases with the number of ports but the more complex structure of the 26-node network makes the interaction of ports/node and channels/link less predictable.

However, a low number of channels/link will at some point increase the average number of hops when the number of ports/node increase. The percentage of increase in average number of hops is lower (5-10 %) than for the 11-node network due to longer paths in the 26-node network.

As seen in figure 14, even for the optimised logical networks the average number of hops is larger than 2 due to a low number of ports/node and channels/link. In figures 16 and 18, the average number of hops is lower than 2 due to sufficient number of ports per node and channels per link.

5. DISCUSSION AND CONCLUSION

In this study a number of relevant issues have not been covered and some additional questions remain. A few of them are listed below:

The demands were generated randomly for all node pairs in a uniform way. In real life, however, other types of patterns are common, e.g. server or hub-like patterns where large traffic is carried between a few nodes to/from all other nodes while the traffic between non-hub nodes is negligible. The benefit of wavelength re-configuration in this case is to be further evaluated.

The restriction of a connected network can perhaps be relaxed if re-configuration occurs frequently.

An important factor in determining the gain of having a re-configurable network is the time-scale upon which demands change. (A typical scenario would be the daily change of demand between working areas at daytime and residential areas at evening.) Each network reconfiguration will lead to some loss and misdirection of packets. Loss of packets might occur when cross-connection is done at each OXC while misdirection might occur during connection set-up of a path in the network. The loss of packets in the optical layer therefore depends on the switching time of the OXCs, which is on the order of 10 ns for electrical switch cores, while misdirection of packets depends on the speed of the management system controlling the optical network. Thus, for each network and type of OXC and for the time/volume-characteristics of each traffic demand, an optimal time between network reconfiguration can be expected. Also, by introducing signalling in the network, complexity (=cost) is added and possible extra capacity is needed. Security/reliability in this case is also an interesting issue.

Another issue relating to packet loss and throughput is the need for transfer of information regarding the logical topology state of the optical network to the packet layer /8/.

The reason for re-configuring the whole (sub-)network at once, i.e. having a centralised management, is to avoid possible deadlocks in decentralised connection set-up. For example, if the IP-routers themselves were to control the attached OXC and negotiate with other routers/OXCs, authority over the limited wavelength/port resources is not clear.

This method relies on the possibility of getting statistics on packet numbers and destinations. How this can be realised in practise is not clear.

In conclusion, it has been shown that physical re-configuration can reduce the number of hops in a given physical network. The hop-reduction is in the order of 5-25% depending on the demand variation and increases in general with the number of ports/node. The hop-reduction decreases somewhat with the size of the network.

6. REFERENCES

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