Optical Network Analysis under Non-Uniform Traffic Distribution

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Abstract ¾ **Multihop regular networks are analyzed for applications under non-uniform traffic distribution, taking the conventional SPF (short path first) algorithm as the routing protocol. Simulations of Manhattan Street and Shuffle Net topologies without buffer memories, under constant bit rate and variable bit rate traffic flow distributions, are analyzed using the criterion of packet loss fraction. The results show that traffic bottlenecks are caused by packet losses produced either when full capacity of heavier loaded network links are reached or when optical packets arrive within the same time frame at optical switching nodes. The results and the methodology adopted are general with applicability not only restricted to optical networks.**

Keywords ¾ **Optical networks, non-uniform traffic distribution.**

I. INTRODUCTION

Optical networks will require an optical packet switching functionality to support the explosively increasing demands of future broadband communication services. In backbone networks, the transport of high rate tributaries is provided as a continuous and uniform traffic flow, whereas at network edges or gateway nodes, the traffic flow presents a more burst type characteristic behavior. In the backbone, many users are multiplexed into a single transport data flow, such that long distance optical links are generally characterized by continuous and uniform traffic. Closer to the edges, the optical network also supports non-uniform traffic demands, but usually with centralized control management.

In this work, we consider multihop regular two connected mesh topologies in order to provide greater flexibility, scalability and finer granularity to optical networks for broadband communication systems. First, the redundancy of optical paths avoids unnecessary demand for extra bandwidth. Second, the nodes are capable to perform the functionality of optical packet switching, such that the network management is decentralized. This strategy avoids waste of resources that generally occur in the broadcast and select topology, and also in the ATM technology. In addition, the possible association of optical packet switching with coarse WDM offers greater flexibility and maneuvering margins for optical networks. Some important issues include: better granularity, higher efficiency of bandwidth utilization, scalability and lower cost.

However, the non-uniform traffic distribution in optical networks is still an important issue not fully investigated, which has a great impact on the network performance. In a less aggregated traffic flows, the analysis of non-uniform traffic distribution becomes essential to determine the operation conditions, as well as the network behavior under different traffic loads.

This work is organized as follows. In section II, we describe a network structure comprising 2×2 optical switching nodes, which will support possible expected demands of future non-uniform traffic distribution. In section III, we present the method we used to perform the simulation analysis with the Network Simulator (NS-2) [7], developed at UC Berkeley. In section IV, the main results obtained are presented with the Shuffle Net (SN) and Manhattan Street (MS) network topologies, assuming a non-uniform distribution of the traffic load. Finally, in section V, we present the conclusion and comment possible issues of future work with our simulation studies.

II. NETWORK STRUCTURE

The network structure is a regular uniform distribution of optical switching nodes that provide access to users or gateways to other optical networks. Each node is located at the edge of a square, in order to obtain the maximum distribution of nodes. Simple network topologies as SN and MS can be easily matched to represent the physical layer of regular uniform distribution of optical switching nodes in an optical network. We assume only two input and output ports with an additional add-drop functionality per node in order to keep the complexity of a node as low as possible. A small number of output and input ports in conjunction with a buffer-less strategy can be more easily implemented without an excessive increase of node cost in

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such optical networks. Therefore, we can resolve the contention between optical packets towards the same output port, with a deflection strategy more well known as hot potato routing [2].

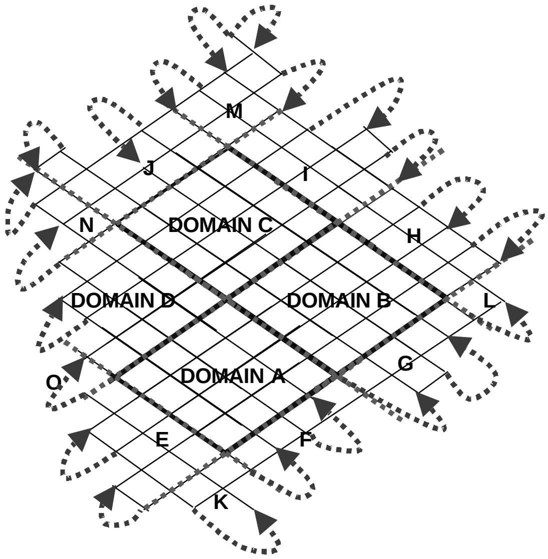


Fig. 1. Schematic illustration of a Manhattan Street topology distributed over an optical network. The optical switching nodes are located at the edge of square areas. The network is arranged in separate domains of 16 nodes with two input and output ports per node. The arrows shown at the border represent possible closing links within incomplete domains.

One important advantage of such networks is the robustness regarding faults and link failures, due to the existence of alternative routes in a distributed network. The need of robust networks for data digital transmission without dependence on the amount of links installed in older analog telephone communication networks has been pointed out already in 1964 [1]. Nowadays, robust architectures such as SDH networks employ ring topologies with link redundancy to achieve survivability. In the present work, we move a step further with a network structure incorporating an increased link redundancy. The redundancy of optical paths provided by such topologies contrasts with the conventional SDH ring protection implanted for long distance optical links employed to transport great traffic volumes.

The scalability of the network can be achieved by adopting the hierarchical procedure, as shown in Fig. 1. In this example, the network is divided into domains of 16 nodes for a single hierarchical level. For a packet to move to a higher hierarchical level, it may proceed to an edge node or utilize an available alternative path, like for instance, an edge node of a neighbor domain when the number of hops needed is smaller. Once in a higher level, the optical packets skip nodes of lower hierarchical domains and travel longer distances, either on a different fiber or different wavelength. Therefore, in a two hierarchical level network of 16 nodes per domain, the network can serve a total of 256 optical switching nodes, offering good scalability as shown in Fig.1. The network configuration shown in this figure incorporating two input and output ports per node, can be easily adapted to the MS logical topology.

Another logical topology often investigated and compared to the MS is the SN [3]. Several investigators compared the performance between these logical topologies, and the SN presents greater performance with higher throughput and lower delay. These characteristics are dependent on the average number of hops that a packet takes to reach its final destination under deflection routing. However, the MS topology can more easily match the regular physical network shown in Fig. 1, since the number of hops performed by deflected packets may become much larger with the SN. Here, we are mainly interested in the characteristics of non-uniform traffic distribution where the network links present a variable amount of traffic. The optical nodes have an add and drop functions to provide a sink and source of access to users or gateway nodes of another optical network, such that each node generates and absorbs traffic form the network. One important open issue is the role played by buffer memories, which has been analyzed [4].

We may also assume a network with open domains, where an optical packet can leave a domain and move into another to find the shortest route to its destination. Some routes may even pass through more than one domain. The deflection probability of packets that take longer routes to reach their destinations distance can be approximately evaluated by the simulation analysis presented in Section III. The packets are not transmitted through an optical path as in a connection oriented network, but rather follow a "best effort" service, where each node decides to which output port the packet is transmitted, with no previous negotiation or resource reservation. However, closed domains might be useful because they may simplify the addressing scheme.

The optical network has finite dimensions with border nodes, which can introduce open connections in the network. In any practical implementation, the open connections associated with border nodes must be somehow closed to provide coherence to the MS like logical network. Some maneuvering options should also be considered for the case of inactivation or destruction of nodes within the network. This is a relevant point, because a great advantage of such networks relies in their safety potential due to the existence of many alternative paths. An example of border nodes with closed connections using a MS like topology is also presented in Fig. 1, where different possibilities are identified. For instance, domains A, B and C are complete, but a packet in D needs to pass through neighboring domains to minimize the hop distance and reach the node where it can change to a higher domain. The open connections at the borders can be evaluated in order to optimize the network capacity and traffic uniformity, and can be implemented with extra fibers or extra wavelengths using as few as possible available physical connections. Some domains may be preferably left incomplete because closing open connections would not work properly. However, an incomplete domain also represents lower levels of service demands (since non existent nodes do not create any demand), and the domain would function as a small overload to the nodes of the superior hierarchy.

III. SIMULATION ANALYSIS

We now turn to the simulation analysis where we have mainly considered the SN and MS logical topologies, as possible candidates for implementation of the optical network. These topologies have been extensively investigated for traffic analysis in the backbone and core networks. We will focus our presentation on possible implementations with non-uniform traffic distributions. Besides, the buffering of packets at intermediate nodes in conventional electronic networks is usually provided with store and forward routing. This approach cannot be simply implemented in optical packet switching using fiber delay lines. Therefore, the deflection routing scheme, also known as hot potato routing, represents an attractive alternative towards a possible implementation of optical packet switching without buffers in these networks. The repeated deflection of packets produce longer traveled distances through the network compared to non-deflected packets, and thus induces larger error bit rate at their final destinations.

Here, we present the simulation analysis of the SN and MS logical topologies to evaluate the network behavior under two types of traffic flows. One is the constant bit rate (CBR) flow, where packets are generated with the same time interval between packets, maintaining fixed the packet size and generation bit rate. The other is variable bit rate (VBR) flow, where packets are generated according to a Poisson distribution of burst and idle times with an average bit rate. The non-uniform traffic distribution analysis is performed under the assumption of the short path first (SPF) algorithm. Such routing protocol considers the non-uniformly distribution of link loads in the network, even when users are uniformly distributed in the network. This behavior is clearly seen in Fig. 2, for a network comprising simple nodes with a 2×2 configuration, where each node generates traffic to all other nodes. In this example, the SPF algorithm was adopted for the routing protocol, and one notices that even with an uniform distribution of traffic among users, there are links in the network with greater loads than others. This occurs because the path distance between nodes has different number of hops.

The results obtained with the Network Simulator (NS), were us logical topologies of conventional SN and MS networks. The NS simulations can be regarded as an alternative method for traffic analysis, which is better adapted to the study of non-uniform traffic flow distributions. These generally occur in optical networks with burst traffic characteristics. In the analytical method based on the one packet model [2], the influence of other packets appears only as a deflection probability, which is more appropriate for the case of uniformly distributed traffic in the network

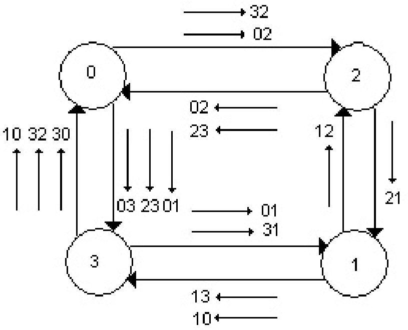


Fig. 2. Network traffic distribution using SPF routing algorithm in a simple 2×2 nodes network. The small arrows indicate the traffic flows and the numbers their origins and destination nodes, respectively.

A. *Comparison of Different Network Topologies*

We employed the NS to determine the packet loss fraction (PLF) with SN and MS topologies of various network sizes. The PLF is defined as the amount of packets that have not arrived at their destination, divided by the total number of generated packets in the network during the total simulation time. In our studies, the simulations were always performed under non-uniform traffic flow distribution, and included network analysis with different total number of switching nodes: SN-8, MS-9, MS-16, SN-24, MS-25, SN-64 and MS-64.

TABLE I:
MAXIMUM NETWORK CAPACITY OF SN AND MS TOPOLOGIES

Topology	**K**	**N**	**`H**	**C (Mb/s)**
SN-8	2	8	2.0000	800.0
MS-9	-	9	1.8125	993.1
MS-16	-	16	2.9333	1090.9
SN-24	3	24	3.2500	1476.9
MS-25	-	25	3.1458	2551.8
SN-64	4	64	4.6250	2767.5
MS-64	-	64	5.0158	2551.8

We first discuss some considerations about the uniform traffic distribution, in order to define parameters to establish some conditions for comparisons. Following the analysis of uniform traffic distribution [3], the network capacity C is the product of the total number of links by the bit rate, divided by the average number of hops that a packet takes to travel to its destination. Therefore, in the case we have N nodes with two links and a bandwidth of S bits/s, the total network capacity is given by (1) [3].

$$C = \frac{2 \cdot N \cdot S}{\overline{H}} \tag{1}$$

Under uniform traffic distribution, all links are equally loaded and the expected number of hops in a SN and MS networks assuming an even and odd number of nodes, are given by (2) [3], (3) and (4) [6], respectively, shown below. The parameter k is the number of columns in a SN network and *N* is the number of nodes in a MS network.

$$\overline{H}_{SN} = \frac{(3 \cdot k^2 - 3 \cdot k) \cdot 2^{k-1} + 2 \cdot k}{k \cdot 2^k} \tag{2}$$

$$\overline{H}_{MSE} = \frac{\sqrt{N^3} + 2 \cdot N - 8}{2 \cdot (N-1)} \tag{3}$$

$$\overline{H}_{MSO} = \frac{\sqrt{N^3} + 2 \cdot N - 4 \cdot \sqrt{N} - 4}{2 \cdot (N-1)} \tag{4}$$

Hence, we can determine the maximum network capacity of these network topologies, as shown in Table I, where we have assumed, only as an example, a link bandwidth of 100 Mb/s for all network topologies.

B. SN and MS Analysis using the PLF Criterion

In order to represent the same traffic conditions with the NS simulator, we followed the methodology where packets are generated in all network nodes, with destination addresses to all other nodes. Thus, we have a total of $N \cdot (N-1)$ traffic sources (or end users) in the network. As a result, the maximum network capacity will be reached when the bit rate (*BR*) generated by each user (or traffic source) is the same and given by (5).

$$BR = \frac{C}{N \cdot (N-1)} \tag{5}$$

This expression defines a relation between the *BR* generated by each user in the network, and the value of the total network capacity shown in Table I. Using (5), we have determined the *BR* under different values of the network capacity for the various network topologies. We have then analyzed the amount of lost and received packets for a given link, and hence plotted the PLF and average link load (ALL), which was calculated assuming the number of packets received as an approximation for the link load, as function of the network capacity according to the SPF routing protocol, and according to a CBR or a VBR traffic. In Table II we present, as an example, the *BR* values used in our simulations for each network topology.

TABLE II:
BR VALUES DETERMINED FOR DIFFERENT FRACTIONS OF THE NETWORK CAPACITY

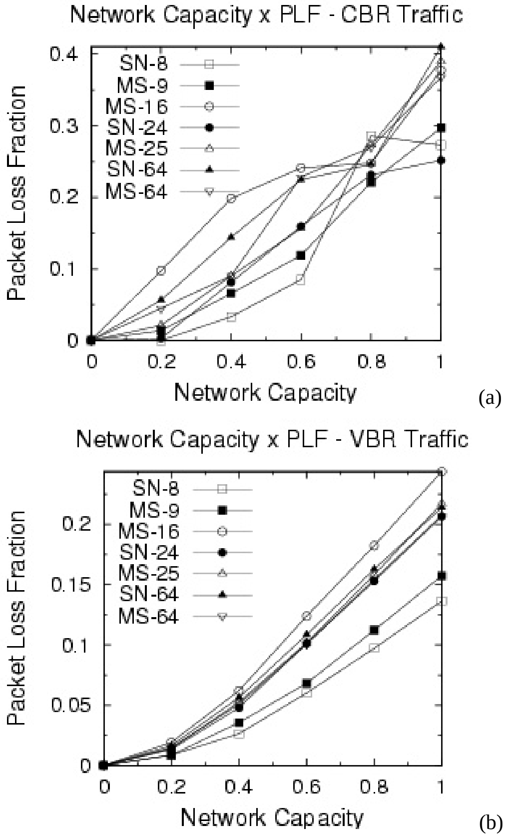
Topology	**BR (Mb/s)**				
	0.2 C	**0.4 C**	**0.6 C**	**0.8 C**	**1.0 C**
SN-8	2.850	5.700	8.550	11.400	14.250
MS-9	2.759	5.517	8.276	11.034	13.793
MS-16	0.909	1.810	2.720	3.630	4.540
SN-24	0.535	1.070	1.605	2.140	2.675
MS-25	0.529	1.050	1.580	2.110	2.640
SN-64	0.137	0.274	0.411	0.549	0.686
MS-64	0.126	0.253	0.379	0.506	0.632

We have plotted various graphs of the simulations obtained with these topologies using the PLF criterion, considering the CBR and the VBR traffic. Besides, a user datagram protocol (UDP) is used in the transport layer to avoid packet loss retransmissions. The simulations were performed assuming a packet generation time of 50 seconds, a link bandwidth of 100 Mb/s, a packet size of 650 bytes and network links without buffers. In the case of VBR traffic, the burst time and the idle time were set to 500 ms.

IV. RESULTS

In Fig. 3, we present the PLF as function of the network capacity for the CBR and VBR traffic flows. From these figures, we can observe that the CBR traffic does not present a monotonic behavior. This can be explained by the fact that when we have CBR traffic, the time interval between two packets with the same destination node remains constant as determined by the BR. When a user detects a packet loss in a node in a given time frame interval, all subsequent packets will be lost to maintain the same traffic conditions in the network. This causes a different result in terms of PLF with a small variation of BR and we can observe a lower value of the PLF with the increase of the BR. This behavior does not occur in the case of VBR traffic because of the Poisson characteristic of packet arrivals. In Fig. 4, the non-monotonic behavior of CBR traffic is shown for network capacities varying from 0 to 0.4 C, and evaluating the PLF at intervals of 0.02 C.

This is also expected near the edge nodes of optical networks, where the traffic is naturally more burst like and most probably not uniformly distributed. From the figures above we notice that with most topologies, packet losses occur even at low loads in the network. But such losses occur mostly in few links, which are load saturated, as shown in Fig. 2. Depending on the routing algorithm used in the simulations, some links with greater loads than others produce packet losses when their capacity limit is reached. As shown in figs.2 and 3, considerable packet losses also occur under the CBR traffic flow when packets arrive within the same time frame or collide. In such case, all packets sent by a given user will be lost.



(a)

(b)

Fig. 3. PLF × network capacity with (a) CBR and (b) VBR traffic flows.

The PLF can also be used to determine the amount of deflected packets when using a hot potato protocol as the contention resolution method. In the case of hot potato routing, we may assume no packet losses when packet contention occurs. Therefore, packet losses can be regarded as packet deflections in the network. In other words, we can evaluate the number of packets that will take a longer path to reach their destinations by the PLF analysis.

In Fig. 5, we show the PLF behavior from 0 to 0.4 C network capacity, with point intervals of 0.02 C, for the analysis of SN-64 and MS-64 topologies under CBR and VBR traffic flows. From these figures we can see that the PLF is much lower in the VBR case despite having packet losses even for lower loads. In the case of VBR traffic flow, we can also observe the monotonic behavior of the PLF in these topologies due to the Poisson distribution of packet arrivals when we consider the VBR traffic flow.

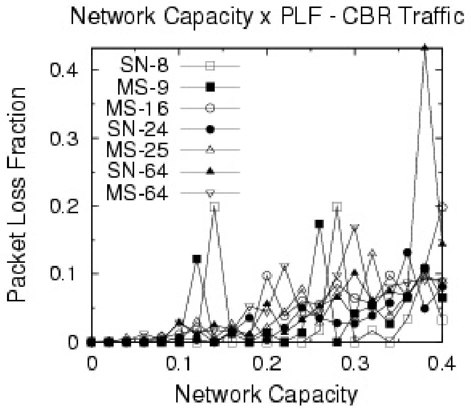
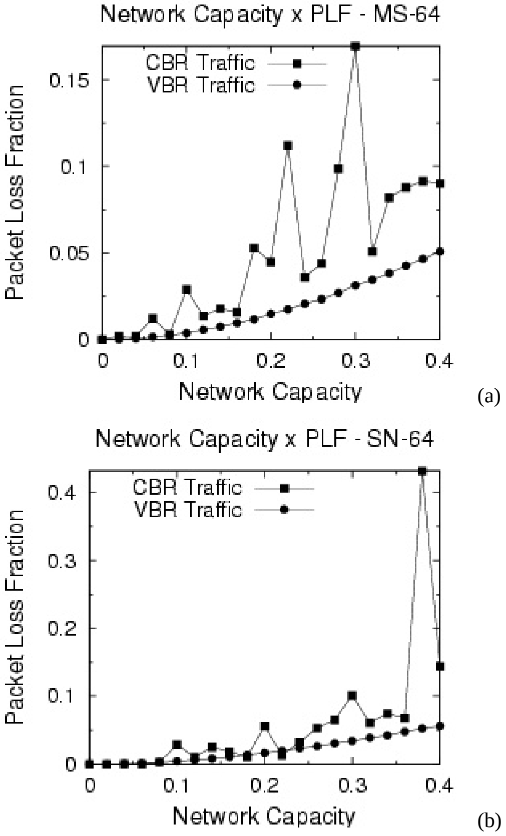


Fig. 4. PLF × network capacity with CBR traffic flows.



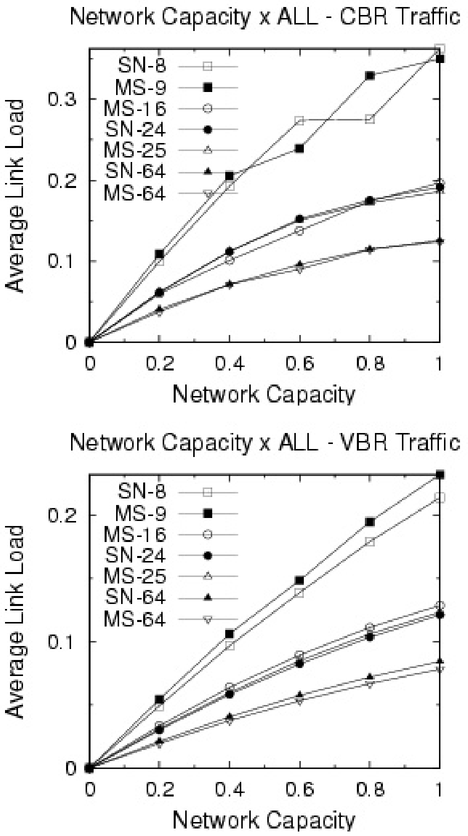
(a)

(b)

Fig. 5. PLF × network capacity for (a) MS-64 and (b) SN-64 networks.

We have also examined another important parameter obtained from the simulations: the average link load (ALL) [8], which is shown in Fig. 6

The main result shown in these Figures and obtained with the simulation analysis is that the average link load becomes smaller when the size of the network increases at full capacity. This fact has already been expected, since the network traffic is not uniformly distributed. Otherwise, we should expect the average link load to reach the value of one when the network is at its full capacity. However, some links may have packet losses because their loads are greater than in other links. Hence, the average link load at full network capacity load is lowered when the number of links increases in the simulation analysis.



(a)

(b)

Fig. 6. ALL × network capacity for (a) CBR traffic flow and (b) VBR traffic flow.

Another important result is the smaller value of the ALL parameter in the VBR traffic flow when we compare with the CBR case. This result can be explained by the intrinsic characteristic of the VBR traffic flow that comprises a burst and an idle time in addition to the average bit rate generation. As we set these times to 500 ms, the number of packets generated for the VBR traffic flow is nearly half of the CBR case. These behaviors are not in conflict since our work mainly focused in a qualitative analysis of optical networks under two different kinds of traffic flows.

V. CONCLUSION

In this work, we presented a possible network structure that provides easier flexibility and scalability to support non-uniform distributed traffic demands in optical networks. Next, we presented the results obtained with the NS simulator for optical networks with different topologies under non-uniform traffic flow distributions. The non-uniformity is due exclusively to the adopted SPF routing algorithm undertaken in our study. The analysis considered networks with switching nodes and optical links without buffers. Great packet losses were obtained at switching nodes, associated to links that may have reached their full capacity. Another cause of packet losses is packet collision at switching nodes that become more significant in the CBR traffic analysis. Optical networks should be robust to packet losses under different traffic flow conditions. From our simulations analysis, the significant PLF obtained in such networks cannot provide an acceptable quality of service. However, our results characterize such networks under non-uniform traffic flow distributions, and also provide useful insights for contention resolution studies of optical packet switching for optical networks. In traffic analysis with quality of service, a possible solution might involve the assumption of deflection routing as the contention resolution method, which would also provide a more uniformly traffic distribution despite using the SPF routing algorithm. In addition, a better traffic distribution can be obtained employing other algorithms and protocols with the assignment of appropriate weights from the corresponding optical link loads, but at the expense of a greater complexity of the optical network. Finally, the results presented here are quite general and are also applicable to other types of networks.

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