Proposition of a Hybrid Topology for Photonic Switched Optical Networks

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***Abstract*—Use of Photonic Switching in Optical Networks seems to be one of the best solutions for traffic optimization in Metropolitan Access. Here we propose optical packet/burst switching (OPS/OBS) networks as a future-proof solution for high-throughput in the highly variable traffic pattern of the metro-access. Through analytic modeling and computer simulations we evaluate network performance of mesh networks having a hybrid topology of the Manhattan St.-type. We combine nodes of interconnection grade-2 and grade-3 in order to optimize and balance simultaneously network performance and cost. For performance metrics the parameters packet loss fraction and average number of hops are adopted, link and node loads are investigated, and effective network capacity is evaluated. Results clearly indicate improvement of capacity over grade-2 networks, and possibility of cost savings over complete grade-3 installations.**

Keywords- Photonic Switching, Optical Packet Networks, Link-failure, Optical Fiber Communications.

I. INTRODUCTION

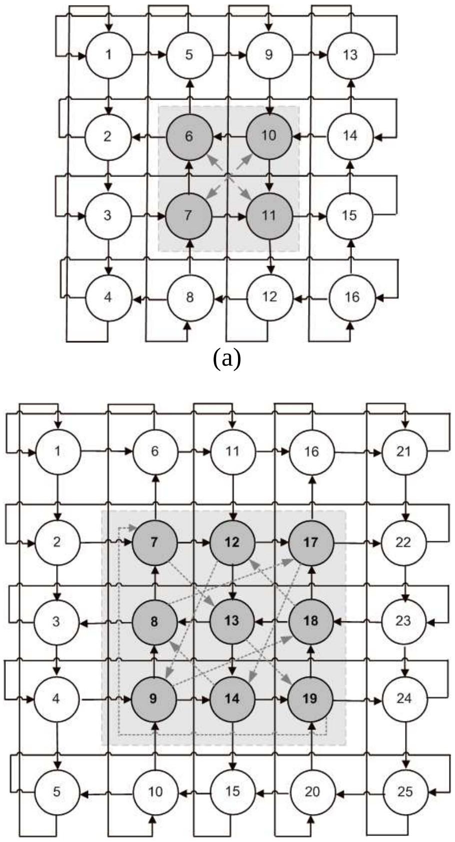
Access networks are client centric local networks, which today easily extend to the metropolitan level due to the omnipresence of optical fibers and their high-capacity systems [1]. Today, passive optical access networks such as Gpon and Epon [3] are established solutions for metro-access, mainly in residential and small business application areas. However, the ever-increasing traffic in these networks requires increasing flexibility and availability of transport capacity, which is not totally compatible with the centralized control of these passive networks [3]. On the other hand, we believe that asynchronous OPS/OBS mesh topology solutions [1,2] can overcome these limitations and are better suited for packet-oriented applications [8, 9]. Furthermore, avoiding opto-electric conversions along optical path route nodes saves time and energy.

In this work we focus on hybrid OPS/OBS network architectures based on mesh topologies. The simplicity of construction of the optical nodes when Photonic Switching is adopted is our base of choice on already demonstrated experiments [7,9]. The term hybrid comes from combination of nodes with different degrees/grades of interconnection (number of input-output ports) in the same network. The main idea is that a better techno-economical performance may be achieved by higher grade central nodes and lower grade edge nodes. The performance of the OPS networks is analyzed and evaluated according to basic packet-network parameters such as average number of hops (ANH) and packet loss fraction (PLF). The present work is based on single wavelengths; and various single-wavelength networks can be interconnected with WDM systems [5,10]. It should be noted that the presently proposed networks, as well as other proposals [2] and demonstrations [7,9,10] are better suited for application in limited areas, mainly metropolitan traffic, not considering physical impairments. In case of geographical expansions, larger networks (more than 25 nodes) should be broken down to twice 16 or three times 9, according to specific situations [2]. In case of capacity demand, we have recently demonstrated [6] that increasing the interconnection grade is a more valuable solution than increasing node count.

II. HYBRID MESH NETWORK TOPOLOGY

The OPS/OBS optical network architectures proposed in the present work are based on modified Manhattan St. (MS) (Fig. 1). The MS mesh topology is attractive for optical networks because it has high connectivity, traffic flexibility, and robustness to failures [2,4]. We adopt further distributed switching, where optical packets are routed asynchronously through the network, directed only by header information. We consider networks with N nodes, with $N=m^2$, m=[4;5;6]. The optical nodes are interconnected with unidirectional links; so that each link connects an output port from one node to an input port in the next node.

The classical MS is 2x2 (2-input/2-output) nodes, that is in graph theory a *grade-2* node; another configuration is 3x3, that is *grade-3* [4]. The hybrid networks proposed here (Fig.1) are a composition of grade-2 and grade-3 aiming at optimizing *performance* at the core nodes (grade3) and optimizing *cost* at edge nodes (grade2). It should be noted that the cost-per-user is higher at the 2x2 (grade2) node, but the total equipment/installation costs are less than the 3x3 (grade3) nodes, which have lower cost-per-user because of increased throughput capacity.



(a)

(b)

Fig. 1: OPS/OBS hybrid network topologies: a] MS-16 ; b] MS-25.

The detailed dynamics of the original grade-2 optical node is described in [7], where our original experimental demonstration was presented. The principle of operation has been extended to the other configurations. An optical packet arriving at the node has its header processed and recognized for the optical switch control electronics. The optical layer is bufferless and asynchronous, so that an optical packet does not remain in a given node: it is always forwarded – either to its preferred out-port or deflected to an available port; therefore, in the network traffic simulations to avoid collisions and resolve contentions the spatial deflection routing (DR) protocol is adopted. Optical switching is controlled by fast electronic logic circuits (ns timescale), operating on packet-by-packet basis, determined simply by processing the optical packet header.

III. BASIC THEORY AND PARAMETERS

It is assumed that the total capacity of the networks under consideration is given by the sum of the separate capacity of the network links. This has been given previously [2] for uniform regular mesh networks of grade *k* as

$$C_t = \frac{k.N.S}{\overline{H}} \qquad (1)$$

where $\overline{H}$ is the total average number of hops (ANH) for the optical packets (from all origins to all destinations); *N* is the number of nodes, *S* is the link capacity; and *k* is an integer specifying the node grade.

The hybrid model proposed here requires, however, a generalization of eq.(1). If nodes have different grades in the same network, we set a variable *g* inputs and *g* outputs, and the node configuration is (*gxg*) or grade-*g*., given by,

$$C_t = \frac{\sum_{g=2}^{n} g.N_g.S}{\overline{H}} \qquad (2)$$

where N_g is the number of nodes with a specific grade g, and *n* is the largest grade in the network (usually n ≤ 4).

The traffic is modeled assuming uniform distribution, where each node uniformly generates the same amount of traffic to every other node in the network. The effective number of user nodes (or simply "*users*") in the network for this condition is.

$$N_u = \left(\sum_{g=2}^{3} N_g\right)\left(\left(\sum_{g=2}^{3} N_g\right)\text{-}1\right) \qquad (3)$$

We define the user-share capacity as C_t/N_u , which, using (2) becomes,

$$C_u = \frac{\left(\sum_{g.=2}^{3} k_g N_g\right).S}{\overline{H}.[(\sum_{g=2}^{3} N_g)((\sum_{g=2}^{3} N_g)-1))]} \qquad (4)$$

A useful figure of merit for network performance is defined as performance factor $F_p = C_t/\overline{H}$, which can be applied to any multihop environment that follows (1-2). It means that a more efficient network will have higher capacity, smaller average number hops; this implies also that the network has lower latency.

The calculation of ANH depends on the routing protocol adopted. If Store-and-Forward (SF) protocol is chosen the packets (or bursts) are always transmitted by shortest path to the destination, because they always follow the minimum path generated by Dijkstra algorithm matrix; this, however, may increase latency in an uncontrolled way because evry packet has to wait for the availability of the minimum path. The SF-ANH is calculated with the following expression:

$$\overline{H} = \frac{\sum_{i=1,j=1} Cm_{ij}}{(\sum_{g>1}^{3} N_g) * ((\sum_{g>1}^{3} N_g) - 1)} \qquad (5)$$

where Cm_{ij} is the matrix element for total number of minimum paths of a given configuration.

On the other hand, if Deflection Routing (DR) protocol is used, no buffering is needed and optical packets are immediately forwarded to any out-port available. The calculation of ANH in the DR case is again based on the minimum path matrix generated by Dijkstra algorithm, but it is not always followed because deflections may occur and the optical packet may take a longer path to destination.

Another highly significant parameter is the packet loss fraction (PLF), defined as the ratio,

$$PLF = \frac{p-r}{p} \qquad (6)$$

where $\boldsymbol{p}$ is the total number of packets generated in a given node (origin), and $\boldsymbol{r}$ is the number of packets actually received at destination.

Table I, summarizes analytic results of the ANH, the network capacity and the resulting performance factor. Results were obtained using store-and-forward (SF) protocol, to establish minimum values for ANH and maximum values for *C* and *F*.

Table I – Evaluation of Network parameters for mesh topologies with unidirectional links.

Topology		**Total # links**	**Network Capacity C_t (Gb/s)**	**ANH**		**Performance factor F_p**	
				SF	DR	SF	DR
Grd.2	MS-16	32	27,1	2,9	3,7	9,3	7,3
	MS-25	50	38,5	3,3	3,9	11,6	9,7
Grd.3	MS-16	48	56,0	1,6	2,1	26,2	34,3
	MS-25	75	73,2	2,0	2,5	28,6	35,3
Hibrid	MSh-16	38	33,1	2.5	2.8	11,5	13,2
	MSh-25	59	50,3	2,9	2.9	17,0	17,1

It is seen in Table I that the hybrid alternative has better performance than that (grade2) but remains below that of grade3, thus confirming the expected balance between the network capacity/throughput and the costs of installation and equipment, as mentioned previously. It is also interesting to note that the DR-ANH is only slightly increased from ideal SF-ANH, also pointing to the simpler choice of DR.

IV. TRAFFIC SIMULATION METHODS AND NETWORK CONFIGURATIONS

This section discusses the procedures and conditions for simulations. Fig. **2** presents a diagram of the simulation dynamics for both SF and DR protocols. Note that the SF protocol *always* uses buffering, as previously discussed. The network models use unidirectional links, with uniform traffic distribution (every node generates the same amount of traffic to every other node) during each simulation round time (20ms); the intervals between optical packets vary from 0.1 to 1 packet duration. Every connection is set up with UDP protocol, so that lost packets are not retransmitted. The optical packets have fixed-size of 500 bytes; note that they are easily extensible to 10 or 20 times larger for burst switching, but then the network performance has to be reevaluated. Transmission rate is 2.5 Gb/s, adequate for metro-access environment. The total number of packets generated for simulation rounds (20ms for each data point in Fig.3) is $2x10^5$. Bit-error rate (BER) is assumed better than 10^{-9}. Link length is 10km for all links.

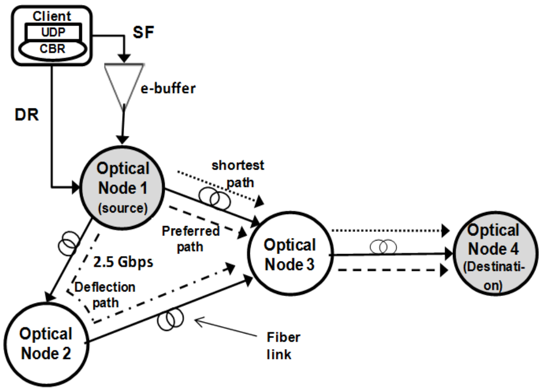


Fig. 2: Simulation Dynamics.

Network traffic simulations the Network Simulator (NS-2)r was used, and data processing and plotting, were carried out with an open version Matlab®.

V. NETWORK RESULTS AND DISCUSSION

In this section compare the traffic simulation results, as described in the previous section, with the results of the average number of hops (ANH) and packet loss fraction (PLF) from Table1.

Fig.3 a and b summarizes these results.

The architecture that has highest capacity with best performance is of course the grade-3; this is explained as this topology offers the largest number of different paths between any node pairs for all optical packets, when compared with other models; however it requires more optoelectronic components and more processing circuits, impacting on higher total equipment cost and operation.

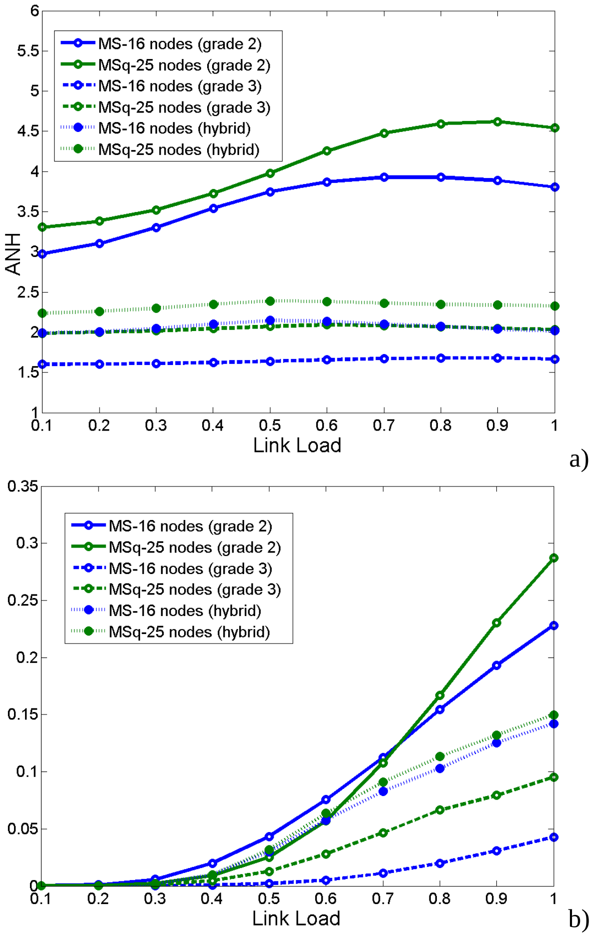


Fig.3 – a) ANH; b) PLF for OPS networks of Table1.

This result is what motivated a hybrid network with composition of grade-3 with grade-2 nodes, the latter being the simplest solution.

The good news is that the performance of the hybrid network is in fact a true balance between grade-2 and grade-3; for ANH it is much better than the grade-2; and for PLF it is just better. Therefore, the simpler grade-2 nodes are used and installed in the edge of the network, where less traffic is expected, and the more complex grade-3 can used in the central nodes which have higher traffic demand, and require increased performance. Further issues such as link and node failure and network protection can be directly adapted from previous works [2,4].

VI. CONCLUSION

We have evaluated and compared optical packet networks in various Manhattan St.-based mesh topologies, through calculations using analytic models and traffic simulation conditions. This work has used the evaluation parameters of network capacity, average number of hops and packet loss fraction in the various network configurations. Comparison of 2x2 (grade2) and 3x3 (grade3) regular mesh architectures and our new proposed hybrid (grade2/grade3) have the various degrees of performance; the grade2 is simpler and the grade3 is better, and the hybrid alternative confirms the expected balance between the network capacity/throughput and the costs of installation and equipment. This demonstrates the present methodology as useful tool for network planning and design. Future work will consider topologies including electronic buffers at node ingress to avoid packet loss at optical input and minimize PLF. We also plan to include cost of link usage and of node failure.

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