Dynamic Optical Networks Demonstrators: Reviewed and Classified

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Abstract: In this work, a number of optical switching testbeds and demonstrators are studied and analyzed. The used methodology is as follows: firstly, the principal figures of merit (FOM) of optical networks are presented, both at the high (protocol) level and at low (physical layer) level. Secondly, a framework for the classification of the several kinds of optical networks and optical switching technologies is devised. Lastly, a number of testbeds covering a broad spectrum of the literature are analyzed and classified according to this framework, and the FOMs reported are analysed. We conclude that some research has yet to be done in order to smoothly integrate the pure physical layer FOMs with the top-level network design parameters.

1. Introduction.

The phenomenal development of electronic integrated circuits has been able to cope with the increasing bandwidth requirements in carrier data transport networks. However, current electronic switching systems have a number of disadvantages: the increasing of clock speed produces a high on-chip power dissipation that is reaching the physical limits and results in high power consumption, and the space footprint of the switching equipments is also very high. Point-to-point optical fibre communication systems have been used for more than two decades to provide high bandwidth transport, and it is generally believed that introducing optical switching technologies into network layer 3 will alleviate the bandwidth requirements associated with switching whilst maintaining reasonable equipment costs, accommodating variable traffic demands, and providing scalability to cope with future demands [1].

A number of electronic-optical hybrid networks and all-optical networks have been proposed in the literature for more than a decade. Unfortunately, there is no general consensus about how to classify all of these prototype networks. In this work, a classification framework, based on important parameters like transparency, granularity, and technological switching requirements, is proposed. The relationship between the granularity and the optical switching reconfigurability speed requirements is also presented.

This paper is organized as follows. Firstly, the most commonly used figures of merit (FOMs) in both the protocol-level and the physical layer level are presented. Secondly, there is a review and analysis of a number of types of dynamic optical networks found in the literature. Thirdly the most significant dynamic optical network testbeds are briefly reviewed and classified. Finally After that, a selection of the most significant testbeds are reviewed and classified according to the purpose and the result published. Finally, there is a brief conclusion and a summary of the paper.

2. Dynamic Optical Networks Figures-of-merit.

The development process of a dynamic optical network comprises of several stages and every stage studies different aspects of the developing network. Early conceptions of the network are commonly based on analytical and simulation studies. As the network concept evolves towards maturity, the experimentation with actual networks prototypes and emulators in the laboratory becomes crucial.

The design process of a dynamic optical network typically starts defining some scalar properties (like the number of wavelength channels per optical fibre), a graph network definition, and a traffic matrix. The network graph $G(V, E)$ is composed of a set of edges E and a set of vertexes V. Additionally, every edge e in E contains a set of properties associated with it, i.e., the span distance in km and the number of optical amplifiers.

The typical FOMs at the simulation stage are the Packet Error Rate (PER) in sub-wavelength granularity networks, and the Circuit Blocking Probability (CBP) in wavelength channel granularity networks. Another important FOM common to both kinds of network is the network throughput (NT), defined as the fraction of the mean network capacity utilisation divided by the total network capacity. At this stage, the physical layer modelling is simplified either by assuming no errors arise from the physical layer or by using simplified probabilistic models that are independent of the transmission characteristics of the network. The PER, CBP, and NT are usually compared with the average network load.

Once the network requirements are defined in terms of network capacity and throughput, the optical physical layer is investigated and new FOMs came into play. The most used FOM in transmission experiments are the Bit Error Rate (BER), and the Optical Signal to Noise Ratio (OSNR) penalty, defined as the difference in dB between the back-to-back OSNR and the measured OSNR to obtain the same BER as in the back-to-back case. The OSNR penalty takes into account additional physical layer impairments like ASE noise, crosstalk due to optical switching, polarization dependant loses, and any other impairment the optical signal incurs. Another FOM in dynamic networks is the dynamic range, defined as the maximum power variation in dB to keep the PER in acceptable levels. The average optical power in dynamic networks is not constant due to add/drop of wavelength channels, the difference in path lengths and number of optical switches that the optical signal traverses. All of these FOMs are usually compared against the received optical power.

3. Classification of dynamic optical networks and optical switches.

As mentioned in the introduction, there is no general consensus among the research community on how to properly classify dynamic optical networks, however, a set of important network properties, that are specific to particular network applications, can be defined and these used to classify the dynamic optical network. The most important parameters are: the degree of transparency, the network granularity, and the optical switching requirements. Other important but secondary parameters are: the ability of the network to cope with traffic variations, synchronization (time slotted or not), and resilience to failures.

The degree of transparency is the ability of the network to transport optical payloads in a format-agnostic manner, thus avoiding expensive and modulation-format dependant O/E/O conversions. Network transparency allows the optical network to smoothly accommodate high layer data payloads of well established legacy protocols, like IP datagrams, Ethernet frames, ATM cells, and SDH/SONET frames. A non transparent optical network is called opaque. Recently, some research has been done in semi-transparent networks, defined as a concatenation of transparent "islands" with O/E/O converters to balance network costs [2]. Transparent WDM circuit switching networks are now being deployed [3].

The network granularity is defined as the minimum quantity of bandwidth that the network is able to allocate. Using the concept of network granularity, dynamic optical networks can be classified, in increasing granularity, into Optical Circuit Switching (OCS), Optical Burst Switching (OBS), and Optical Packet Switching (OPS).

OCS networks, also known as static optical networks, allocate wavelength end-to-end channels that typically last for a long time. The main advantages of OCS networks are: large bandwidth, slow speed switching requirements, low cost, and low technological challenges.

OPS networks allocate sub-wavelength bandwidth in a packet by packet basis, mimicking the store-and-forward approach of classical packet switching electrical networks, in the optical domain. Every packet has a header with the information required to reach its destination through the network. This header could be time multiplexed with the payload, or being encoded in a different orthogonal modulation format or band. The main advantages of OPS are the network flexibility to cope with changing traffic demands and excellent resilience features. However, OPS networks require sub-nanosecond optical switching technologies, and optical buffering to store contending optical packets.

OBS networks comprise a broad category that falls in between of OCS and OPS, and tries to incorporate the advantages of the two approaches. In OBS networks, the information is aggregated in the edge routers to form long-size packets or bursts and the routing is determined before the burst is transmitted, removing the need for optical buffers in the network. Signalling information is carried on a separated wavelength channel. OBS networks could be classified into two broad categories: Type I signalling (aggregation time is small, bursts are in the range of kB, burst path is not acknowledged), and Type II signalling (aggregation time is long, bursts are in the range of hundredths of Kb, and burst path is acknowledged before transmission). The advantage of Type I networks is the simplicity of design at a cost of some performance degradation due to bursts losses. Type II networks have better network throughput and the technological requirements are more relaxed, but as a central node is required to control and acknowledge all burst path requests there could be scalability problems in networks with a high number of nodes [4].

The classification of the dynamic optical networks according to the granularity allows us to establish a set of optical switching speed requirements for core switching nodes. Table 1 summarizes the most important switching technologies (see [1] for more details). The correlation between optical switching technologies and application granularity becomes manifest.

Network type	Switching time	Suitable switching technologies
OCS/OBS	~ ms	Opto-mechanical, MEMS, Thermo-optical PLC [5], LCOS [6]
OBS	~ µs	PLZT [7]
OPS/OBS	~ ns	AVC [8], SOA Broadcast and Select (B&S), SOA Crosspoint matrix, AWG and Tunable λ

Table 1: Optical switching requirements for dynamical optical networks.

4. Dynamic Optical Network Testbeds Review.

Table 2 summarizes the testbeds analysed in this work and their main attributes.

Name	SW Technology	Synchronisation	Granularity	FOM analyzed
WONDER [9]	Tunable Tx/Fixed Rx	Time slotted	λ	Layer 2 PER vs. OSNR
Osaka University [10]	LiNbO3 2x1 node	Time slotted	Sub-λ	Power penalty
Data Vortex [11]	SOA B&S 2x2 node Data Vortex arranged	Time slotted	Waveband	Power penalty Dynamic range Cascadability
OSMOSIS [12]	SOA B&S	Time slotted	λ	User-perceived BER
Tokyo University [13]	Thermo-optic PLC	Asynchronous	OBS	Layer 2 PER vs. network load End-to-end delay
PHOSPHORUS [14]	AVC	Asynchronous	OBS	Extinction ratio
KEOPS B&S [15]	λC + SOA B&S	Synchronous	OPS	Power penalty Cascadability
KEOPS WSS [16]	λC + MUX/DEMUX	Synchronous	OPS	Power penalty
WASPNET [17]	λC + AWG	Synchronous	OPS	Power penalty Cascadability
OPORON [18]	λC + AWG	Asynchronous	OPS	Extinction ratio
UC Davis [19]	λC + AWG	Asynchronous	OPS	Power penalty Cascadability

Table 2: Optical switching tesbeds experiments and their attributes.

The WONDER and Osaka University testbeds correspond to MAN networks with ring topology. The former has a main controller node that controls when nodes in the network can transmit information. Every burst-mode receiver is tune to a fixed wavelength that can be share among receivers. The latter employs a slow acousto-optic tunable filter to select one wavelength, and then add/drop optical packets addressed to that node. In both testbeds, the fibre spans between nodes are about 30 km.

The Data Vortex and the OSMOSIS project are examples of high performance computing (HPC) interconnections. The testbed consists of core nodes of sizes 12x12 and 64x64, respectively. The Data Vortex splits payload information into several wavelengths (waveband switching). As HPC systems are design for very short distances, no long fibre propagation is considered. The OSMOSIS project is more focused in the switching control algorithm, and little information was released regarding the optical layer.

Both the Tokyo University and the PHOSPHORUS projects testbed implement OBS networks, and the focus of both testbeds are to demonstrate that OBS could be realized with current off-the-shelf components.

The rest of the testbeds correspond to OPS and employ either the B&S switching architecture with SOA gating, or wavelength conversion followed by a wavelength routing device (like an AWG). The synchronization attribute here refers to the ability of the core switch to either route optical packets asynchronously in a non-blocking manner or operates in a slotted manner and there is a packet synchronization stage before packet switching.

Most of the results reported are the power penalty incurred by a combination of switching and propagation through a fibre span. Some testbeds also report the cascadability, defined as the number of times the optical signal is able to circulate the core switch and propagate in some fibre span.

7. Summary.

This paper presented the main FOMs used in dynamic optical networks design in both the first and the second stages. A brief classification of the several types of optical networks, along with the switching requirements and suitable technologies, was pointed out. Some significant testbeds developed in the recent years were presented, and their main results discussed.

During the last two decades several dynamic networks testbeds and demonstrators have been proposed. However, it is not yet clear how the experimental results of laboratory or field testbeds fit into the topology and protocol design stages. Some recent work [20] is being conducted to try to incorporate the physical layer parameters into the routing and wavelength assignment for network optimization.

Little research has been done to integrate the physical layer fundamental limits with the protocol layer design parameters [3]. Our future research will be focused on investigating the fundamental physical limitations in dynamic optical networks and applying these results into early dynamic network design stages.

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