Why Optical Packet Switching failed and can Elastic Optical Networks take its place?

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Abstract

In this special issue devoted to the memory of Prof. Fabio Neri we would like to look back at the time of the international research projects where some of us collaborated with him. On the basis of our personal experience of the time and the current viewpoint, we will discuss why Optical Packet Switching is a technology that never came to market in spite of the great amount of research that was devoted to it during the last three decades. Then we will explore why Elastic Optical Network came to the stage more recently somewhat overcoming the OPS technical proposal both in the interest of the researchers as well as of the industry.

Keywords: Optical Packet Switching, Elastic Optical Network

1. Introduction

The discussion presented int his paper starts from a quantitative analysis of the bibliography on the OPS and EON technologies, with the aim to provide a big picture of what happened in the last 25 years. A detail analysis including sub-topics and/or style of the papers (research, test-beds, theoretical, etc.) is well beyond the scopes of this manuscript. We referred to the IEEE Xplore for this analysis and extracted the list of papers.

For Optical Packet Switching, which is a well consolidated topic, we used the INPSEC Controlled terms, searching for "Optical Packet Switching" or

"Photonic Packet Switching". We choose this option after a number of different trials because a search on the keyworks did not prove satisfactory. Searching for a combination of keywords such as "Optical", "Packet" and "Switching" lead to a number of false positive, in which all these words appeared not linked together. For instance combinations like "Packet switching" and "Optical networks" would be selected even if the content of the document had nothing to do with OPS.

For Elastic Optical Networks on the other hand there is no INPSEC Controlled terms and therefore we searched for the two combinations "Elastic Optical Networks" and "Flexible Optical Networks" in the document title.

These searches could probably be optimized, nonetheless the goal was to perform quantitative analysis of the production of scientific literature on the specific topic, therefore we believe that having consistency on the topic is sufficient. It may well be that the absolute number per topic may not be fully consistent, nonetheless the results obtained are quite clear and easy to read, therefore we took this approach as valuable.

We manually got into the list and pruned elements that did not fit, checking title and abstract per document. Finally we outline that the IEEE Xplore database reports the major journals and conferences on Optical networking in general and is therefore a good representation of the amount of bibliography produced on a specific topic.

Figure 1 reports the number of papers referring to OPS from 1995 to 2020, per year, total, conferences and journals (we included magazines in the journal count). The Figure is obviously self explanatory. The topic started to gain interest in the mid '90s and boomed between 2000 and 2010, then started to fade with a current number of publications that is below that of 25 years ago. This is something that is typical, a technology at first captures the interest of researchers, then either it enters the market and is employed in the industry or is somewhat abandoned. In both cases the interest of the scientific community decreases significantly and the number of publications on that topics decreases.

Figure 2 shows the same results for EON. In this case the number of publications was almost 0 up to 2010, then boomed and is still at quite high levels.

The overall message is quite clear. OPS is a technology that was very popular for a quite long time. It kept its pace for about 15 years overall (from 2000 to 2015). EON just started to be a significant subject of scientific investigation around 2010 but gained popularity quickly and soon overcame

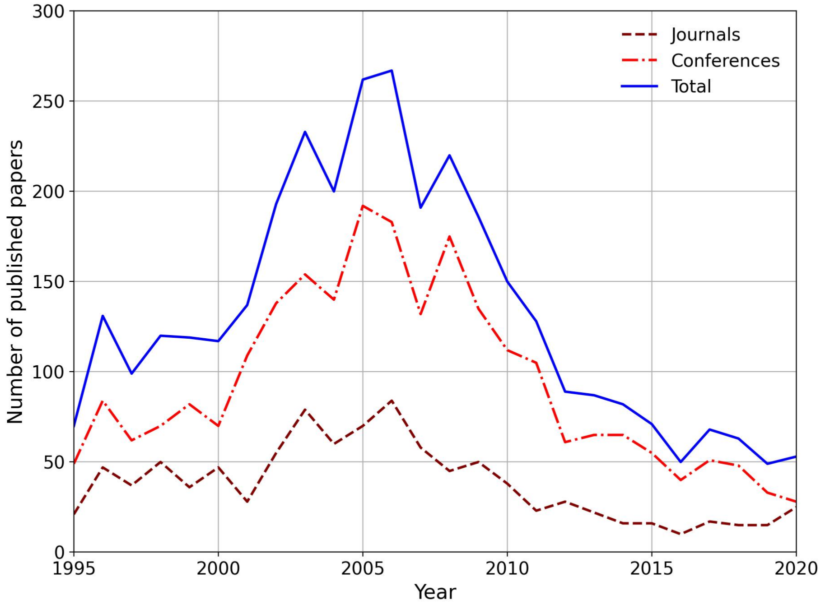


Figure 1: Yearly number of papers about OPS in the time window 1995–2020.

OPS.

If the number of published paper on a given subjects may be considered a *measure* of the popularity of a research topic, then we get the clear message that OPS was very popular for quite a long time. The interesting issue is that the decline of OPS perfectly matches the rise of EON as shown in Fig. 1, Moreover the market application of OPS to date are negligible, while EON, in spite of having been at the edge of research for a shorter time is already leading to market applications.

We emphasize here that we focused on Optical Packet Switching without considering Optical Burst Switching. Whether OPS and OBS can be considered variations of the same technology was a matter of debate and we could probably still argue about it. Surely OBS aimed at switching short bunches of data directly in the optical domain and poses several challenges that are in common to OPS with variable length packets. OBS had years of great popularity between 2000 and 2010 but then faded in a way very similar to OPS. We believe it is basically affected by very similar problems and therefore we focus just on OPS.

In this manuscript we would like to rely on our experience as researchers

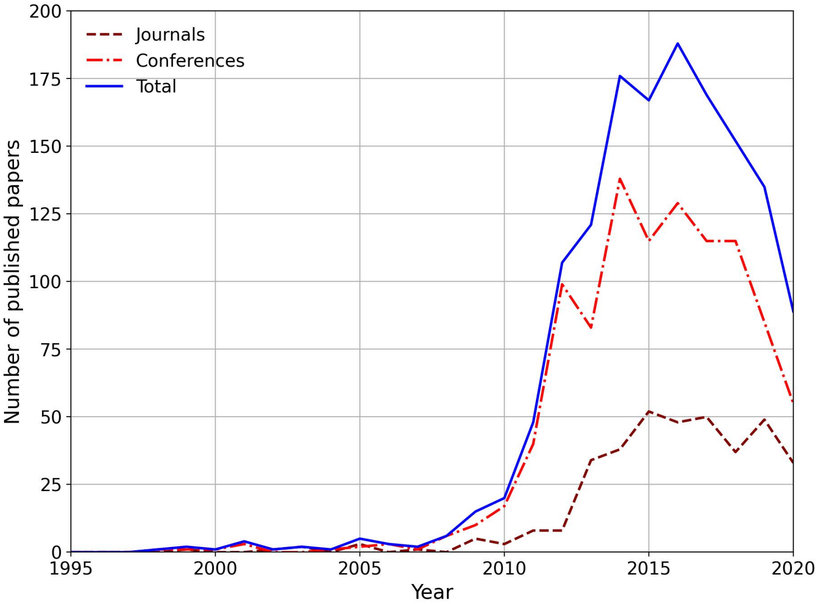
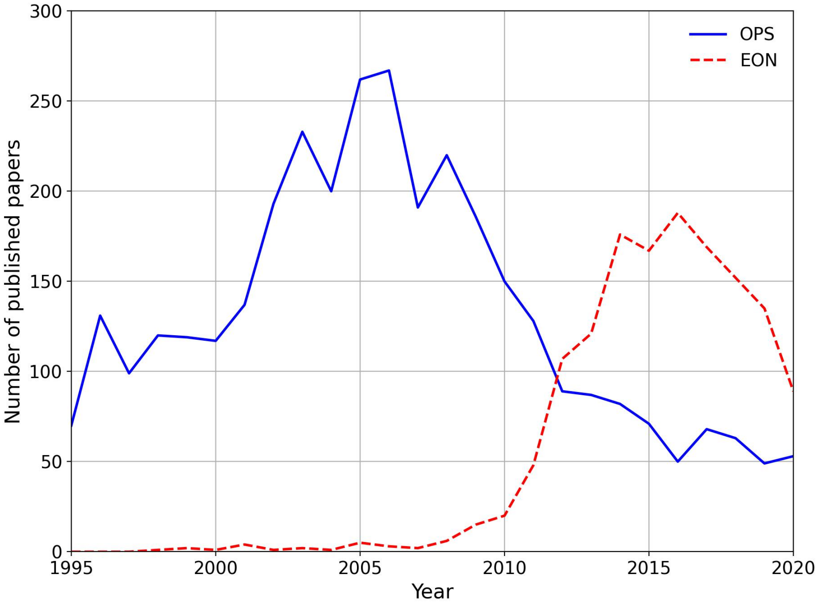


Figure 2: Yearly number of papers about OPS in the time window 1995–2020.



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that were directly involved in the rise of the OPS boom and then also dealt with EON, to discuss why in our opinion the decline OPS happened and is almost coincident with the rise EON. We start with two sections where we provide our view of the historical motivations as well as pros and cons behind both the OPS (Section 2) and the EON (Section 3) proposals. Then we will build on this in Section 4, providing our point of view on why EON in the end overcame OPS and what could be the future of these technologies.

2. Optical Packet Switching

In the early 90s the research in broadband networking was dominated by the idea that an ubiquitous broadband packet based technology should be developed to support the Broadband Integrated Services Digital Network (B-ISDN). The B-ISDN was supposed to be designed, managed and made available to the end users following the well established paradigms of the regulated telecom services, that had driven the expansion of the telephone network as well as the rise of the first public data network (such as the narrowband ISDN).

The approach to which all big telecom manufacturers and operators were referring to, was the Asynchronous Transfer Mode [1]. ATM assumed a packet based transfer mode, exploiting high speed switching of small fixed size packets (the ATM cell) with the aim to allow both Quality of Service control as well switching with minimization of queuing and congestion.

The first OPS studies started with reference to the B-ISDN and ATM paradigms, basically with the final goal to provide faster switching as well as faster line rate. This led to several years of studies that tried to demonstrate that optical switching could be a viable alternative to implement fast ATM switches. ATM assumed a shift of paradigm and the introduction of new network hardware and software and this could be a good motivation towards the development of new switching devices and nodes based on all optical technology. In Europe the Race ATMOS Project was the main big project starting in this direction, together with other projects and proposal [2], [3].

Nonetheless the first years of study made clear that an effective implementation of an optical packet switching system matching the requirements of the ATM technology was not an easy task. There was a basic mismatch: the short size of the ATM cell (53 bytes) would lead to very short packet duration as long as the line rate would increase, thus putting a huge stress on the switching speed of the nodes, if a reasonable system efficiency had to be achieved. Figures 3 and 4 provide a quantitative view of this issue. Assume that t_s is the time required to reconfigure the optical switching devices and

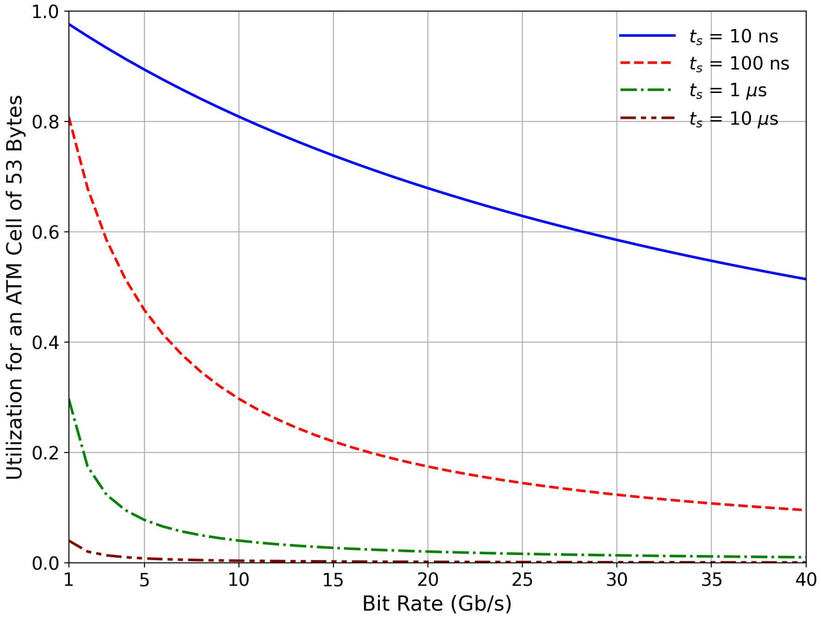

Figure 3: Efficiency of optical switching of packets as small as ATM cells. The utilization of the link is affected by the time that is needed to reconfigure the switching devices, requiring guard bands between packets that decrease the utilization of the links.

that t_p is the time duration of a packet, such that $t_p = \frac{D}{B}$, where D is the packet size (in bits) and B is the link bit rate (in bits/second). Indeed the maximum utilization of the links achievable would end up to be:

$$\rho = \frac{t_p}{t_s + t_p} \tag{1}$$

In Fig. 3 is plotted the utilization of an ATM cell varying both t_s and B in a range of values that can be considered reasonable for the optical technology [4]. It is quite clear that a reasonable utilization can be achieved if and only if devices able to switch in the sub-microsecond range are available. Moreover given the trend towards faster and faster line rates this limit is continuously challenged.

Another way to look at this problem is shown by Fig. 4. In this case we consider the problem of *storing* the packet while the required switching configuration is achieved. This storing can be implemented with a delay line, whose length will determine the amount of time the packet can be hold, waiting. The Figure shows that again the switching speed is crucial,

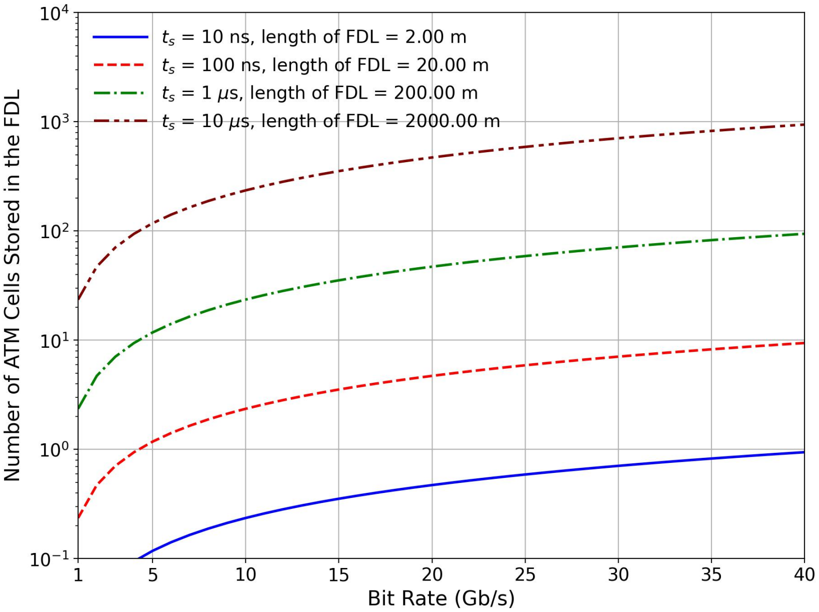

Figure 4: Waiting for switch reconfiguration the packets must be *stored* in delay lines that becomes very long if the ratio between the packet duration and the switching time is not favourable.

otherwise very long delay lines are needed, that will make the switches more bulky and will affect the overall transmission effectiveness.

This was in our view the first key problem. OPS started on a wrong basis, it aimed at providing fast ATM switching but the nature of the ATM transport format was inherently hostile to the application of optical switching because of the difficulties in implementing fast optical switching devices.

This became clear to the scientific community with the works developed during the second half of the 90s. For instance on the networking side the EU funded Keops project [5] [6], that was one of the most successful projects on the topic of the period, proposed a specific format for the optical packet, suitable to match the requirements of the switching technology and longer than a single ATM cell, thus becoming a sort of container grooming ATM cells belonging to the same network paths [7].

But while these studies were developed in the real world the Internet came to be the de-facto standard for packet networks. The economy of scale of the IP technology took pace and soon a large part of the public data networks were IP based. The B-ISDN proposal faded and optical switching had to find a way to become appealing to this new scenario. Fast switching of fixed length packets was not the key point any more, while the problem of switching variable length IP packets was the new goal. Unfortunately the TCP-IP paradigm goes along with buffering and congestion control, a major weakness of optical switching because of the lack of optical RAMs.

Additionally, in 1997 the Internet Engineering Task Force (IETF) started the process of standardization for the Multiprotocol Label Switching (MPLS) in order to manage the delivery of data packets within a network. MPLS brought the concept of tunnels to connect different sites of the network, a concept closer to that of virtual circuit switching, enabling the efforts in traffic engineering and allowing the network operator to configure personal virtual connections through a network. The built tunnels could be used to transport data packets between network nodes in a circuit like manner, avoiding the packet misordering and jitter that are common problems in IP networks. The base of the MPLS control protocols was then applied to construct a solution to operate in optical networks, providing easy managemant and traffic engineering tools for advanced service provisioning: the Generalized MPLS (GMPLS). The GMPLS placed itself as a competing core technology to OPS, since it was logically matching well with a circuit switching technology in the core, that could be used to support the logical tunnels.

Indeed OPS needed to prove that could be used to implement very high throughput IP routers and this required congestion resolution capabilities. A great number of studies were developed between 2000 and 2010 on congestion control in OPS. Delay line buffers were the only real solution that appeared viable and therefore were extensively investigated [11] [12] [13] [14]. Unfortunately they are a far from optimal solution, especially in case of variable length, asynchronous packets (like in IP).

Here let us refer to this case. Works like [20] showed that it is almost impossible to obtain the performance required but, most of all, that this performance are very dependent on the packet format and network set up. In particular the problem of voids inside the delay lines when packets could be asynchronous and of variable length led to a number of dimensioning issues that were well understood but also almost impossible to solve. In Fig. 5 is recalled this basic result. The packet loss rate in a delay line buffer is a function of the length of delay lines which determines the time delay they introduce. What happens, as shown in Fig. 5 is that performance gets worse when the ratio between the delay unit and the packet size decrease or increase, with a quite deep minimum in between. In Fig. 5 is shown a

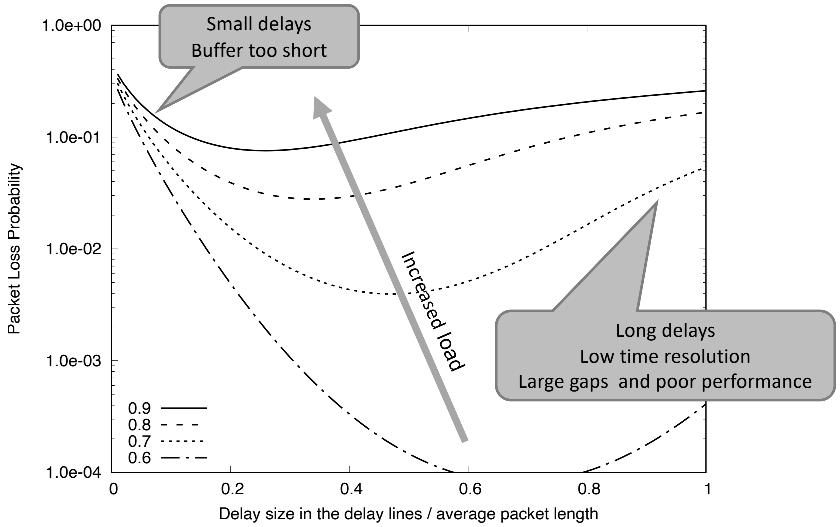

Figure 5: Example of a typical delay line buffer performance figure with variable length packets. The plot is for 64 delay lines per output, which are all multiple of a basic unit and therefore achieve delays from 1 to 64 units. The length of the time unit is reported on the X axis compared to the average packet length. The packet loss probability depends heavily on the average traffic load and on the average packet size.

specific numerical case taken from [20]. Indeed the message here is that an effective use of FDLs for buffering purposes is very difficult to achieve, since it depends both on the specific dimensioning of the delay lines but also on the network working conditions. The performance of FDLs depends on both average load, which is expected and may somewhat be controlled, but also on average packet length which is much harder to predict unless a fixed packet size is defined.

In the end of the day we can conclude that delay line buffering could be a solution for the implementation of short buffers, to solve short time congestion event, effective in a slotted packet switching system like ATM but proved to be too complex and quite inefficient otherwise.

The last wave of studies put the Wavelength domain into play. In a WDM scenario, with large numbers of wavelength per fiber, the in and output links in a switch were actually bunches of links; the many wavelengths on the same fiber. This put an additional degree of freedom into play that, in ideal conditions would indeed ease the issue of congestion control by means of queuing [16]. Contending packet could be simply transmitted on the same fiber but on different wavelengths at the same time. These solutions were originally introduced in the late 90s, for instance again in the Keops project and later by the David project [15].

Unfortunately also this solution had a major drawback. In order to fully exploit it, fast and flexible wavelength conversion was the key, but again the technology fell short. Fast and tunable wavelength converters are optical devices that are not easy to implement on a large scale. An analogy with the previous case is provided in Figure 6. Here we see a comparison between FDL placement and its performance, also including the number of wavelengths in the system. The traffic load was 0.8 per wavelength with an average packet size with 500 Bytes (1.6μs@2.5Gb/s) and the results are shown as function of the delay unit D of the N-delay FDL buffer in a link with W wavelengths [17]. The approached cases include Full Wavelength Conversion (FWC) and Limited Wavelength Conversion inside 2 fixed wavebands with a mix of W and N scenarios. As can be seen, the case with $N = 1$ leads to a packet loss probability that is independent of D. Furthermore, the same problems discussed for FDLs without wavelength conversion appear also with FWC or LWC. Specifically, these results show that the FWC scenario with $W = 16$ and $N = 2$ is exactly the same as the scenario LWC with $W = 32$, $N = 2$ and 2 wavebands. Also, we can see that under certain conditions the performance of FWC and LWC can be the same, managing the number N of delay units.

In an attempt to find another scenario where OPS can bring considerably better performance that other solutions, during the 2012-2016 period researchers focused their attention on Data Center Networks (DCNs) [40]. EU-funded projects like LIGHTNESS and COSIGN [41] focused on demonstrating that a combination of OPS and OCS can fulfill the specific requirements of the DCNs. On the one hand, OPS promised agile switching, high throughput, and low latency for short-live flows while OCS can easily transport the long-live, elephant flows. Nonetheless, the lack of the key OPS components and the emerging of other technologies that alleviate the latency requirements like fog and edge computing, prevented further investment in OPS.

In summary we can say that Optical Packet Switching is a very appealing technology but unfortunately the basic technological building blocks were never really available with a degree of integration and an economy of scale that even barely resembled those of electronics.

This is the key issue that became clear as an outcome of the last big project funded by the EU on the topic [18], [19]. The so called network of

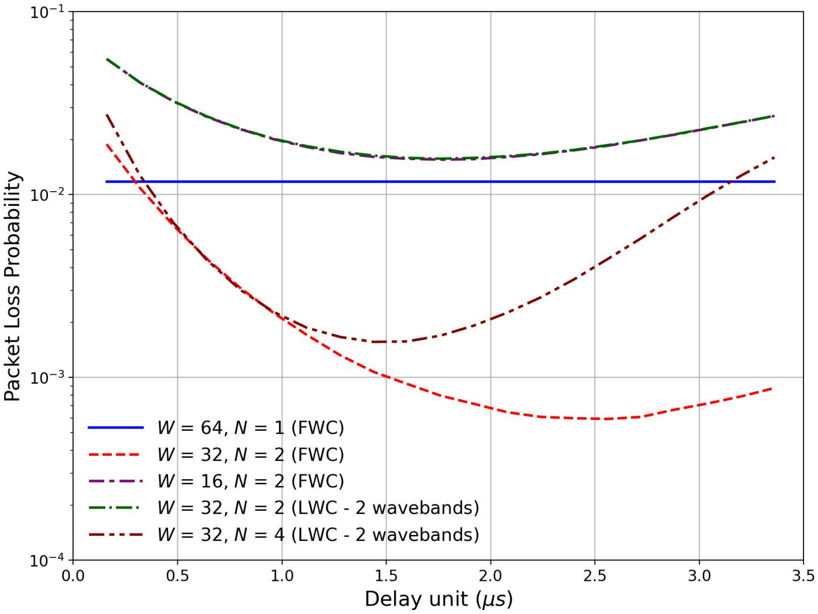

Figure 6: Example of a typical FDL buffer performance in a WDM scenario with Full Wavelength Conversion (FWC) and Limited Wavelength Conversion (LWC). The packets have an average length of 500 Bytes and the normalized load is 0.8.

Excellence that worked in three phases from 2004 to 2011, called e-Photon-One (Optical Networks: Towards Bandwidth Manageability and Cost Efficiency), e-Photon-One+ and BONE (Building the Future Optical Network in Europe) put a lot of effort in doing exactly what the title of the first project says: find a way to demonstrate advantages and cost efficiency of optical network in general and OPS in particular. It is worth noting that Prof. Neri was very active in these projects. He cordinated the proposal preparation and led ePhoton-ONe and ePhoton-One+ and was still very active in Bone, even though leaving the leadership to other colleagues.

One of the most notable examples of the effort of those years was the "US/EU Workshop on Key Issues and Grand Challenges in Optical Networking", held in Bussels in 2005, chaired by Prof. Fabio Neri and Prof. Biswanath Mukherjee, co-sponsored by the NSF, COST and the EU. This workshop gives the idea of the momentum of the initiative. By invitation 30 researchers, 15 from the US and 15 from the EU, joined and after a full day of discussion elaborated a vision document about perspectives of optical networking, both in terms of research as of applications. In this document OPS is identified as a technology for the third generation of optical networks, following the introduction of optical links and the deployment of WDM. The document also identified the key need for specific devices, emphasizing the importance of 3R optical regenerators as well as fast optical switches as an enabler for the transition from one technology to the other.

This is to say that the key problems were well understood, potential solutions envisaged and key issues outlined. OPS was a technology the scientific community had tackled very effectively. But it in spite of the many excellent scientific results it could become reality if and only if some basic components could be made available at a good degree of integration and at a reasonable cost. This was an effort that, both from the economic and engineering point of view could be put in place only by large telecom manufacturers. Unfortunately such a breakthrough never happened for a number of reasons that we will explore further in Section 4.

3. Elastic Optical Networks

The expectation for the first basic components for OPS at a viable cost, level of integration and usability was expected at the turn of 2010. When it appeared clear that this expectation was not going to be fulfilled it became evident that a possible deployment of OPS in the Internet was unlikely and researchers moved their interest towards other solutions, less appealing than OPS but that looked more feasible in the short/medium term. The Elastic Optical Network (EON) was the technology of choice. The interest in the EON started around 2008 and can be considered the definitive killer of OPS in the sense that its performance, flexibility and associated cost completely displaced OPS from the optical networking arena.

In 2008, Jinno et al. [23] presented their spectrum-sliced elastic optical path network (SLICE) architecture. SLICE offers *elastic* optical paths that can be expanded and/or contracted according to the traffic volume and user request. SLICE is therefore considered the first EON proposal. Besides, it consists of the (today well-known) building blocks of: bandwidth-variable transponders (BVT) at the network edge, bandwidth-variable wavelength-selective switch (BV-WSS) in the network core, and the optical orthogonal frequency division multiplexing (OFDM) as a highly spectral-efficient, bandwidth-variable modulation format.

Immediately, SLICE became the breakthrough technology that researchers were waiting for after the disillusion of OPS. The number of new contributions in this field soon began to grow, not only because SLICE offered an alternative and viable solution to OPS, but also because it could overcome other fundamental problems of wavelength-routed networks.

For example, a limitation of the wavelength-routed networks is associated with worst case design in terms of transmission performance. In order to address this problem, the concept of a novel adaptation scheme in SLICE, called distance-adaptive spectrum resource allocation [24] was presented in 2010, in which the minimum necessary spectral resource is adaptively allocated according to the end-to-end physical condition of an optical path. Modulation format and optical filter width are used as parameters to determine the necessary spectral resources to be allocated for an optical path.

In 2011, Tomkos and Klonidis [25] proposed DESPINA (Dynamic Elastic and Scalable Photonic Infrastructures and Network Architectures) as a step forward EON. DESPINA can collect a large number of channels with variable bit rate and format (i.e. bandwidth) characteristics and aggregate/disaggregate traffic to links or established paths according to the connectivity requests in the network. One of the key element becomes the Routing and Spectrum Allocation (RSA) algorithm, which, besides the path and the wavelength, is able to select the bandwidth, the modulation format and other tuneable parameters.

In 2012, the initially proposed SLICE architecture officially became the

EON concept [26]. In those four years, EON research had transitioned from theory to experimentation. For example, a field trial of EON based OFDM transmission was tested over 620 km distance with 10G/40G/100G/555G, and an EON network testbed with real-time automated adaptive control plane was also demonstrated [27]. In addition, standardization initiatives also started. For instance, ITD Study Group 15 introduced a flexible DWDM grid (usually referred as flexi-grid) into its Recommendation G.694.1[1], where the allowed frequency slots have a nominal central frequency (THz) defined by $193.1 + n \times 0.00625$ (n is a positive or negative integer including 0), and a slot width defined by $12.5 \times m$ GHz (m is a positive integer).

As early as 2013, EON was becoming a reality in the research community, but some concerns began to arise about its cost. In [28], authors compared different approaches to allocate/deallocate time-varying traffic in terms of cost/efficiency. In [29] authors compare the mixed-line-rate (MLR), bandwidth-variable (BV) and multi-flow (MF) models. Evaluation results show that the MF model needs about 50% fewer add/drop parts than the MLR and BV models and its ability to exploit resource sharing also leads to a reduction in network cost. One conclusion of this period of cost analysis is that operators would like to migrate their infrastructure to use BVTs if 50% savings are possible [30].

Thinking on making EON a viable and cost efficient solution for short term deployment addressing the requirements for flexibility, scalability, resilience, and adaptability, the Architecture on Demand nodes was proposed in [33]. This architecture supports component's modularity to achieve a practical approach and enable future services to easily be added to the network functionality.

In logical terms the analysis of EON network performance was addressed from many different points of view. Generally speaking EON networks proved to be a very effective approach, able to guarantee a good network flexibility and efficient utilization. For instance, in Figure 7 it is shown the utilization of a link operated in the C-Band (4400 GHz) with and without EON. The utilization of the EON handling services requiring 50 GHz (50%) and 100 GHz (50%) is very similar when the WDM cases with fixed bands of 50 GHz and 100 GHz are used. The problem to allocate channels limiting spectrum

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[1] ITU-T G.694.1 : Spectral grids for WDM applications: DWDM frequency grid, Oct. 2020, http://handle.itu.int/11.1002/1000/14498

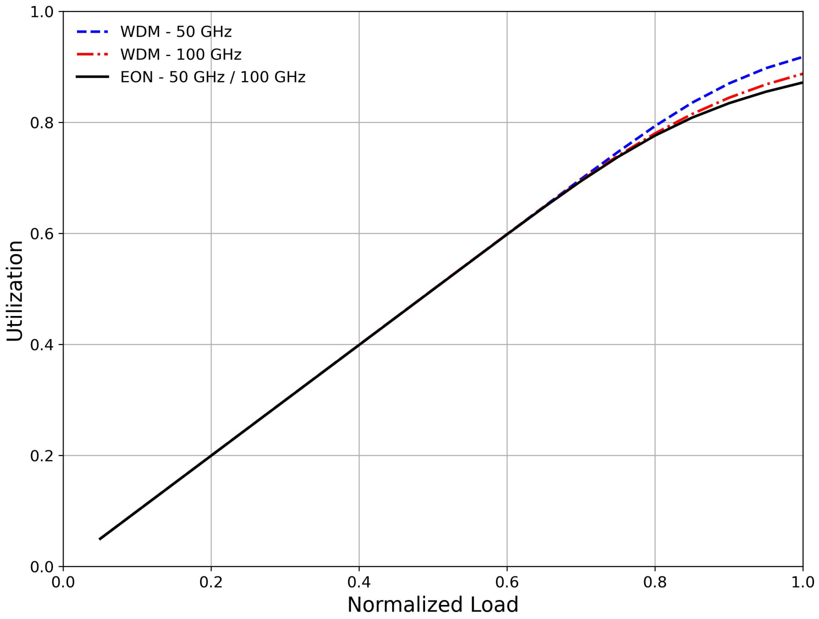

Figure 7: Utilization of an optical link operating in the C-Band with WDM of 50 GHz and 100 GHz channels and with EON supporting equally distributed services requiring bandwidths of 50 and 100 GHz. As function of normalized load, the maximum theoretical utilization is a line crossing the origin with angular coefficient of $\pi/4$.

fragmentation, providing fair performance as a function of the path length and bandwidth requested etc. were dealt with. For instance [34] bandwidth reservation techniques traditionally used in circuit switching networks were applied and in [35] the problem of a fair performance as a function of the path length was addressed. As a matter of fact an EON network promised to deal with mixed line rates, mixed required bandwidths and mixed modulation formats.

At the same time, another capacity limitation was broken with the development of multi-core fibers, that are promising and economically attractive candidates to realize Space Division Multiplexing (SDM) in optical core networks [32]. The selection of an end-to-end optical path added another dimension and became the Space, Modulation, Routing and Spectrum allocation problem.

Nonetheless, in 2014, the great expectation of EON began to calm down. A first study showed that migration to EON would not be attractive before 2019 [31]. Ultimately, the main goal of EON is to provide optimal bandwidth allocations, i.e. greater network capacity. Hence, it is important to know when this augmentation of capacity will represent a real solution for operators, in other words, when the network capacity will be a problem.

Results in [31] show that a network based on flexi-grid could extend the lifetime of the network five years with respect to the legacy DWDM. Results also predicted that current DWDM capacity will not be exhausted until 2019. We know now in 2021 that, in spite of the Covid-19 pandemic pressure, capacity exhaustion is still not a problem. The pure argument of capacity improvement is not a short-term driver to deploy flexi-grid solutions. Even though in the next few years the capacity in terms of spectrum is not yet an issue, and thus migrating to flexi-grid just because of the lack of spectrum makes it not urgent, a key driver to migrate to flexi-grid is the demand of high-speed channels and the availability of cost-effective 400 Gbps and 1 Tbps transponders.

Moreover practical implementation of EON remains some way off. One of the important challenges faced by the research community was to develop a new sliceable BVT, which supports sliceability, multiple bit rates, multiple modulation formats, and code rate adaptability. In 2016 [36] it was shown that with current modulation formats and for the current generation of transponders, a granularity of 50 GHz is sufficient to benefit from almost the full gain in spectral efficiency, which is achievable with 12.5 GHz granularity. This conclusion is of very high interest for practical network deployment using flexi-grid WSSs.

Since 2016, the main contributions in EON focused, on the one hand, in the design of new planning and operational algorithms to allocate, deallocate and defragment optical paths (with or without protection) [38] [39] and, on the other hand, in the development of the key components like the BV-T and the BV-WSS [37]. But, such devices have not arrived at the marketplace yet. It is not likely that they will arrive at the market anytime soon for at least two reasons: (i) the capacity of the current DWDM networks is not exhausted; (ii) the major equipment providers are investing on powerful photonic switches and intelligent routers to extend the capacity of current DWDM networks beyond 500 Gbps.

As a consequence, the interest of the research community in EON started to decrease as well. We can observe this in Figures 2 and 1, where, starting from 2016, the number of papers published referring to EON decreases. They were around 200 in 2016 and are now less than 100 in 2020.

In Figure 8, the key moments of EON over the recent years have been re-

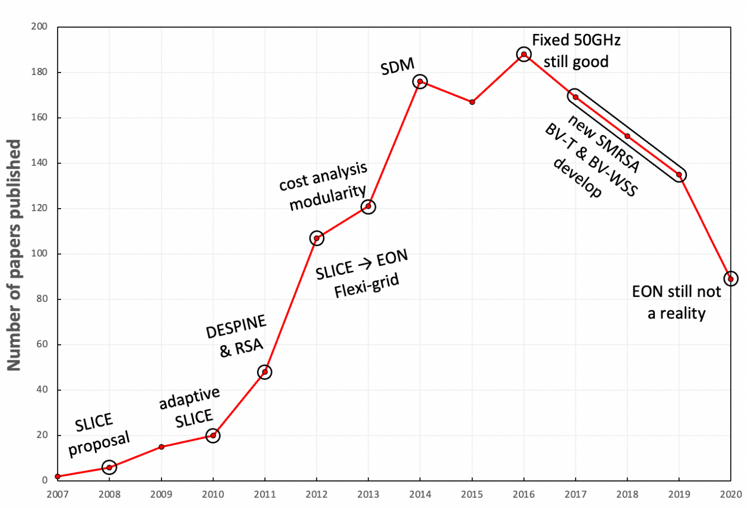

Figure 8: Development of EON vs number of paper published over the years.

lated with the number of published papers. We can see that SLICE triggered the beginning of the EON era in 2008, which then reached its pick in 2016. With the delay in the development of the EON components, the great excess of fibers still available in core infrastructure and the advent of 5G, most of the researches moved to other subjects.

From the above, it can be inferred that EON deployment possibilities are far away in the future.

4. Discussion

In the end of the day our view is that both OPS and EON are technologies that were conceived and studied with the same aim: empower optical networks with more flexibility and achieve a better utilization of the available resources. The problem is the usual problem of networking, find an optimal way to accommodate the traffic fluctuations. In IP/MPLS networks that are the de-facto standard today, this is done on a per packet basis.

OPS aims at the ambitious goal of achieving the same, by exploiting the time and the wavelength domain in a joint effort, in order to provide a very high switching granularity. EON on the other hand is an approach that accepts a more coarse granularity in the time domain, focusing on the wavelength domain. In general terms EON can be classified as a circuit switching technology, with circuits of custom capacity.

We have been actively involved in research on both topics, participating in some of the most relevant international efforts at lest at the European Union level. We have tried here to summarize our experience looking back at the works and at the expectations of the time. Unfortunately most of these expectations were not satisfied. We can say that OPS never came to the market as a successful technology and also the future of EON is not clear. In this manuscript we have outlined the main causes of this failure. For OPS this is indeed related to *technology availability*. As we have discussed OPS is not achievable without fast optical switching, tuneable wavelength converters and optical regenerators that are key to implement fast optical switching fabrics, optical buffers, optical routers etc. and these devices did not come to the market with the cost factor and flexibility of application that was required. Similar issues are related to the development of EOL even though it is not fully clear yet whether some market solution will appear in the near future.

We can say this happened because the technical problems we have outlined are too difficult to solve, or refer to technologies that are too expensive. Nonetheless the research community provided solutions to most of the problems but still without success. This may be related to the fact that other factors came into play and had a very significant impact in this specific field.

The former is an economic factor. Historically speaking two very important economic crisis hit the industry when these systems were supposed to move from the research lab to industrial production. The former was the ".com bubble" around year 2000, which was mainly a crisis that involved the stock market, but caused important cost cuts and restructuring. The latter was the big economic crisis of 2008 that, as we all know, had a very important global effect and indeed determined the strategies of the big telecom manufacturers.

The latter is a technical factor. Conventional optical core networks, improved a lot, more or less on the same period, thanks to the deployment of DWDM which was a sort of holy grail, given that with little investment it was possible to turn a single fiber into of large bunch of channels. This was simple to implement and capable to solve many capacity issues, that put the need of improved utilization and flexibility in the background.

OPS could still find application in small implementations for specific cases, but this would never create the economy of scale capable of pushing the investment needed to finalize the engineering of the required building blocks. As a consequence the appeal for the OPS/OBS vanished.

EON had the advantage that the deployed infrastructure was adapted to handle wavelengths and the technology was mature for generating subcarriers in an efficient way. The advent of WSSs can make the EON a cost effective solution to achieve some efficiency in the bandwidth utilization, preserving the circuit switching paradigm. Nonetheless, the market is moving very slowly towards EON. As far as we know, there is no BVT or BT-WSS devices available in the market and we were unable to find any estimation about their realization.

Finally the advent of the smartphones and of other smart terminal to support end user services like smart TVs, Internet of Things, and so on, emphasized the need to invest on empowering the access, that was still relying on the old PSTN copper infrastructure in most of the world. Significant public investment are being made to deploy G-PON to achieve Fiber to The Home (FTTH) in most of the developed countries and this relieve the push on the development of new optical networking technologies. This is in parallel with the advent of 5G, with the net result that most of the investment is currently in the access. On the contrary, there is still a great excess of fibre installed in the cities (i.e., dark fibers) that operators can turn into operational when needed.

In the end of the day, it looks like the current optical infrastructure is still good enough as well as the upgrade to EON is more expensive than what we though. At the same time the focus of public and private economic investment is in the access infrastructure, especially wireless. Therefore we can conclude that EON is more appealing and viable than OPS and it could eventually hit the market, nonetheless the future for both of them is unclear.

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