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Optical fiber transport systems and networks: fundamentals and prospects

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Abstract

This article presents first the history of the optical fiber transport networks, from the introduction of the first high capacity systems in the 1990s to the 10 Gbit/s per channel WDM (Wavelength Division Multiplexing) systems deployed today, and the tremendous evolution of performance within this period. The effects of propagation in optical fibers and their consequences for optical system engineering, the architecture of today's optical transport networks, the choices made in France are recalled. We then have a look at the future of optical transport networks from an operator's point of view: the expected evolutions in terms of transmission system capacity and network architecture are presented. We conclude that capacity, transparency, and agility are the main drivers of the evolution of optical fiber transport systems and networks and that a lot of changes have yet to be expected in these domains during the next decade. ***To cite this article: M. Joindot, S. Gosselin, C. R. Physique 9 (2008).***

Résumé

Systèmes et réseaux de transport à fibre optique : Etat des lieux et perspectives. Cet article présente d'abord l'histoire des réseaux de transport à fibre optique, depuis l'introduction des premiers systèmes à grande capacité dans les années 1990, jusqu'aux systèmes actuels utilisant le multiplexage en longueur d'onde (WDM) à 10 Gbit/s par canal, et l'évolution fantastique des performances durant cette période. Les effets liés à la propagation dans les fibres et leurs conséquences sur l'ingénierie des systèmes optiques, l'architecture des réseaux de transport optiques actuels, les choix faits en France sont rappelés. Nous examinons ensuite l'avenir des réseaux de transport optiques du point de vue de l'opérateur : les évolutions attendues en termes de capacité des systèmes de transmission et d'architecture de réseaux sont présentées. Nous concluons que capacité, transparence et agilité sont les principaux moteurs de l'évolution des systèmes et réseaux de transport à fibre optique et que beaucoup de changements sont encore attendus dans ces domaines durant la prochaine décennie. ***Pour citer cet article : M. Joindot, S. Gosselin, C. R. Physique 9 (2008).***

Keywords: Optical fiber; Transport networks; Submarine cables; Wavelength Division Multiplexing

Mots-clés : Fibre optique ; Réseaux de transport ; Câbles sous-marins ; Multiplexage en longueur d'onde

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1. Introduction

Much research effort has been devoted to optical transmission for more than forty years. A long time was needed to achieve optical fibers with losses compatible with their use in telecommunication systems. All the bricks used in a system, modulators, receivers, amplifiers, ... were topics about which many research teams worked very actively worldwide. Research about optical telecommunications remained basic research work, without any practical application, but the first systems entered the networks at the beginning of the 1980s. A new era was opened in the history of telecommunications.

This article describes the main milestones of the history of the optical fiber transport networks, analyzes engineering issues and architecture of today's transport networks, and gives a prospective view of the evolutions to be expected in the next decade. In Section 2, we explain how optical fibre became the unique transmission medium in transport networks. We describe the first optical transmission systems, analyze the revolution brought by wavelength division multiplexing, and the key issues related to the optical fiber itself. Section 3 describes today's transport systems and networks. We analyze the effects of propagation in optical fibers, their consequences on optical system engineering at 10 Gbit/s per channel, and describe the typical architecture of today's optical transport networks. In Section 4, we present an operator's point of view on the evolution of optical transport networks in the next decade. We explain in particular why capacity, transparency, and agility are the main drivers of these evolutions.

2. The advent of optical fibre as the unique transmission medium in transport networks

2.1. First optical transmission systems

The first operational optical systems introduced in the telecommunication network in 1982 had a bitrate of 34 Mbit/s and used a wavelength of 850 nm, which rapidly moved to 1300 nm. Nevertheless, their capacity remained too small to compete with the systems used in the core of the network, also called backbone or transport network. In the middle of the 1980s, this backbone network relied on two types of transmission systems, the coaxial cable systems on one hand, the radio relay systems on the other hand [1,2]. The maximum capacity per coaxial cable was usually 140 Mbit/s, but some 560 Mbit/s systems were put into service around 1985. As far as radio is concerned, the digital radio relay network was developed between 1975 and 1985: the systems used, working in the 6 or 11 GHz bands, transported usually 8 × 140 Mbit/s channels (7 active and 1 emergency channel), i.e. around 1 Gbit/s per link. The strong idea of network planners was to build a network based on both cables and radio, which were quite complementary: cables offered stable transmission conditions, compared to radio which is affected by propagation impairments. However, cables were subject to failures, in the case of civil engineering works for instance, while radio is clearly protected against that. The objective was to equally share the traffic between both networks.

All these systems were purely digital, which means that the signal was detected in each regeneration site, and the signal sent on the following span was completely "clean", the memory of the previous spans being in the possible detection errors. The regeneration spacing was respectively 4 km, 1.8 km, and roughly 50 km for the 140 Mbit/s and 560 Mbit/s coaxial systems and the radio relay systems[1] at 1 Gbit/s.

In the backbone network, the first optical systems were introduced in 1988. They used an optical carrier at a wavelength of 1300 nm and carried a bitrate of 140 Mbit/s and 560 Mbit/s per fiber. The regeneration spacing was respectively 52 and 42 km, which was dramatically larger than the corresponding values for the abovementioned existing coaxial cables at the same bitrate. Comparing these values shows immediately why optical systems provided an enormous advantage over the existing cable transmission systems at that time, in terms of implementation and maintenance cost as well as network monitoring. Nevertheless, the optical fiber did not provide any capacity increase, and did not compete with radio relay systems in terms of regeneration spacing. The idea remained then to build a backbone network based on optical fiber (instead of coaxial cable) and radio systems. The progress in optical technology allowed rapidly increasing the regeneration span to 90 km, by moving the wavelength from 1300 to 1550 nm, where the attenuation of the fiber is minimal.

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[1] The radio links used in the backbone networks were designed to accept a regeneration span of roughly 50 km. As today in the case of optical systems, the infrastructure had to be able to support different generations of systems.

During this period also, the so called Synchronous Digital Hierarchy (SDH) replaced the plesiochronous hierarchy which had been in use up to now in digital transmission: the 140 Mbit/s multiplex was replaced by the 155 Mbit/s Synchronous Transport Module (STM-1) which became the elementary block of the new hierarchy. In the beginning of the 1990s, optical systems with a capacity of 2.5 Gbit/s (STM-16 resulting from the electrical time division multiplexing of 16 STM-1) were available and the decision was taken to implement in France a new backbone network called RLD (Réseau Longue Distance) only based on optical systems offering this capacity, with one wavelength per fiber and optoelectronic regeneration roughly every 100 km. With the advent of this new family, the optical technology overcame definitely all the previously existing technologies, included the radio relay systems, which could not compete in terms of capacity, as well as cost and transmission quality.

In 1994, 11 000 km of optical cables were already in place in France, and the total length reached 20 500 km in 1997, when the network could be considered as completed. They were equipped with 2.5 Gbit/s transmission systems, and interconnected through electronic switches (DXC: Digital Cross Connects) allowing to recover the electrical data and switch data from one system to another one, providing then the reconfiguration and protection of the network.

As far as the intercontinental links are concerned, the optical technology also overcame the existing ones. The first optical cable TAT (TransATlantic cable) 8 was laid in 1988 between Europe and North America, offering a capacity of 280 Mbit/s per fiber pair, using optoelectronic repeaters spaced by roughly 40 km. Three years later, it was increased up to 120 km in the TAT9 cable, having a capacity of 560 Mbit/s per fiber pair [3]. As in terrestrial networks, the undersea coaxial cables could not compete in terms of capacity as well as repeater spacing. The intercontinental satellite systems, providing some tenths of thousands of telephone circuits, could keep a part of the market, but lost also their position with the following technical evolutions of optical transmission systems, which will be described later.

Compared to the other existing media, the optical fiber could be considered, when it appeared, as a perfect non-selective and time invariant transmission medium, just characterized by its attenuation: compared to radio and coaxial channels, that was clearly an enormous advantage. Although the optical fiber is intrinsically a dispersive medium, it appeared non-selective because the bitrates and transmission distances were too small to allow a significant signal distortion during propagation. The choice of the fiber was in these conditions not critical, the only parameter to be taken into account being the losses. Nevertheless, a small chromatic dispersion at the working wavelength is better in terms of signal distortion, if the bit rate has to be increased. The so called G.652 or standard single-mode fiber (SSMF) had precisely been designed to exhibit a zero chromatic dispersion at the wavelength of 1300 nm, used by the first systems; this fiber was used in the cables of the French backbone network deployed in the nineties. However, as the optical systems used the 1550 nm wavelength, the dispersion at the working wavelength became 17 ps/(nm.km): even if the 2.5 Gbit/s signals were not affected when propagating over 100 km, this situation would not remain for higher bitrates, and compensation would be required. A new fiber called G.653 or Dispersion Shifted Fiber (DSF), with a zero dispersion wavelength at 1550 nm, was proposed. This a priori attractive medium was chosen by some operators. Unfortunately, if a very small dispersion is quite favourable for single channel, it is a very significant drawback in the case of wavelength division multiplexing.

2.2. Optical amplification and Wavelength Division Multiplexing: a dramatic booster for optical fiber technologies and bit rate increase

At the end of the 1980s, the development of erbium-doped fiber amplifiers (EDFA) [4–6] led to a dramatic breakthrough in design and engineering of optical transmission lines. Doped fiber amplifiers are based on the transfer of optical power between an optical pump and the optical signal inside a doped fiber. EDFAs are particularly suited to optical fiber transmission, since erbium spectral gain profile matches the low attenuation band of single mode fiber (the so-called C band, ranging from 1530 to 1565 nm). Without any optical-to-electrical-to-optical (OEO) conversion, EDFAs allow one to compensate for optical signal power attenuation due to propagation along the line fiber. Typical engineering of terrestrial lines consists of line fiber spans of about 80 to 120 km, the loss of each span (around 20 to 30 dB) being compensated for by an EDFA. Note that the fiber spans of submarine lines are shorter (about 40 km) so as to limit noise accumulation and to allow much longer optical reach [3]. EDFAs are characterized by a simple design, and noise performances which are close to the theoretical limit: they were thus initially used as optical reach extenders and replaced advantageously OEO repeaters of single-wavelength transmission systems. For example, optical fibre amplifiers were introduced in the mid-1990s in submarine cable systems, both on transatlantic cables (TAT

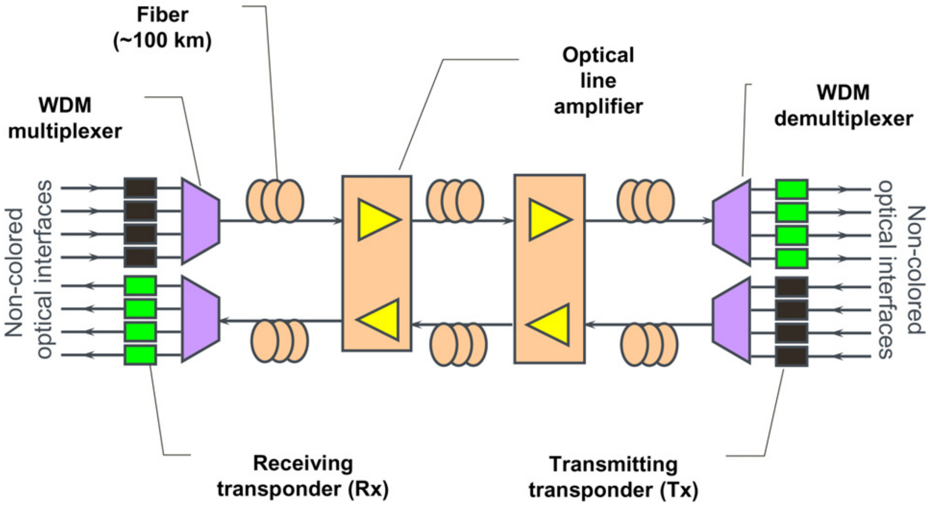

Fig. 1. Architecture of a WDM transmission system (one fiber for each direction). Each EDFA replaces advantageously N OEO repeaters, N being the number of WDM channels per fiber. For simplification, the system has been represented with $N = 4$ WDM channels per fiber and 3 fiber spans.

12/13) and TransPacific Cables (TPC 5): these systems had a total capacity of 5 Gbit/s per fibre, and used a single wavelength channel per fiber [3].

But the key advantage of EDFAs came from its association with Wavelength Division Multiplexing (WDM), which consists in transmitting different optical carriers at different wavelengths in the same fiber. Of course, the idea of using optical frequency domain to multiplex several channels in a given fiber was not new, because it allowed sharing of the optical fiber transmission medium. The key point of combining WDM with EDFAs is that a single component (the EDFA) allowed one to simultaneously and independently amplify all WDM channels (see Fig. 1). This brings to EDFAs a dramatic cost advantage compared to OEO repeater solutions which require, in each repeater site, as many repeaters as the number of channels. Another key feature of amplified WDM systems is their "pay as you grow" capability: once fiber and amplifiers are installed, transmitting and receiving terminal equipment can be provided as required, on a per-channel basis, which thus allows simple capacity upgrades and smooth capital expenditures for operators. The cost advantage of amplifiers increases with the number of WDM channels and the number of repeater sites, which explains the dramatic success of WDM amplified systems in long distance terrestrial and submarine networks (optical reaches between few hundred km up to several thousand km). EDFAs are also transparent to optical signal formats (frame format, modulation format and bit rate), which is interesting when considering transmission system upgrades, both in terrestrial and submarine contexts. In a sense, the EDFA was the key technological enabler of wavelength division multiplexing.

As described in Fig. 1, OEO conversions are only performed at the transmitting (Tx) and receiving (Rx) ends of the WDM transmission systems. Indeed, the advent of amplified WDM transmission was nothing else than coming back to analogue transmission techniques. This gives to these OEO converters (called transponders) specific and important functionalities in network operation, because transponders are the only points of the system where signal can be processed digitally. The functionalities of transponders are the following:

- 3R regeneration of the signal. The 3 Rs stand for re-amplification, re-shaping, and re-synchronization. 3R regeneration is performed in the electrical domain, and is associated with a decision process on all received bits of information;
- Wavelength conversion: the transponder is the interface between the client of the system and the WDM network. In particular, the client signal (usually provided on a standardized short reach optical link at 1310 or 1550 nm, also called "non-colored" or "black & white" optical interface) is not directly compatible with the wavelength grid of WDM channels. OEO transponders allow simple wavelength adaptation through re-transmitting of the optical signal at the appropriate wavelength;

- Modulation format adaptation: as for the wavelength, the optical signal has to be formatted so as to allow the required level of performance of the WDM link. 2.5 Gbit/s transponders used On-Off Keying Non-Return to Zero format, but higher bit rates require more and more sophisticated modulation formats;
- Forward Error Correction (FEC) [7,8]: channel coding allows to identify and to correct bit errors thanks to redundancy in the transmitted signal. FEC was not used in 2.5 Gbit/s transponders, but is a key of 10 Gbit/s and higher bit rate transponders. FEC allows not only relaxing the constraints on the bit error rate, but it also provides a quality estimator, by counting the number of corrected symbols within a code word. The most encountered code is now Reed Solomon (255,239), which is widely used in a lot of applications. More powerful error correcting codes have been demonstrated and will be included in next generations of systems;
- Digital frame format adaptation: since the optical signal to be transmitted may be in various frame formats (e.g. Synchronous Digital Hierarchy, Gigabit or 10 Gigabit Ethernet), digital processing of the signal in transponders has to include appropriate frame format conversions, which include adding/removing of the FEC overhead;
- Network supervision and management: overhead bits in the frame format allow network supervision and management operations which are needed to ensure the required performance and availability of the WDM channels.

Amplified WDM became quickly a very successful technology for transport networks. The first terrestrial systems, installed in the mid-1990s, consisted of only 4 WDM channels of 2.5 Gbit/s each, but the number of WDM channels then began to increase dramatically. At 2.5 Gbit/s per channel, the optical signal could be transmitted along several hundred km without significant impairments (except noise accumulation due to optical amplification). Compared to radio technologies, optical fiber was thus considered as the "ideal pipe". A few years after the first WDM systems were installed, 16 to 32×2.5 Gbit/s systems were available, with a spectral channel spacing of 0.8 nm (100 GHz) in the C band. Spectral efficiency increased even further with 50 GHz spaced 64×2.5 Gbit/s WDM systems. To further increase the overall capacity per fiber, one solution could have been to further decrease channel spacing to e.g. 25 GHz, thus increasing the total number of 2.5 Gbit/s channels in the C band (1530–1565 nm). Although this solution could be implemented practically, the critical issue was then to control very accurately the wavelength stability of laser sources as well as wavelength characteristics of WDM multiplexers/demultiplexers. Technical challenges included also channel intermodulation due to Kerr effect in the line fiber [4]. Another issue was related to the network management complexity of transmission systems having a very high number of WDM channels. The increase of the bit rate per WDM channel thus became very soon the key to further increases of WDM system capacities: the first $N \times 10$ Gbit/s WDM systems were installed in North America and Europe at the end of the 1990s.

The evolution of WDM system capacities is illustrated in Fig. 2 in the case of terrestrial line engineering. Fig. 2(a) positions each available system or R&D experiment in logarithmic scale in terms of number of WDM channels per fiber versus bit rate per channel. As explained above, available systems moved quickly from 2.5 to 10 Gbit/s per channel at the end of the 1990s, whereas the number of channels increased significantly, up to 240 channels at 10 Gbit/s per channel at the end of Internet Bubble [9]. Industrial offers are now moving to 40 Gbit/s per channel, with a lower number of channels (about 80 channels). R&D experiments now concentrate on very high bit rate per channel [10,11], with the objective to develop 100 Gbit/s systems to transport future 100 Gigabit/s Ethernet client signals. Note that typical systems which are now available have more than 1 Tbit/s overall capacity per fiber, as illustrated by the diagonal of Fig. 2(a). The evolution of overall capacities per fiber in function of time is illustrated in Fig. 2(b) for terrestrial systems: one clearly sees the dramatic slope increase related to WDM introduction around 1995. Since the end of the Internet Bubble, capacity has been increasing at a much slower rate, illustrating also the new technological challenges related to channel bit rates of 100 Gbit/s and higher.

Let us just mention another proposed solution to increase the capacity per fiber: it consists in using not only the C band, but also other spectral bands, the L band (1565–1625 nm) and even the S band (1460–1530 nm). Many experiments have been made in the laboratories using C and L bands simultaneously to achieve capacity records [10]. Nevertheless, the fact that C and L band must be amplified separately, because there is no discrete fiber amplifier working in both bands,[2] impacts negatively on the cost budget. Only the fiber is shared between the channels, and not the amplification module, and we have practically two systems in parallel. Moreover, the link budget is degraded both by losses in couplers needed to separate and merge C and L band channels at the input and output of the amplification

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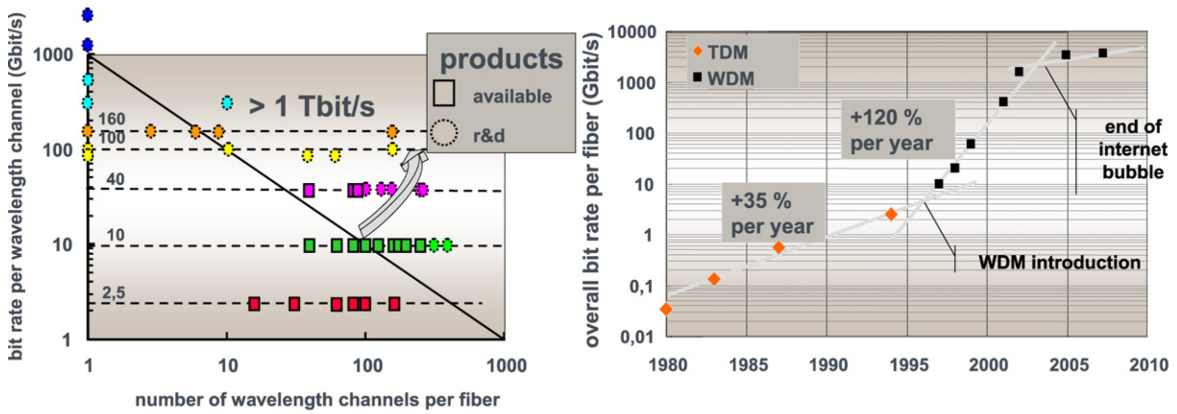
[2] In fact, Raman amplification techniques allow simultaneous amplification of several bands [12], but raise other significant operational challenges related to the use of high power optical pumps into the line fiber itself.



(a) (b)

Fig. 2. Evolution of WDM system capacities, (a) number of WDM channels per fiber versus bit rate per channel for available terrestrial systems and R&D experiments, (b) evolution of overall fiber capacity in function of time for available terrestrial systems.

site, and by the higher loss of the fiber in L band. This is why many operators prefer to have densely located channels within the C band only.

2.3. *What about the fiber?*

A basic constraint in the terrestrial backbone networks is the compatibility of different generations of systems with the existing infrastructure. Indeed, building a cable network is very expensive, and the operator wants to change only equipment and keep the cables: as an example, the cables of the historical operators, which the WDM systems are deployed over today, have been laid in the 1990s, for the single channel regenerated systems installed at that time, before the WDM era. Moreover, not only the cables themselves are imposed, but also the location of the amplification sites. Installing new sites in order to improve performance is absolutely excluded. When moving for instance from 2.5 Gbit/s to 10 Gbit/s per channel, for a given modulation format, the required optical signal to noise ratio (OSNR), defined as the ratio of the signal power to the noise power in a reference bandwidth, must be increased by 6 dB [13]. It would be theoretically possible to achieve that by inserting new amplification sites in between the already existing ones, as it will be explained in Section 3.2: but this solution cannot be practically implemented, because the insertion of new sites requires changes in power supply, network monitoring... and increases operational costs. For these reasons, the infrastructure remains unchanged, and the systems must be able to work correctly on it. In the aforementioned example, the 6 dB OSNR difference between 2.5 and 10 Gbit/s was provided by error correction (FEC), introduced in the first 10 Gbit/s systems and now present in all WDM systems. The same constraint exists when moving from 10 to 40 Gbit/s: techniques as error correction, Raman amplification, efficient compensation of impairments through signal processing ... can provide the missing dBs in order to match the existing cables to higher bitrates.

Beyond this very important condition, the fiber type itself must be discussed [14]. It has already been explained in Section 2.1 how the so called SSMF has been chosen; let us just recall that its high dispersion value, which is detrimental in single channel transmission, provides a protection against inter channel effects in WDM transmission. Dispersion can be compensated for easily, but dispersion compensation impacts the cost of optical links very significantly. This is the reason why the fiber suppliers tried, in the nineties, to develop the “fiber matched to WDM” [14]. The idea was to reduce the dispersion value in order to decrease the cost of compensation (or even suppress it totally at 10 Gbit/s) while keeping a high enough value to ensure a good protection against non-linear cross effects. In other terms, the objective was the best trade-off between dispersion and non-linear effects. Different fibers of this family, called NZDSF (Non Zero Dispersion Shifted Fibers), were developed along the years by different manufacturers: starting from 2.5 ps/(nm.km), the dispersion increased, which proved that the searched trade-off had not been found. Different fibers called True Wave©, Leaf©, True Wave RS©were developed by different fiber manufacturers. The Teralight© fiber, having the highest dispersion (8 ps/(nm.km)) within the NZDSF family, appears certainly as a good fiber for 10 Gbit/s systems. But SSMF, which has been designed when WDM did not yet exist, appears well suited to this transmission technique. This has been clearly demonstrated by the performance of actual systems operated in transport networks, and it can be noted that all the equipment vendors announce significantly longer transmission distances when their systems are installed over standard single mode fiber than when they use NZDSF fibers. More information can be found in the data sheets.

Some operators deployed massively dispersion shifted fiber (DSF), before the WDM era, in order to avoid dispersion in single channel transmission. They have now to cope with the constraint on non-linear effects, especially Four-Wave Mixing: solutions like unequal channel spacing or use of L band can be a solution in this case [15].

The problem is quite different in undersea systems. Here the systems and the cable are designed together, which gives many more degrees of freedom than in terrestrial networks. In particular, the repeater spacing can be chosen, amplifiers are equally spaced, and line fiber is not SSMF, but usually a low negative dispersion fiber (typical dispersion -2 ps/(nm.km)) compensated for by standard single mode fiber[3] [3]. If the compatibility constraint does not exist as in terrestrial systems, it must be nevertheless noted that upgrading existing systems is quite usual today: the objective of an upgrade is to increase the capacity of an existing systems by adding new channels, increasing the channel bit rate, or using new modulation formats which allow better receiver sensitivity. The vendor and the operators in charge of this upgrade are then facing, in some sense, the same compatibility constraints as in terrestrial systems.

3. Optical transport systems and networks today

3.1. First limitations of optical fibers

As explained in Section 2.1, the optical fiber was considered at the beginning as a quite ideal non selective and time invariant transmission medium, while the coaxial cable was very selective[4] and the radio channel was subject to multipath fading impacting the transmission quality. This is in fact quite false, and this optimistic view was due to the fact that the optical fibers were used at "low" bitrates, over short enough distances and with low enough powers making the propagation impairments quite negligible.

The first characteristic of the fiber is its chromatic dispersion, i.e. the derivative of the group delay versus wavelength: as it is proportional to the length, it is usually specified through the chromatic dispersion parameter D, expressed in ps/(nm.km). For the widely used Standard Single Mode Fiber (SSMF or G.652 fiber), D is roughly 17 ps/(nm.km) at 1550 nm and 0 around 1300 nm: it can be considered in first approach as constant over the spectral bandwidth of a WDM multiplex (less than 30 nm), but a more precise analysis needs to take into account the dispersion slope, which is the derivative of D versus wavelength (0.058 $\mathrm{ps}^2/(\mathrm{nm\,km})$). The dispersion broadens the envelope of the optical signals, and results into overlapping of the electrical impulses after detection, and then bit error rate degradation.

Typically, at 10 Gbit/s, the maximum transmission distance is around 80 km when using SSMF, while it exceeds 1000 km at 2.5 Gbit/s. This is why the 2.5 Gbit/s systems with 100 km regeneration span are quite insensitive to the dispersion of the SSMF. However, in the case of (amplified) 10 Gbit/s WDM systems, it becomes evident that dispersion must be compensated for. This compensation is usually performed by the so called dispersion compensating fibers (DCF) inserted along the transmission line, exhibiting a dispersion of opposite sign of that of the line fiber. In order to reduce the impact of the DCF losses on the link budget, the compensating fiber is located between the two stages of the line amplifiers, in the amplification sites [14]. Because the dispersion does depend on the wavelength, a perfect compensation occurs usually only at a given wavelength. A relation between the dispersion and the dispersion slopes of the line fiber and the dispersion compensation fiber allows a perfect compensation for all wavelengths [1]. DCF has a very important weight in terms of cost: research has been conducted in order to reduce it, but the insertion of DCF spools remains the universally used method in the existing networks today because no alternative solution could be practically used in the field. For the operator and system designer, the chromatic dispersion offers the advantage of being well known: it is time invariant and does not deviate very much from the specified values. The main conclusion

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[3] This is not the only solution. Dispersion managed fibers, consisting in the concatenation of pieces of fiber having opposite sign chromatic dispersion, is another approach.

[4] The notion of selectivity is relative and depends on the bandwidth of the transmitted signals. In the case of coaxial cables, we mean that digital signals at some tenths of Mbit/s are completely distorted after typically a few kilometers, while they can support transmission over some hundreds of kilometres of standard single mode fiber.

is that dispersion can be compensated for without any difficulty, which is not the case for other impairments to be mentioned in the following.

Non-linear effects are the second impairment. They are mainly due to Kerr effect, i.e. to the dependence of the refraction index versus the field intensity. The transmitted power (typically 0 to 3 dB m at the amplification span input in a WDM system) appears as relatively low, but it is spread over a very small area (80 μm^2 mode effective area in a SSMF), which results into a very high power density, which is the relevant parameter for non-linear effects. Non-linear effects can be divided into single channel effects, like Self Phase Modulation (SPM), and cross channel effects like Cross Phase Modulation (XPM) or Four Wave Mixing: in the first case, a signal is affected by the index modulation created by its own power, in the second one, it is affected by the presence of the other channels. Non-linear effects could be completely neglected in the case of regenerated systems, because the power was too low. But, with the advent of optical amplification and WDM systems, the power had to be increased in order to provide a high enough OSNR and the distortions generated on the different spans are cumulative. This is a come back to analogue transmission, which was used in long distance telephone lines over cables before the digital techniques occurred.

An important issue is the coupling between linear and non-linear effects during the propagation: while in radio systems, the propagation medium is generally linear and non-linearity occurs only at the emitter (power amplifiers), the non-linear effects are distributed in an optical fiber, so that the chromatic dispersion and non-linear effects act simultaneously in each elementary section. This is the basis of the so- called Split Step Fourier method classically used to analyze the propagation in the fiber [16]. The coupling between linear and non-linear effects has a particular consequence: a high value of chromatic dispersion, which is detrimental in single channel transmission, offers on the contrary an efficient protection against inter channel effects, especially Four Wave Mixing, because channels in interaction travel at different velocities. On the contrary, the channels of a multiplex near the zero dispersion value are very much impacted by FWM and suffer a high penalty. This is the reason why the SSMF offers a significant advantage over DSF in WDM systems using the C band.

The third impairment, which is very important from an operator's point of view, is polarization mode dispersion (PMD). A lot of works and publications, theoretical as well as experimental, have been devoted to this issue for many years, only some of them are mentioned in the references [17–21], and we will just recall the impact on systems. In a perfect isotropic cylindrical waveguide, all the propagation modes are degenerated, which means that they do not depend on the polarization of the field. But, if any deviation from a perfect cylindrical shape occurs, due to the manufacturing process or a mechanical stress, this degeneracy does not exist anymore: the propagation constant, in other terms the group delay experienced by a signal depends on its polarization. This is what happens in polarization maintaining fiber (PMF): an impulse launched into the fiber onto any polarization state can be expanded over the principal modes, these impulses travel at different velocities, and then are received at the output separated by a delay which is proportional to the length of the fiber.

In an actual fiber, there are not two principal modes, but two orthogonal (assuming no polarization dependent losses) principal states of polarization can be defined within a domain around a given frequency, over which the received field can be expanded. The main difference with PMF is that the delay between the two delayed replicas of the signal, called differential group delay (DGD), is random. It follows a Maxwellian distribution the mean value of which, called PMD, is the relevant parameter. Assuming a perfect and strong mode coupling, i.e. a strong energy exchange between the modes along the propagation, it can be shown that this delay grows as the square root of the fiber length, instead of the length in the PMF case. The fiber is characterized by its "PMD parameter" expressed usually in $ps/km^{1/2}$: one can recognize behind this dependence a three dimensional diffusion process. The mathematical theory of Polarization Mode Dispersion can be found in [22].

The arrival of two impulse replicas at the receiver results into symbols overlapping in the signal, called intersymbol interference, and then into transmission penalty. A very important feature of polarization mode dispersion is its randomness: indeed DGD is not bounded and can always exceed the maximum tolerable value with a non-zero probability. In other terms, there is always a non-zero probability that the system does not work, which corresponds to some outage probability. The aforementioned time invariance and stability of the optical channels must be revisited, and the behaviour becomes very similar to what the radio channel experiences in the presence of multipath fading.

It is usually considered, following a rule of thumb, that the maximum tolerable PMD value (assuming an outage time of 10^{-5}) equals 10% of the symbol duration, i.e. respectively 40 ps, 10 ps and 2.5 ps in the case of 2.5 Gbit/s, 10 Gbit/s and 40 Gbit/s binary modulation schemes. It must be noted that the relevant parameter is the ratio of the DGD to the symbol duration, which depends on the symbol rate (in Gbaud) and is identical to the bitrate in the case

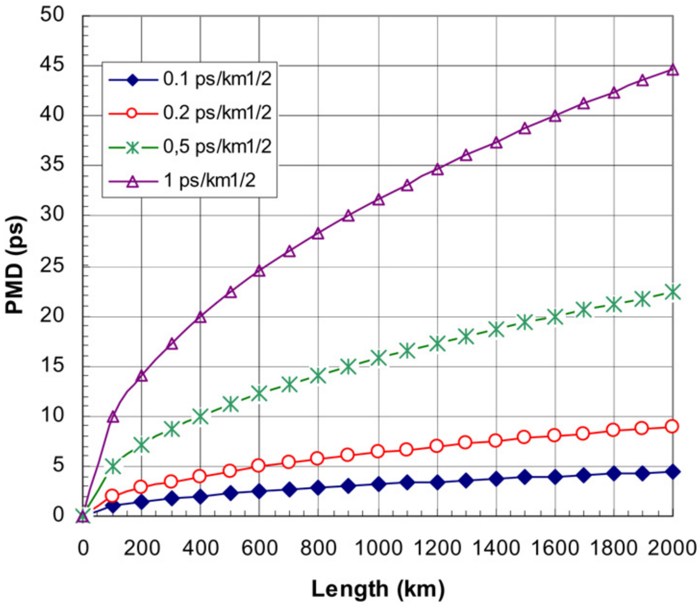

Fig. 3. PMD (in ps) versus fiber length for fibers having different values of the PMD parameter ranging from 0.1 to 1 ps/ km$^{1/2}$.

of binary modulation schemes, which have been mainly used in optical systems up today. The use of more than binary modulation schemes is an interesting way to reduce the PMD penalty for a given bit rate.

PMD is a quite limiting factor of the optical networks. The newest fibers, with a PMD parameter of about 0.1 ps/km$^{1/2}$, do not introduce any severe limitation (roughly 4000 km at 10 Gbaud), but they are not very much encountered in the backbone networks, which have been deployed in the nineties, at least by the historical operators. The main part of the deployed fibers exhibit a PMD parameter between 0.3 and 0.5 ps/km$^{1/2}$, and some quite bad fibers laid before 1995 can exhibit very high and then very bad values. The optical reach at 10 Gbaud is then limited to some hundreds of km, and PMD becomes a drastically limiting factor, much more limiting than the optical noise of the amplifiers.

Fig. 3 depicts the PMD (in ps) versus the length for three values of the PMD parameter, 0.1, 0.2, 0.5 and 1 ps/km$^{1/2}$. Recalling that the maximum tolerable PMD is 10 ps for a 10 Gbit/s system with binary modulation, it appears that a fiber with 0.5 ps/km$^{1/2}$ introduces a drastic limitation in the deployment of an optical network.

Much research has been devoted to PMD compensation. Optical compensators have been tested in the laboratory as well as in the field and could prove their efficiency [23], but the cost remained too high; indeed the main drawback of this compensation technique is the requirement of one compensator per channel, which is very expensive. Generally speaking, the objective in WDM technology is to share the optical devices between the channels of the multiplex, as it is for the amplifiers. It must be noted that, at 40 Gbit/s, compensation of PMD is necessary and industrially proposed.

The operators are very much interested in PMD metrology, because they must have the best knowledge as possible of their optical cables, in order to know their potentiality. In the case of too high value, it is quite important to be able to determine whether it results from a quite medium value along the whole cable or if there exists a particularly bad section. According to the situation, the replacement strategy is quite different. This is why the polarized reflectometry received attention from some operators, but it is not yet widely in use.

3.2. Engineering and performance of 10 Gbit/s WDM systems

The existing backbone networks are essentially based on WDM systems with a bit rate of 10 Gbit/s par channel. The first systems appeared at the end of nineties had an optical reach of 600–700 km, but the technological evolution made Long Haul (LH) and later Ultra Long Haul (ULH) systems possible: a longer optical reach reduces the number of opto-electronic conversions in the network and then its cost, which is quite interesting for the operators. Commercial systems with 80 channels, 50 GHz spaced apart, and then entirely located in the C band, are available today. The optical reach on a low PMD fiber reaches typically 2000 km.

The used modulation format remains generally OOK (On Off Keying) in most of the systems deployed in 2008, but more sophisticated transponders begin to appear, in order to provide a better sensitivity and robustness to propagation effects [24,25]. Modulation formats other than OOK, like Carrier Suppressed Return to Zero (CSRZ) or duobinary are proposed, and equalizers begin to be introduced. In 2004, the first Maximum Likelihood Sequence Estimator (MLSE) [26] was proposed and demonstrated its efficiency to combat signal degradations due to propagation. But it must be noted that all the systems use direct detection.

The first physical phenomenon to be considered in designing an optical amplified link, excluding any other impairment, is the amplifiers noise. It is cumulated along the fiber, and is always dominant compared to the receiver noise, which can then be ignored. An improvement of the signal to noise ratio at the receiver input for a given link can be seen equivalently as a gain in transmission distance, the so called optical reach, for a given required signal to noise ratio at the receiver input. Assuming perfect identical optical amplifiers compensating exactly for the losses of the fiber sections, *OSNR* (defined as the ratio of the optical signal power to the optical noise power within a 0.1 nm bandwidth) is given in dB by the relationship [1]:

$$OSNR = P_{\mathrm{em}} + 58 - NF - G - 10\log_{10} N \tag{1}$$

where P_{em} is the power per channel launched into each span in dBm, NF the noise figure (in dB) of the amplifiers [27], N the number of amplification spans, G the amplifier gain in dB (equal to the span loss). This relation is valid for a working wavelength of 1550 nm, which is mainly used today in long distance transmission systems. In the case of L-band systems used in Japan or USA, to exploit DSF-based links, it has just to be slightly modified to take into account the different value of the working wavelength.

Improving *OSNR* for a given N, or increasing N for a given *OSNR*, can be achieved by having shorter amplification spans, a better noise figure of the amplifiers, more power per channel launched into the fiber. There is practically no degree of freedom with the amplification span, at least for terrestrial systems, as mentioned in Section 2.3. If recent amplifiers exhibit lower noise figures, the improvement is limited and noise figure cannot be lower than 4 dB typically.[5] Increasing the launched power per channel is limited by the performance of available optical amplifiers, the non-linear effects and the associated penalty and finally strong safety constraints in an operational environment. The highest available output power which is practically usable is 30 dB m today. Each vendor specifies the performance of its systems through engineering tables, which give the maximum number of spans over which the transmission is possible, for different values of span loss. For instance the theoretical relation shows that the number of spans is divided by two if the loss per span is increased by 3 dB. In fact this is not so simple, but the basic idea remains. In an actual network, all the spans are not identical and the actual link does not fit to any situation described in the engineering tables. If it does not deviate too much, standard rules can be applied, if not the vendor and the operator conduct a specific study.

Two important remarks can be done. First, the fiber loss is a quite important issue: one could believe that fiber amplifiers let the problem disappear, but amplification cannot be performed without the addition of noise; reducing the losses results into a smaller amplifiers gain and then in a smaller required power per channel for a given *OSNR*, as it appears in relation (1). The second remark concerns the influence of the span length. Let be a given total transmission length L, corresponding to an attenuation A_{tot}(in dB) and consider an amplification span length $\Delta = L/N$, N integer. *OSNR* can then be expressed:

$$OSNR = P_{\mathrm{em}} + 58 - NF - A_{\mathrm{tot}}/N - 10\log_{10} N \tag{2}$$

It can be shown that *OSNR* increases very rapidly with N, the gain due to the smaller span loss being dominant before the penalty due to the higher number of amplifiers.[6] For a given transmission length, the *OSNR* becomes higher and higher when the span length decreases. We will come back to that in the next sections.

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[5] This is valid for discrete amplifiers only. Raman amplifiers exhibit an equivalent noise figure which can be considerably lower and even negative. This is due to the fact that the Raman amplifier is equivalent to a lumped amplifier located in the transmission line.

[6] Mathematically, the function $-1/x - 10\log x$ is not monotonous. It reaches a maximum and decreases after. But it can be shown, by computing the derivative, that this maximum value corresponds to an attenuation per span of 4.34 dB, which is quite unrealistic.

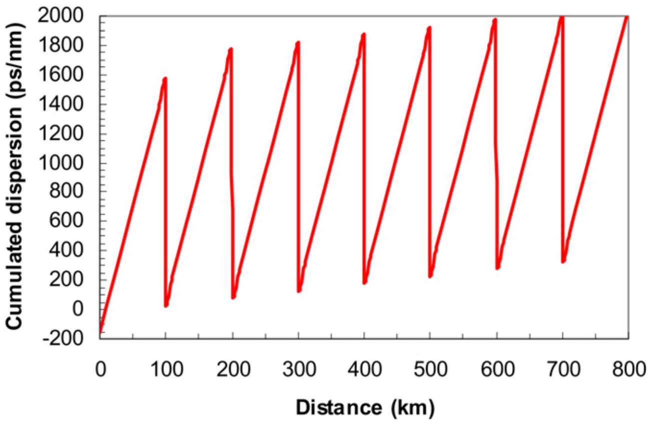

Fig. 4. An example of dispersion map for a WDM with the following characteristics. Amplification span 100 km; fiber dispersion $D = 17\ \text{ps}/(\text{nm}\,\text{km})$; precompensation $PreC = -150\ \text{ps}/\text{nm}$; under-compensation per span $UC = 50\ \text{ps}/\text{nm}$.

The gain function of an optical fiber amplifier depends on the spectral location and power of the WDM channels to be amplified [6], and the flatness of the gain curve is particularly important, because it ensures that all the channels exhibit the same OSNR at the receiver input. The amplifiers used in the first WDM systems in the nineties, with a very limited number of channels, could be very simple; this is no more the case and a manual adjustment of the gain curve, which has to be performed again each time new channels are added, is clearly not possible. The amplification modules in systems today consist in two stages, with the dispersion compensating fiber and an additional attenuator inside. This attenuation is fixed in order that the gain would be as flat as possible. Moreover, many systems today include dynamic gain equalizers [28], generally installed in some amplification sites and compensating for the deviations from an ideal flat gain curve.

OSNR can also be improved by using Raman amplification [6,12]. The advantage of this distributed amplification scheme is to reduce the equivalent noise figure, because the signal is amplified while propagating in the fiber, instead of being amplified at the receiver in the conventional EDFA configuration. Backward Raman amplification (with the pump at the receiving end) is the most commonly proposed by vendors, in some difficult situations (high loss span for instance), it can be combined with forward amplification (pump at the emitting end). Assuming a given link, Raman amplifiers allow to decrease the launched power, due to the improvement of the noise figure they bring, and then reduce non-linear effects. This advantage can be very interesting for low dispersion fibers, like NZDSF. Despite these potential advantages, Raman amplification is not very much used in networks, especially those using SSMF: quite practical problems, like eye safety (use of high power pumps) and the necessity of very clean connectors are not very well considered in an operational environment. Power consumption and cost can also be viewed as drawbacks of Raman amplification. Nevertheless, some situations require it: this is for instance the case for unrepeatered undersea systems, where the loss between emitter and receiver can reach 60 dB. Raman amplification combined with powerful error correction is commonly used in this case.

Limitations due to chromatic dispersion are the second impairment suffered by the propagating signals: it must be compensated for, as already mentioned, and compensation is provided by dispersion compensating fiber (spools) located in the amplification sites, in between the two amplifier stages in order to reduce the impact in terms of signal to noise ratio [29]. In purely linear regime, the only condition would be the compensation of the dispersion by the DCF; but practically, non-linear effects and dispersion interact, and the transmission quality depends strongly on the variation of the dispersion along the line, the so called dispersion map. Fig. 4 depicts an example of dispersion map. More can be found in [29].

This map is practically determined by the pre compensation, the post compensation, and the under or over compensation of each span, defined as follows. A DCF located at the emitting side introduces a dispersion *PreC*, called the pre-compensation. In each amplification site, a DCF compensates partially for the chromatic dispersion of the transmission link or the span. The difference between the span dispersion and the DCF value is the under-compensation *UC*. Finally, some dispersion is added in the receiver, this is the post-compensation.

Each supplier has its own engineering rules, depending on the fiber type which the system will be deployed over, and installs the DCF when deploying a system in a terrestrial network. At 10 Gbit/s per channel, and with the currently used channel spacing (50 or 100 GHz), the most detrimental non-linear effects are cross effects (Cross Phase Modulation, Four Wave Mixing) which are dominant compared to intra channel effects, like Self Phase Modulation. This is not true anymore at 40 Gbit/s, where intra channel effects are the most important [30].

A key issue is polarization mode dispersion (PMD), which is a characteristic of the transmission medium. The vendors specify for each equipment the tolerance to PMD, described by the penalty versus the differential group delay (DGD) which can be converted into tolerance to PMD when the required outage time is specified and the probability distribution of DGD is known (generally, the Maxwellian one is considered). Using these data, the operator can then determine what links can or cannot support the deployment of a given system and define its strategy (replacement of some bad fiber sections for example). Many operators conducted very extensive measurement campaigns in order to have the best knowledge of their cable infrastructure in terms of PMD, because this is a key information to be taken into account in the network evolution strategy. Beyond the value of the PMD itself, DGD variations in the time and wavelength domains are very important. If, for instance, a link experiences very slow changes of DGD that means that the system can remain "trapped" in a bad situation and then the outage time can exceed the value which is expected when considering the theoretical Maxwellian distribution.

In conclusion, in the back to back configuration, i.e. in the absence of propagation impairments, the receiver requires some minimum OSNR value, $OSNR_0$, in order to achieve a maximum acceptable bit error rate. As all the receivers include now FEC, a BER lower than around 10^{-4} (or even 4×10^{-3} for the newest FEC generation) ensures that the BER at the decoder output will comply with the required transmission quality [7,8].

Taking into account the penalties due to residual dispersion, non-linear effects, possible presence of Optical Add/Drop Multiplexers (OADM) along the link, PMD, and eventually an increase of span losses due to repairs after cable failures, and assuming the additive behaviour of these penalties, we obtain the margin M which will be added to $OSNR_0$ to obtain the required $OSNR$ at the receiver input. It is again important to note that the link design needs data from the vendor (those relative to the system) and from the operator (relative to the fiber characteristics, especially PMD).

3.3. The optical transport network today: electronic nodes connected by point-to-point WDM systems

As indicated in part 2, the introduction of the first optical transmission systems at the end of the 1980s was associated with the replacement of the old plesiochronous hierarchy by the Synchronous Digital Hierarchy (SDH), or its variant in North America, Synchronous Optical NETworking (SONET). This new way of organizing transport of digital information brought tremendous advantages to operators for supervising and managing network configuration, faults and performance (Operations, Administration and Maintenance, OAM). Transport network nodes thus consisted of SDH/SONET equipment, either digital crossconnects (DXC) or Add/Drop Multiplexers (ADM). SDH ADMs are a particular case of DXC having two line ports and several add/drop ports: they were specifically suited for ring topologies, and were very popular up to a few years ago because ring configuration allows very simple network protection mechanisms at link or circuit level. Transport network nodes were thus purely electronic nodes performing configuration, protection and grooming functions at Time Division Multiplexing (TDM) level. Configuration of SDH circuits was controlled in a centralized way through network management, and grooming and cross-connection were only performed at TDM level.

In a way, SDH rings did not really cope with the wavelength dimension of transport systems and its potential for cross-connection functions. This limitation appeared at the beginning of the 2000s, because it was very difficult to manage interconnection between several SDH rings which were multiplexed on the different WDM channels of a fiber ring: SDH ADMs do not allow efficient and simple interconnection between several SDH rings. This was a strong motivation for the advent of new transport nodes capable of interconnecting wavelength channels. More generally, the evolution of traffic needs, the new functional requirements (quality, survivability, provisioning speed, transparency ...), together with the need to optimize transport network resource usage, were drivers towards a real optical layer based on a new generation of transport network nodes called Optical Crossconnects (OXC) [31]. These new network nodes were developed during the Internet Bubble, with two technological options:

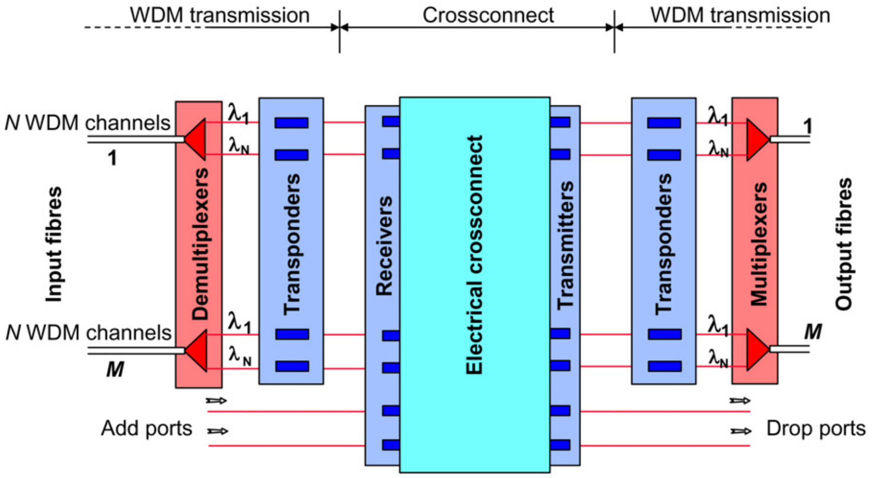

Fig. 5. Opaque node configuration in today's transport networks: crossconnection at wavelength and sub-wavelength traffic granularity is performed by an OEO switching fabric, connected to WDM transmission equipment through standardized short reach non-colored (black & white) optical interfaces. Note that a WDM channel going through the node has to experience at least 6 OE or EO conversions (2 in each WDM OEO transponder and 1 at each OE (receiver) and EO (transmitter) interface of the switching fabric, even more if the electrical switching fabric consists of several stages connected by an optical backplane).

- OEO crossconnects, based on an electronic switching fabric and optical interfaces both at the input and the output;
- OOO (optical-optical-optical) crossconnects (also called Photonic Crossconnects, PXC), based on an optical switching fabric and optical interfaces both at the input and at the output.

The advantages of photonic crossconnects were already well anticipated:

- Transparency to channel bit rate, transmission and modulation format: PXC ports are thus interface-agnostic, and are compatible with short reach client interfaces as well as long reach WDM network interfaces at any bit rate or formats possible;
- Reduced cost and power consumption due to less OEO conversions: photonic switching fabrics avoid any unnecessary bit processing and are the simplest way of crossconnecting big pipes at wavelength level.

But these advantages had a serious counterpart: OOO crossconnects are unable to manage traffic granularities finer than the WDM channel. This possibility to crossconnect or to aggregate traffic (grooming) at sub-wavelength level (TDM circuits such as the SDH/SONET Virtual Containers) has been the key to the introduction and global deployments of OEO crossconnects in transport networks since the beginning of the 2000s. Opto-electronic interfaces also allow monitoring and management of performance and faults between the equipment boundaries.

The configuration of a typical crossconnect node in today's transport networks is illustrated in Fig. 5: the main feature of this architecture is that different pieces of equipment (e.g. WDM transmission equipment, OEO crossconnect) are connected together through standardized short reach optical interfaces working at specific bit rates (typically around 10 Gbit/s) and wavelengths (typically 1310 or 1550 nm). These short reach optical interfaces, also called "black & white" or non-colored interfaces, are not suitable to long reach WDM transmission and were designed for standardized short reach interconnection between various pieces of equipment. This configuration is called "opaque", because all pieces of equipment are "isolated" from the outside by an opto-electronic conversion allowing equipment monitoring and management information to be added or dropped from the digital frames.

Apart from its key advantages in terms of network and equipment monitoring and management, and the related possibility for operators to purchase equipment from multiple vendors, this opaque network configuration has a serious drawback: the number of OE (optical-to-electrical) or EO (electrical-to-optical) conversions experienced by a WDM channel along its path through the network can be very high. Knowing that about 70% of the cost of $N \times 10$ Gbit/s WDM transmission equipment come from OEO transponders, many R&D studies have been sticking to the objective of reducing the number of OEO conversions in future optical networks [32–35]. These issues of decreasing the number of OEO conversions in the network will be addressed in part 4 of the paper.

4. Prospects: towards ultra-high capacity agile and transparent optical networks

4.1. More capacity: towards 100 Gbit/s per wavelength

The need for higher transport capacity has been and will certainly stay for a long time the key driver of optical transport network evolution, even if this evolution has been slower since the end of the Internet Bubble. As an example, the total core network load related to 20 million residential customers having very high broadband access (typically 100 Mbit/s thanks to Fiber-To-The Home technologies) may reach about 50 Tbit/s [32]. This will result typically in a source traffic demand of about 1 Tbit/s or higher per core network node, and thus a total capacity per node reaching several Tbit/s when taking into account transit traffic. These figures illustrate the strong need for an increase of optical transport network capacities in the long term, both on network nodes and line systems.

As explained in part 2, the increase of the bit rate per WDM channel became very soon the key to increases of WDM system overall capacities, and available WDM systems moved quickly from 2.5 to 10 Gbit/s per channel at the end of the 1990s. On the one hand, increasing the number of WDM channels brings a cost advantage due to fiber and amplifier sharing, but the marginal cost advantage becomes lower when the number of channels is already significant; on the other hand, increasing the bit rate per wavelength allows to decrease the number of costly OEO transponders for a given capacity per fiber, thus allowing cost reductions of each bit/s. Together with the technical reasons given in part 2 (wavelength requirements on sources and passive components, non-linear channel interactions), these strong economical drivers led to significant developments towards higher bit rates per channel, e.g. 40 Gbit/s, 100 Gbit/s, or even 160 Gbit/s. But the signals are more and more subject to transmission impairments when the bit rate increases, and moving from 10 Gbit/s to higher bit rates requires a lot of problems to be solved, and in particular the sensitivity to PMD is dramatically increased: when the bit rate is increased from 10 to 40 Gbit/s for a binary modulation, the symbol duration is divided by four, and then the maximum tolerable PMD value is also divided by four (cf. Section 3.1). As far as the impact of PMD is concerned, it is assumed a binary modulation format, which means that the symbol rate is equal to the binary data rate which is used. We will come back to this point later.

Significant research activities on 40 Gbit/s WDM transmission began in the early 2000s, and a lot of start up companies, with research teams coming often from the big vendors research labs, were particularly active during the Internet Bubble period: the first WDM transmission equipment working at 40 Gbit/s channel bit rate were ready in 2002, with a capacity of 1.6 Tbit/s per fiber (40 × 40 Gbit/s channels) and an optical reach of more than 2000 km on low PMD standard single mode fiber [36]. It included a PMD compensator and could tolerate a PMD of 8 ps, which is a quite nice figure at this bit rate.

Increasing the bitrate from 10 to 40 Gbit/s requires an additional 6 dB gain in OSNR [13]: it can be achieved by the use of more efficient error correcting codes, providing roughly 2 dB gain compared to the Reed Solomon (255,239), the introduction of Raman amplifiers [12], and the use of other modulation formats than OOK, allowing a better sensitivity. Phase modulation with differential demodulation is a possible candidate for 40 Gbit/s links over long distances: binary modulation (DPSK), which provides theoretically about 2.5 dB gain in OSNR, has been studied extensively [13], DQPSK has also been proposed because it allows to divide the symbol rate by a factor 2 compared to a binary modulation format and then to reduce the impact of propagation impairments like chromatic dispersion or PMD. One has also to mention that 40 Gbit/s systems also suffer from reduced tolerance to non-linear effects, even more reducing system power margin and thus, reach.

Unlike 10 Gbit/s generation, no significant deployments of 40 Gbit/s systems occurred up to now in optical transport networks. One reason was that traffic increase was not sufficiently high to drive replacement of 10 Gbit/s systems. Another strong reason was also the slower cost decrease of 40 Gbit/s transponders compared to what happened with 10 Gbit/s transponders. Physical limitations of fibers at 40 Gbit/s, and in particular PMD, have of course slowed down deployment of 40 Gbit/s systems, because operators refrained from replacing optical cables unless strictly necessary. The deployment of 10 Gbit/s systems needed the replacement of some very bad pieces, installing 40 Gbit/s links would have been much more expensive.

Following the SDH hierarchy, 160 Gbit/s appeared as the next step after 40 Gbit/s. Very nice experiments were carried on by different academic and industrial partners to investigate the transmission at such a bitrate, which are very difficult to solve. Besides the gain of 6 dB in OSNR again, the sensitivity to PMD is such that compensation is absolutely required to develop a practically usable system. The European project TOPRATE, demonstrated the transmission of 8 × 160 Gbit/s channels on more than 400 km of standard single mode fiber installed in the field [37].

A very deep and significant change occurred in 2004, with the publication of the first laboratory results about 100 Gbit/s transmission experiments: since that time, an intense research and development effort has been made and it is now practically sure that the next generation of WDM systems, after the 40 Gbit/s generation, will transport 100 Gbit/s per channel [38]. This development is strongly boosted by the 100 Gbit/s Ethernet, which is pushed by the Ethernet community, after the 10 Gbit/s version available today. Since 2005, a lot of results have been published in major journals and conferences, using different types of modulation, among them DQPSK (Differential Phase Quadrature Phase Shift keying) and PDM-DQPSK (Polarization Division Multiplexing DQPSK) [13]. Higher levels modulation schemes (QAM 16, 64, 128) are being studied in the laboratories [39] and very recently PDM-QAM 16, providing a spectral efficiency of 8 bit/s/Hz, has been demonstrated [40]. These are just examples, the interested reader is invited to go to papers more focused on the topics of modulation.

Far beyond the change in the multiplicative factor, this is a deep change on a technological point of view and also for the operators, because the infrastructure constraints can be seen differently. First, the coherent detection comes back. A lot of work had been devoted to optical coherent (heterodyne or homodyne) reception between 1985 and 1995, and many publications about this topic can be found in this period. Ref. [41] gives an historical survey.

The expected advantage was a better sensitivity of the receivers, limited by the electronics thermal noise: that was exactly what wireless communications had experienced, moving from the direct crystal detector to the heterodyne receiver, where the incoming signal beats with a local oscillator.

But the advent of the fiber amplifiers provided the expected sensitivity enhancement, integration of the receivers was difficult, and coherent detection was forgotten in optical telecommunications, direct detection through a photodiode being the standard feature of transmission systems. The situation changed dramatically in recent years, and quite different coherent receivers can now be implemented, due to the dramatic progress in signal processing capability of integrated circuits, solving the problems encountered ten years before [42]. Carrier recovery is in particular performed in a completely different way through the concept of intradyne receiver [43]. Coherent detection opens the way to two major evolutions:

- The use of more than binary modulations formats is easier than with direct detection. Phase modulation, and more generally combined amplitude and phase modulation formats which are not usable with direct detection, become possible with coherent detection. The symbol rate can then be reduced for a given bit rate, and so is the impact of different linear impairments; nevertheless, resistance to Kerr non-linear effects, directly impacting signal phase, becomes a much more stringent issue [44];
- The demodulation process is linear, in other terms, the demodulated electrical signal sees exactly the same transfer function as the optical field, and equalization can be performed more easily and more exactly than behind a quadratic detector.

In fact, the first application of coherent detection in a commercial system has been proposed in 2008 by Nortel at 40 Gbit/s: each WDM channel transmits two QPSK signals at the same wavelength over orthogonal polarizations (PDM-QPSK, for Polarization Division Multiplexing QPSK) [45]. The symbol rate is then only 10 Gbaud, which reduces the impact of PMD very significantly: in other terms, the tolerance to PMD of a 40 Gbit/s PDM-QPSK system is not worse than for a 10 Gbit/s OOK system.

PDM-QPSK has been widely investigated and many results have been published since 2006 [44]. A spectral efficiency of four bits per symbol is achieved and the symbol rate is only 25 Gbaud for a bit rate of 100 Gbit/s. The four dimensional signal can be demodulated in the receiver following a MIMO (Multiple Input Multiple Output) approach, similar to what is done in wireless systems. Today, the signal processing circuits can be implemented at 10 Gbaud and not yet at 25 Gbaud, but that should be possible in the coming years.

The objective of this paper is not to review in details the state of the art of 100 Gbit/s per channel transmission. We would just point out that the future optical systems for backbone networks will include much more efficient receivers, based on advanced signal processing and using demodulation processes which are classical in wireless technology. In other words digital communications are entering the optical transmission world, which used up to now relatively "simple" techniques. In this sense 100 Gbit/s systems represent clearly a deep change, while the 40 Gbit/s systems developed in 2002/2003, as well as the 160 Gbit/s experiments, were in continuity with the 10 Gbit/s generation.

For the operators, these changes can bring important consequences: the reduction of the symbol rate, combined with the signal processing potentialities, will probably relax the constraints in terms of PMD, compared to what happens with the 40 Gbit/s "classical" systems. But the issue of non-linearities is far from being negligible, especially when it comes to combining coherent systems with 10 Gbit/s OOK channels over an existing infrastructure.

4.2. More transparency: towards photonic nodes and photonic networks

As explained in Section 3 and illustrated in Fig. 5, today's optical transport networks mainly consist of electronic nodes (the so-called OEO crossconnects) connected by point-to-point WDM links. This configuration is certainly the most appropriate for operators at the moment, because each node allows crossconnecting of both WDM channels and sub-wavelength TDM circuits such as SDH Virtual Containers. This ability for electronic nodes to manage sub-wavelength granularities was a key to the global deployments of OEO crossconnects in optical transport networks at the beginning of the 2000s. This configuration also allows multi-vendor interoperability through the use of standardized short reach optical interfaces for interconnection of the OEO crossconnect with the WDM transponders.

Despite its operational advantages for operators, node and network opacity would probably be a strong limitation to the development of core network capacity in the future. Along with capacity, we thus believe that transparency[7] will be the second key driver of optical transport network evolution in the next decade. One should first remember that the transparency of optical fiber amplifiers was a key to the dramatic success of WDM line systems. One should also realize that first transparent optical network domains are currently being deployed in the form of Ultra Long Haul (ULH) WDM links equipped with Reconfigurable Optical Add/Drop Multiplexers (ROADM) as intermediate nodes. ROADMs are indeed a simple version of transparent photonic nodes designed for a node degree of 2 or 3, allowing transparent connectivity in simple topologies through their wavelength add and drop ports. It may be anticipated that ROADMs will be popular in ring topologies, e.g. in metropolitan area networks, so as to perform at WDM level the functionalities which were achieved by SONET/SDH ADMs at TDM level some years ago. One could say of course that this evolution towards transparency is limited to specific network domains and topologies (ULH links with intermediate add/drop nodes, or ring topology), but these first deployments are driven by cost reductions, which would also promote optical transparent networking in more generic core network mesh topologies, with more sophisticated photonic nodes based for example on Wavelength Selective Switches (WSS) [46,47].

The development of core network capacity as well as the requirement for operators to decrease the cost of each transported bit/s will trigger the advent of optical transport network solutions with much less OEO conversions than in today's networks. These OEO conversions do represent about 70% of WDM system costs at 10 Gbit/s per channel, and this cost fraction will even be higher for 40 Gbit/s or 100 Gbit/s system generations. OEO conversions will also be an issue in terms of electrical power saving requirements. As an illustration, power consumption of a 10 Gbit/s opaque interface port of an OEO crossconnect is typically about 50 W (even higher for a WDM OEO transponder), to be compared to about 6 to 10 W for an optical transparent interface port of a photonic crossconnect [48]. This drawback of opaque ports and OEO transponders in terms of power consumption will of course be more dramatic at higher bit rate per port.

Given this strong driver towards more transparency, the key question is then: how will optical transport networks work with much less OEO conversions? Various levels of answers are possible on this question, and the migration towards more transparency will surely be very gradual and take several years. This evolution can be illustrated in two different node configurations as depicted in Fig. 6:

- In scenario (a) of Fig. 6, transparency is implemented only at switching level, through the use of OOO crossconnects instead of (or preferably as a complement to) OEO crossconnects [48]. The optical network stays opaque because transponders terminate WDM channels in each node. Most probably, these photonic (OOO) crossconnects would be used in core nodes of several Tbit/s capacity or more, so as to alleviate the load of the OEO crossconnects which do not scale easily to huge switching capacity;

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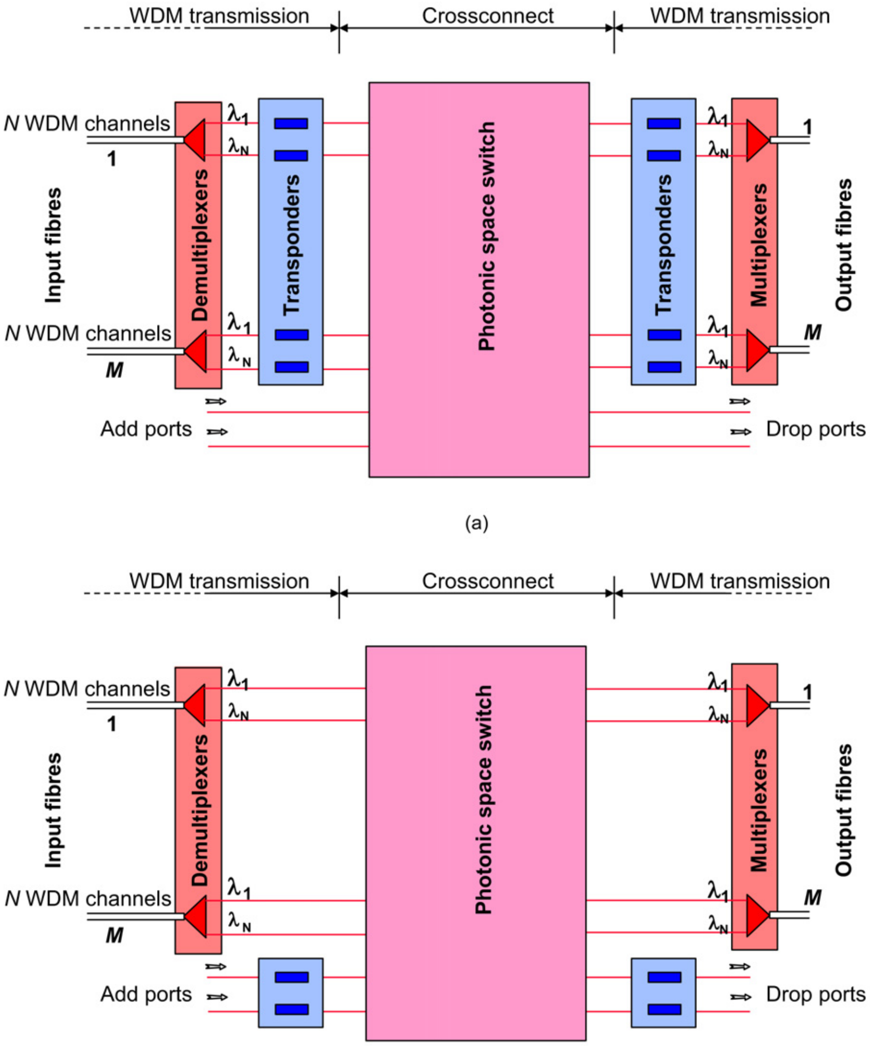
[7] We define as transparent a piece of equipment or a part of the optical network in which no OE or EO conversion is performed on the signals or channels going through it.



(a)

(b)

Fig. 6. Node configurations for future optical transport networks: (a) Photonic crossconnect in an opaque network; (b) Photonic crossconnect in a transparent network. Note that for a node of degree 2 (such as a node in a ring topology or on an intermediate node of an ultra long haul WDM link), configuration (b) is equivalent to the well known Reconfigurable Optical Add Drop Multiplexers (ROADM).

- In scenario (b) of Fig. 6, WDM transponders are moved to add and drop ports of some of the network nodes. These nodes then become fully transparent for WDM channels going through them, thus resulting in transparent network domains (also called “transparent islands”), with much less transponders than in today’s opaque configuration (because through-to-total traffic ratio is typically around 75% [48]). The interesting point is that this scenario, although very prospective for a large transport network in a meshed topology, is in fact being implemented now in the form of WDM ULH links with ROADMs. The engineering and operational constraints on a simple linear or ring topology are indeed much less complex than on a general meshed topology.

Note that in both scenarios, an OEO crossconnect can be connected to the wavelength add and drop ports of the photonic switch in a hierarchical configuration, thus allowing grooming and multiplexing at TDM level. Instead of choosing between OEO and OOO crossconnects, operators would probably need to install both types of equipment in some given high capacity nodes, thus allowing both optical by-pass of transit traffic and access to TDM multiplexing levels.

Scenario (a) of Fig. 6 is already challenging, because opto-electronic interfaces of OEO crossconnects can perform many control and management functions thanks to the access to digital frames and thus to overhead bytes (in-band signalling). These functions include fault and performance management, connection verification, topology discovery, signalling, routing and restoration [48]. Various strategies can be considered to solve the control and management issues related to the use of photonic crossconnects in opaque networks, one of which being the use of the opaque functions located in WDM transponders and in client equipment, together with out-of-band signalling between photonic crossconnects and between photonic crossconnect and client equipment (see [48] for details). Automatic port and topology discovery is thus possible through out-of-band signalling, as standardized in the Link Management Protocol [49,50]. Other functions such as WDM channel provisioning, network protection or restoration are also possible in photonic crossconnects with this strategy [48].

The dramatic challenges associated with transparency appear in scenario (b) of Fig. 6, which implements transparency at network level. In particular, WDM channel routing and wavelength assignment in a transparent optical network has to take into account physical impairments that the channel may encounter along its way inside the network (optical noise and crosstalk, spectral narrowing in optical passband filters, chromatic dispersion, polarization mode dispersion, fiber non-linearities . . .). Taking into account these engineering constraints in optical network design and control led to significant research effort for about one decade, through the advent of “translucent” optical networking [33–35]. This concept permits WDM channels to be regenerated in some network nodes. A key issue of translucent or transparent optical networking is also related to the wavelength continuity constraint,[8] leading to somewhat inflexible usage of wavelength resources in the network. One should also note that multi-vendor interoperability will be a key issue of these new translucent optical networks. Given all these difficulties and challenges, the most probable and reasonable scenario for operators will be the advent of some limited transparent optical network domains interconnected by opaque nodes. A transparent network domain, also called “transparent island” [35], will preferably be composed of single-vendor pieces of equipment. It will for example take the form of a transparent WDM ring with ROADMs, or be implemented as an ULH WDM link with intermediate ROADM nodes. As far as transmission is concerned, the filtering effects of ROADMs must be taken into account: this has been the subject of some R&D studies [51–53] and these effects are taken into account in the engineering rules of the vendors. The opaque nodes interconnecting the transparent islands will first consist of OEO crossconnects, but it may be anticipated that some of these high-capacity opaque nodes will then incorporate a photonic crossconnect as a complement of the OEO crossconnect. In general, the evolution towards more transparency will require significant effort on network control and management, as anticipated in [54].

4.3. More agility: towards dynamically switched photonic networks

After capacity and transparency, we believe that agility is the third key driver of future optical transport network evolutions. The increasing competition on leased-lines and Virtual Private Network services strongly encourages operators to offer quicker provisioning of connections, or even customer-controlled switched connections at the transport network level [32]. The agility of the transport network is thus related to the possibility for the network to automatically and dynamically control and manage connections, either for network protection or restoration purposes, for traffic engineering purposes, or at the customer’s demand. The introduction of OEO and/or OOO crossconnects is one of the requirements for transport network agility. But another key aspect of agility is the introduction of a control plane. Much effort has been done for several years by Internet Engineering Task Force (IETF) [55], International Telecommunication Union – Telecommunication (ITU-T) [56], and Optical Internetworking Forum (OIF) [57] to standardize control techniques for optical transport networks, under the concepts of Generalized Multi-Protocol Label Switching (GMPLS) control plane, Automatically Switched Optical/Transport Network (ASON/ASTN), and User Network Interface/Network to Network Interface (UNI/NNI) [58–60].

Even if agility requirements are already taken into account in upper network layers and in particular in the IP layer, the move towards transparency will result in agility requirements in the optical transport layer, not only at TDM level, but also at WDM level. Indeed, increasing the reach of optical transmission systems may result in an inefficient usage of transmission resources if no agility is provided in the configuration of wavelength channels. Imagine a motorway

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[8] Instead of opaque nodes, transparent nodes do not allow native wavelength conversion, which result in additional constraints for wavelength assignment.

from Paris to Vladivostok without any road interchanges in-between: such a configuration would be nonsense in terms of road resource usage, and the same conclusions apply to optical transport networks with more and more transparency. Thus, the so-called transparent islands will need wavelength agility provided by photonic crossconnects (among them ROADMs) and control plane techniques listed above.

We believe that agility in optical transport networks will surely be implemented at the wavelength channel level during next decade, and thus take the form of optical circuit switching. But statistical multiplexing techniques in the optical domain itself could bring agility down to the level of optical packets or optical bursts. The concept of Optical Packet Switching (OPS) [61–63] is probably as old as the concept of all-optical network, but much research effort is still necessary to envisage realistic implementation in optical networks, in particular because of the absence of random access memory in the optical domain. Nevertheless, realistic implementations of OPS could be considered in small scale optical networks with a simple topology, e.g. in metropolitan ring networks [64]. The concept of Optical Burst Switching (OBS) tried to solve some of the issues of OPS, in particular the queuing issues, and can be seen as a balance between optical packet and optical circuit switching, in which bandwidth is reserved in a one-way process (instead of the two-way process of circuit switching), and in which data payload cuts through intermediate nodes without being buffered (instead of packet switching). Different flavours of OBS have been proposed (see for example [65–67]), but control issues and traffic performance (burst losses) remain difficult challenges.

5. Conclusions

For 15 years, the optical technology has completely transformed the backbone networks: the capacity per link was multiplied by some hundreds, the number of regeneration sites decreased dramatically, leading to an enormous reduction of the operational cost. The transmission quality reaches now a level absolutely unknown before.

The first driver of these evolutions is capacity: after a very rapid increase with the introduction of the first WDM systems at the end of the nineties and during the Internet Bubble, the capacity increase in transport networks slowed down, but it is now increasing again, in relation with a strong growth of traffic. The 100 Gbit/s per channel will be deployed in terrestrial networks, a lot of new undersea cable projects are being studied, and 40 Gbit/s systems will be deployed on transoceanic routes.

It is important to note that the physical infrastructure, i.e the optical cables composing terrestrial networks, was deployed in the mid of the nineties, before the WDM era and for much smaller capacities. The optimality of this fiber and its compatibility with the future evolution of the networks is then a key issue: in fact the standard single mode fiber appears as a very good candidate for the 40 Gbit/s and even the 100 Gbit/s generations of systems. That means that operators having installed SSMF will have the opportunity of exploiting yet the potentiality of this fiber. A dramatic change could occur if fibers with a very significantly smaller loss would become available. This is for instance what has been expected from photonic fibers, but is not yet proven. A fiber for long distance transmission with a loss of 0.05 dB/km, instead of 0.22 dB/km today, would be a deep revolution in backbone network design and engineering. An active research is conducted about photonic fibers, but it cannot be concluded today that very low losses could be obtained.

Beyond the capacity which optical communications can only provide, transparency and agility are the other drivers of optical transport network evolutions. They describe the current deep change in nature of the optical backbone networks compared to what existed before. Instead of a collection of high capacity point-to-point links connected by electronic switching nodes, “transparent islands” will appear, first in the form of ultra long haul WDM links equipped with ROADMs as intermediate nodes, and then with more sophisticated photonic crossconnects. After the optical fiber amplifiers, which were the first transparent bricks of optical networks, photonic nodes will thus be the next step towards optical transparency, although opaque nodes will remain necessary at the boundaries of transparent islands. The move towards more transparency will also require more agility in future optical networks. Agility will first be obtained through the combination of advanced control plane techniques and photonic nodes, leading to circuit switching at WDM channel level. In a longer term, agility of optical transport networks could also scale down to the level of optical bursts or optical packets.

These three drivers – capacity, transparency, agility – lead to very difficult technical challenges for the research community, but the advent of Fiber-To-The Home technologies throughout the world, and the resulting throughput and operational requirements on transport networks, will probably strengthen these drivers of optical transport network evolutions and help solving the related challenges.

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