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Optical telecommunications/Les télécommunications optiques

Multi-wavelength fiber networks

Réseaux optiques multi-longueur d'onde

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Abstract

This paper describes the main trends and design issues in the design of current generation of WDM optical networks, and the enabling factors and motivations that will push to build the next generation transport networks. The latter will benefit from new optical technologies (ultra-long haul, switching, ...) to reduce the network cost, and from new control technologies (Generalised Multi-Protocol Label Switching) that will make them dynamically flexible to better serve the changing traffic demands of emerging services. The paper covers all aspects of the network: network design and planning, system and architecture design, technologies, control and management. It also includes an overview of current state of the art and observations/statistics learnt from network studies. ***To cite this article: L. Berthelon et al., C. R. Physique 4 (2003).***

Résumé

Cet article décrit les principales tendances et les défis de conception de la génération actuelle des réseaux optiques WDM, ainsi que les éléments techniques et motivations qui pousseront à développer des réseaux de transport de nouvelle génération. Cette nouvelle génération de réseaux utilisera de nouvelles technologies optiques (ultra longue distance, commutation optique, ...) pour réduire le coût des réseaux, et de nouvelles technologies de contrôle (Generalised Multi-Protocol Label Switching) qui les rendront flexibles de façon dynamique pour mieux répondre aux demandes de trafic variable liées aux services émergeants. Cet article couvre tous les aspects des réseaux : conception et planification de réseau, conception de l'architecture système, technologies, contrôle et gestion. Il inclut également un survol de l'état de l'art des réseaux optiques, et des observations et statistiques pertinentes obtenues à travers diverses études de cas de réseaux. ***Pour citer cet article : L. Berthelon et al., C. R. Physique 4 (2003).***

Keywords: DWDM; Optical networking; GMPLS; OXC; OADM; Transparent networks; All-optical networks; Optical network management; Control plane; Core network; Metro network; Very/ultra-long haul; Opaque networks; Optical switching; Optical network planning; Optical system design

Mots-clés : DWDM ; Réseau optique ; GMPLS ; OXC ; OADM ; Réseaux transparents ; Gestion des réseaux optiques

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1. Introduction

With the emergence of WDM (wavelength-division multiplexed) optical transmission systems, the feasibility of optical-layer (wavelength-switched) networks has raised a lot of interest in the research community and in telecom network operators. As a result, dense WDM (or DWDM) transmission and wavelength routing/switching technologies are used in combination to build an overlay transport network, both in backbone and metropolitan networks, in which the switched entity is the wavelength itself, whatever the transport signal data format. In the first generation of industrial developments, fully opto-electronically regenerated networks were deployed with point-to-point WDM transmission. In the following generation are introduced all-optical switching and very/ultra-long-haul (1500/4000$^+$ km) transmission technologies, and distributed control to meet increasing traffic, allowing operators savings in CAPEX (capital expenditure) and OPEX (operational expenditure). The first savings (CAPEX) arise from minimum use of regeneration. The second (OPEX) comes from the introduction of optical flexibility and cost-effective automated allocation of network resources to the bandwidth requests. This second generation and related design challenges (technology, planning, optical engineering rules, control and management) are described in Section 3 with an equipment-supplier perspective. The other sections more specifically address the context of optical backbone (Section 4), next-generation metropolitan networks (Section 5).

2. First generation optical networks

2.1. Characteristics

The first generation of optical transport networks was developed on the basis SDH/SONET legacy [1,2], a technology for single-wavelength transmission systems based on Time-Division-Multiplexing (TDM). The WDM point-to-point transmission technology was then introduced to overcome fibre congestion while maintaining switching in SDH/SONET layer (e.g., VC-4/OC-12 granularities) with Add-Drop Multiplexers (ADM) and Digital Cross-Connects (DXC). The architecture of the SDH/SONET networks is depicted in Fig. 1, where WDM increases the point-to-point transmission capacity.

Optical or opto-electronic (OE) switching technologies have then allowed to build wavelength-switching Network Elements (NE) such as Optical Add/Drop Multiplexers (OADM), and Wavelength Cross-connects (WXC, i.e., network elements capable at wavelength level of interconnecting signals exiting optical interfaces). These NEs can support remote provisioning and protection/restoration of end-to-end wavelength connections, allowing operators to offer secure wavelength services. Each wavelength path through the network meets one OE regenerator at the output or input of each link, representing two costly regenerator functions at each network node. The required transmission performance is adapted to link distance, i.e., regional ($<$100–200 km) for metro core, and long-haul (LH, few 100s km) or at most, very long-haul (VLH, up to $\sim$1500 km) for continental (Pan-American, Pan-European) backbones.

2.2. Network services

The main services provided by transport networks are related to the management functions [3] which are already the key points of SDH/SONET networks: Performance, Fault, Configuration and Security. Beside this first set of services, the network Protection/Restoration capability [4] is also a key feature. Introducing equivalent functions and services in the WDM layer is the current challenge of 'next-generation optical networks'. This evolution is mainly based on the '*digital wrapper*' approach (ITU-T standard G.709) normalised by the international telecom union (ITU) [5], which defines the framing of optical channels

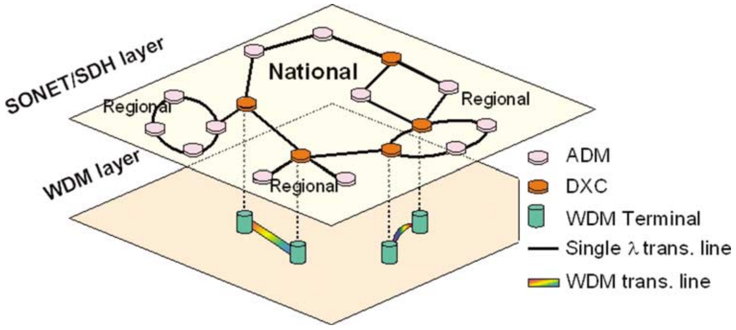

Fig. 1. Architecture of a first generation optical network.

for encapsulating several data types (IP, Gigabit Ethernet, SDH/SONET, ATM, ...). Additional overhead satisfies management needs: monitoring, performance, fault and protection.

2.3. Network planning and design

The transmission network design is based upon a strategy (Fig. 2) defining key steps from traffic engineering to network-solution pricing. This planning/design procedure is quite flexible and allows a constant control from network planners. The basic rule is to follow a client/server relation [6]. Different optimisation criteria can be considered for the multi-layer design (SDH + WDM), especially considering SDH and sub-wavelength grooming, network partitioning and layering.

However, this methodology is based on static traffic matrix and no traffic variations are taken into account. This point is not a real drawback for well-known traffic demand as mainly voice or leased-line traffic. However if the original traffic demand is unpredictable (IP), this planning process should, over-dimension the transport network, possibly to a large extent.

2.4. Optical line design issues for point-to-point systems (including OADMs)

2.4.1. Chromatic dispersion management

Especially at 10 Gbit/s rates and higher, chromatic dispersion causes spreading and distortion of the WDM signals. Managing this dispersion along the line is mandatory to minimize transmission impairments. Currently, Dispersion Compensating Fibers (DCF) are used inside dual-stage optical amplifiers, providing dispersion-slope compensation of the line fiber to avoid differences in performances among channels and per-band compensation at the receiver.

Dispersion management is more complex for links including OADMs. Indeed, for every OADM node and terminal, the accumulated dispersion must be within the dispersion tolerance of the transponder (Fig. 3) for each channel. Fig. 4 describes a typical dispersion management with OADMs.

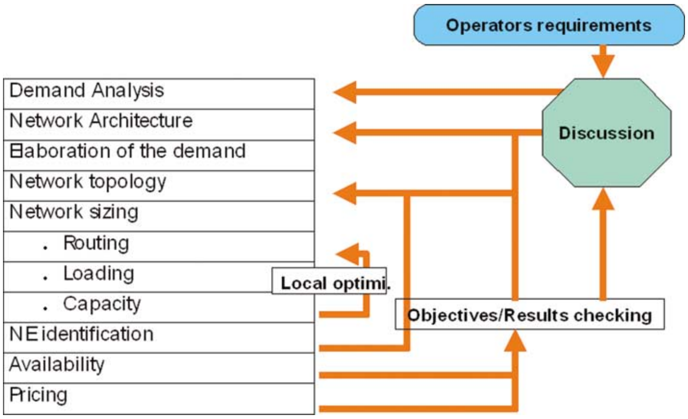

Fig. 2. Transmission network planning and design strategy.

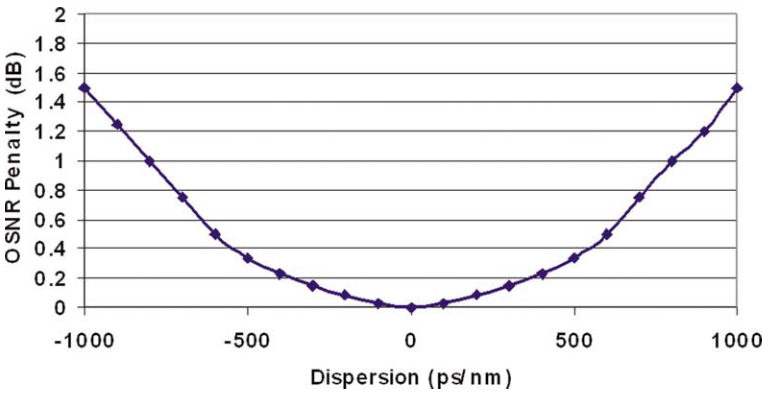

Fig. 3. Chromatic dispersion tolerance at 10 Gbs/s.

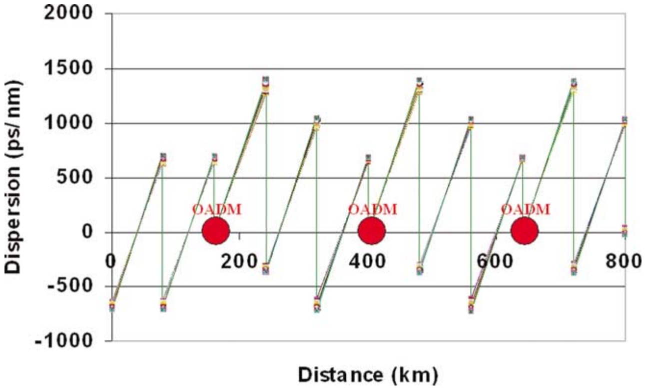

Fig. 4. Typical dispersion management with 3 OADMs.

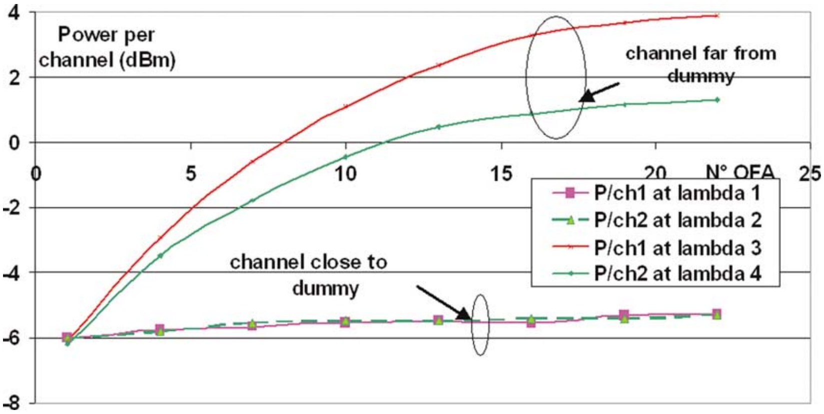

Fig. 5. Per channel power into line fiber versus number of amplifier.

The knowledge of the line fiber dispersion is important to insert the correct amount of DCF at each amplifier.

2.4.2. Loading and protection

As most of the DWDM systems are installed with a limited initial capacity, solutions providing safe installation are very important. In such systems, per-channel power control is one of the major issues. The technical problem is to maintain this per-channel power constant while the channel count changes.

There are various reasons for the channel count to change:

- System upgrade resulting from traffic increase. Any channel should be added incrementally, without introducing impairments on the working channels;
- Fiber break before an OADM resulting in an instantaneous drop of channel count.

The per-channel power must be controlled to provide sufficient optical signal-to-noise ratio (OSNR) and avoid nonlinear effects. The basic idea is to place working channels close to a specific ‘dummy’ channel. The dummy is used to saturate the line-amplifiers gain thus keeping it constant while working channels are added one by one.

Wavelength allocation of channels and dummy channel technologies are important design factors. The working channels must be sufficiently close to the dummy channel (Fig. 5) for the function to work properly.

2.5. Metro and core networks, state-of-the-art

Targeting backbone networks, commercial products were developed to build meshed and interconnected ring topologies, with WDM transmission systems of 100 channels at 10 Gb/s in C-band at 50 GHz channel spacing, and potentially up to more than 200 channels in S + C + L bands. Switching products include OADMs with improving flexibility, and opaque WXCs with a main trend based on OE technologies, but also, more rarely, based on optical switching matrices.

In the metro area, most of the optical products cover rings and point-to-point links with more or less flexible OADMs, supporting in general 100 GHz channel spacing in C-band, with 2.5 and 10 Gb/s channel rates. Also emerging are low-cost optical solutions for metro access networks, based on coarse WDM with 20 nm-spaced 2.5 Gb/s channels (and soon 10 Gb/s) over the 1300–1600 nm spectrum.

3. Next generation optical networks

3.1. The enablers

3.1.1. Transmission technologies

Different transmission technology breakthroughs have stimulated the transmission performance growth, namely: Raman amplification, active gain equalization, improved forward-error correcting (FEC) codes, improved modulation formats (e.g., chirped RZ/NRZ, phase-shaped binary transmission or PSBT), and improved chromatic dispersion compensation with tunability. These new technologies make possible to design VLH and ULH systems with previously unforeseeable performances.

3.1.1.1. Raman amplification. Raman amplification improves the OSNR (Fig. 6) and DWDM transmission over longer distance becomes feasible without OEO regeneration (i.e., OE regeneration followed by optical conversion).

Optical Raman gain (a fiber nonlinearity) allows power transfer between continuous pump waves and WDM signals. These pumps could propagate with or against the signals. Hybrid Raman amplification can be implemented with erbium-doped fiber amplifiers (EDFA) (Fig. 7) or can completely supplement EDFAs for seamless operation over 100 nm bandwidth.

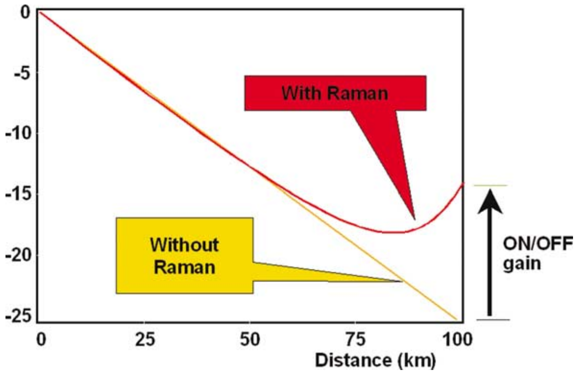

Fig. 6. Raman gain on/off to improve OSNR.

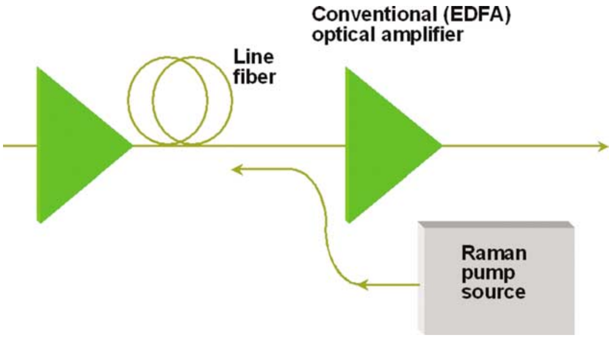

Fig. 7. Hybrid Raman amplifier.

3.1.1.2. Active gain equalization and power monitoring. Optimisation of WDM transmission performance requires precise balancing of the channel powers. The power management along the line is critical in ULH systems. Active gain equalization associated with optical power monitoring are needed to compensate channel power ripple, which stems from EDFA gain fluctuations, noise accumulation or passive components.

3.1.1.3. Tuneable dispersion-compensating modules. Optical networks could have fibers of different dispersion properties. Due to the small dispersion tolerance of transponders at 10 Gb/s and higher rates, it is not possible to use the same dispersion-compensating module for full flexibility and reconfiguration capability. Tuneable dispersion-compensating module (TDCM) are needed to minimize distortion impairments and define a correct accumulated dispersion at the receiver.

3.1.1.4. Forward error correction. Code control through FEC is a powerful means to enhance system performance and extend both haul and capacity. Due to the long distances involved in optical networks, fiber nonlinearity can be important. Then FEC provides 'coding gain' as a means to reduce OSNR requirements or the impairment of fiber nonlinearity. Conventional 239/255 Reed–Solomon codes are typically used in DWDM systems, giving a net coding gain near 6 dB. However, new enhanced FEC provide coding gains up to 8.5 dB. As an additional interest, FEC technologies are relatively inexpensive.

3.1.2. Switching technologies

Other technologies also emerge for flexible all-optical switching, such as used in large-size/low-loss switching matrices. These include 2–3-dimension micro-electro mechanical optical [MOEM] switches, fiber-bending and beam-steering devices, tunable transponders/filters, integrated wavelength-selective switching and blocking elements, etc. These building blocks are cascadable across any all-optical path. The related functions allow one to combine improved transmission and optical flexibility for designing dynamically-switched transparent networks.

3.1.3. GMPLS control technologies and protocols

Networking technologies emerging from the Internet world, and standardisation efforts around GMPLS (Generalized Multi-Protocol Label Switching [7]) and UNI (User Network Interface [8]) are simultaneously enabling to design novel control schemes in optical transport networks, which must face increasing traffic unpredictability. These networking technologies and the related suite of protocols (LMP, OSPF, RSVP-TE, etc., see below) allow faster connection/service provisioning, Bandwidth-on-Demand (BoD), protection/restoration, and automated distributed control.

Today, Internet services dominate the bandwidth usage in many networks, and driven by enterprise applications, TCP/IP traffic management and control capabilities are beginning to replace traditional traffic management. The deployment of DWDM links just began, and it is highly desirable to use these links to interconnect the routers composing the Internet backbone. Recently, there has been a flurry of activities in several standardisation bodies (IETF, OIF, ITU) to push for the marriage of packet, TDM and WDM networking technologies into a unified structure for Internet. The proposal for an IP-centric control plane for next-generation optical networks based on MPLS (now classified under the generic umbrella name of GMPLS [7]) has emerged as the natural next step. GMPLS is a suite of IP protocol extensions that provides common control to packet, TDM and wavelength services. The basic philosophy for the control plane advocated by GMPLS is as follows: the control plane is composed of a set of IP/MPLS-centric algorithms and distributed protocols running in all the nodes of the optical IP network. A set of routing protocols [9] and algorithms – based on appropriate 'optical' extensions to *open shortest path first* (OSPF), *intermediate-system to intermediate-system* (IS-IS), or *border gateway protocol* (BGP) – maintains a synchronized network topology database, and advertises topology-state information to maintain/refresh that database. A constraint-based routing algorithm on each node may then use the information in the topology database and other relevant details to compute appropriate optical paths (for primary and restoration paths). Once a path is computed, a signaling protocol [10] such as the *resource-reservation protocol traffic engineering* (RSVP-TE) or the *constraint-based-routing label-distribution protocol* (CR-LDP) can be used to initiate the paths setup. Optical paths can then be maintained as *label-switched path* (LSP).

In optical networks, multiple physical links may exist between a client and the adjacent network border node or between adjacent network nodes, respectively. For routing purposes, multiple 'data' links may be combined to form a single, so-called *traffic engineering* link (TE-link). This summarization mechanism reduces the routing information to be disseminated through the sub-network. The *link management protocol* (LMP) [11] that runs between neighboring nodes can be used to manage TE-links. Furthermore, it also supports supervision of control channel connectivity, verification of the physical connectivity of transmission links (in IETF terminology: data-bearing channels), correlation of link property information, and the management of link failures. LMP is defined in the context of GMPLS, but is specified independently of the GMPLS signaling specification since it is a local protocol running between data-plane adjacent nodes.

3.2. New network planning and design constraints

New constraints in network design and planning must be taken into account such as *traffic unpredictability* or *optical impairments*, but also new functionality sets are possible with the new technologies described in Section 3.1, such as switching not only wavelengths but groups of wavelengths simultaneously (wavebands) or fibers, or multiple optical granularities. These various issues are addressed in following subsections.

3.2.1. Traffic unpredictability

The emergence of the Internet and related applications are causing a revolution in telecommunications. It has become clear that the common traffic convergence layer in communication networks is going to be IP, the reason being that practically all forms of end-user communications today make use of the ubiquitous TCP/IP protocol. Furthermore, many new services and applications being offered are also IP-based. In contrast, the current network infrastructure has essentially been designed to carry voice traffic, which today is still the top revenue-generating service. However, data-traffic revenues will obviously overshadow voice revenues, as IP-based applications for voice, video, and other multimedia. This is already causing a fundamental paradigm shift in the sale of bandwidth and its provisioning control. Consequently, optical networks that carry this traffic must meet new requirements. New network design could be divided in two steps. In the first step, once the architecture of all NEs is done such as the node architecture, the fiber type, the recovery strategy, the design then tries to dimension the network so that it is able to route all the traffic between nodes. Clearly, this takes into account certain constraints, such as ensuring survivable failure scenarios, guarding physical-layer transmission quality and determining where regeneration is required in the transparent-network case. In this first phase, the major objective is to minimize cost by using optimisation algorithms. In the second step, a more extensive evaluation of the designed network can be performed such as the analysis of network behavior in dynamic traffic conditions. As such, the sensitivity of the network design to fluctuations could be studied. For both steps, traffic routing and dimensioning can be tackled either as one problem or as a sequence of sub-problems, e.g., first solving the routing in an un-capacitated network, followed by the dimensioning of the equipment, as based on this routing. Routing problems often rely upon principles of graph theory. Dijkstra's algorithm [12] finds the shortest route, other algorithms look for the shortest pair of disjoint routes or the K-shortest routes between two nodes [13]. In case of K eligible routes, an optimisation algorithm can pick out the best one considering the overall design objective. The wavelength-assignment problem can be considered assuming that wavelength-selection algorithms use some figure-of-merit to determine which wavelength along a specified route is best suited.

3.2.2. Optical impairments and planning constraints

Unlike opaque (fully-regenerated) optical networks in which all routes across the network are physically possible, planning of spatial routes must take into account optical transmission limitations arising, nonexhaustively, from:

- optical signal-to-noise ratio (OSNR);
- chromatic dispersion (CD);
- nonlinear effects (NLE);
- polarisation mode dispersion (PMD);
- crosstalk cumulation;
- optical filtering functions cascades.

In transparent network, the last one is a stronger limitation compared to point-to-point systems, because optical routes experience an average cascade of about 6 transparent (filtering) NEs, and up to 10 or 12 NEs at maximum (see Fig. 8) in core backbones. Depending upon channel spacing, such cascadability requirements could be approached for relaxed channel spacing, possibly with tighter laser/filter detuning tolerance or with degraded CD tolerance, whereas it is clearly to be discarded for very and ultra dense channel spacing, considering discrete multiplexing/interleaving technologies. In the latter case, either (flatter) band filtering/switching is then the alternative (different switching granularity), or, possibly, future integrated wavelength-selective switching technologies [14] could be another way to go for dense multiplexing, should these technologies prove in the future their effective cascadability and performance reliability when moving from today's infancy status towards volume manufacturing.

Taking into account all transmission limitations, when a spatial route has reached its maximum allowable reach, regeneration means need to be allocated to this route for further transmission, whether at the time of network planning on the basis of an average (static) traffic matrix, or when provisioning dynamically, in real time, an optical route. In order to be able to do this, it is needed to include optical-impairment parameters in the route's computation process, either for centralised-management systems, or in distributed-control schemes [15] with associated signaling, and to design optical engineering rules to be applied with such parameters as inputs. Especially, the impairments can be dependent on the vendors NE architectures (noise contribution for instance), and cascadability performance derived from the technologies specification. Therefore, optical

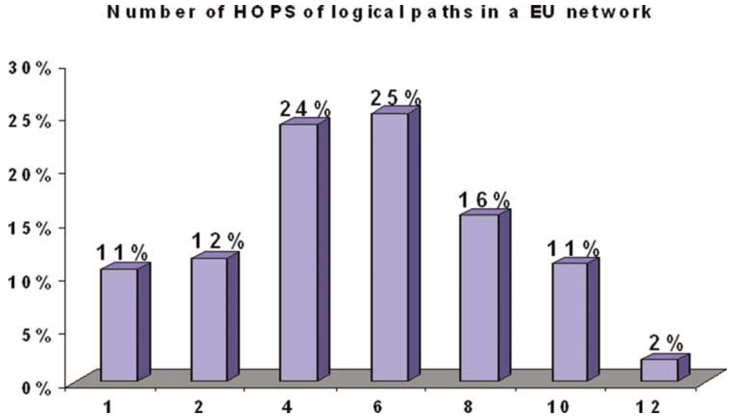

Fig. 8. Traffic statistic on hop number.

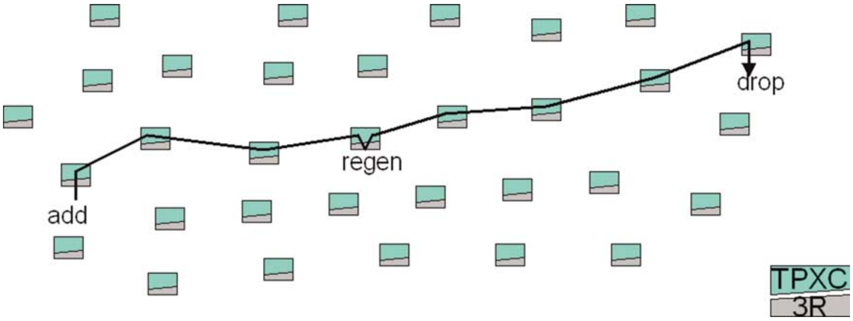

Fig. 9. Flat network design.

engineering rules will likely in the first time be set up for mono-vendor interworking. Indeed, although the status might change in the long term, multi-vendor interworking constraints are considered by industrials as too limiting for the first step and would result in bottom-leveled optical reach, thereby melting the possible cost savings of transparency. This topic is a hot research topic at present, and the design of reliable rules and identification of optical parameters for transparent multi-vendor interworking is still an open challenge, both technically and for standardisation. In the meantime, other multi-vendor inter-working schemes than at transparent coloured level can be proposed, as described next.

3.2.3. Network architecture and design constraints

When designing network architectures many choices are open. They can be cost-driven or operational constraints (management domains, multi-vendor interworking, ...) and offer the following (nonexhaustive) alternatives:

- design of a flat network, managed as a single-network partition by a single operator (Fig. 9);
- design of a two-layer hierarchical network with an express layer composed of fewer more distant network elements (Fig. 10). This case is likely to fit the transparent upgrade of an opaque legacy network;
- design a flat network composed of several interconnected partitions interconnected by opaque gateways (Fig. 11), either managed by different network operators, or composed of transparent partitions of different vendors.

This latter hypothesis could indeed be the shorter-term deployment scenario, before engineering rules are set up and standardised for transparent multi-vendor inter-working.

The functionality of NEs considered for each layer or partition can be of different types: lambda, waveband or fiber switching transparent photonic cross-connects (TPXC), or mixed, and associated or not to regenerative means (either fixed, or flexible with a regenerative WXC). Thus, some nodes could be transparent only, while other nodes could be hybrid, i.e., equipped with transparent switching and gather the regeneration means for a given network area (Fig. 12): the latter scheme has proved to reduce further the network cost with respect to a network only composed of hybrid nodes.

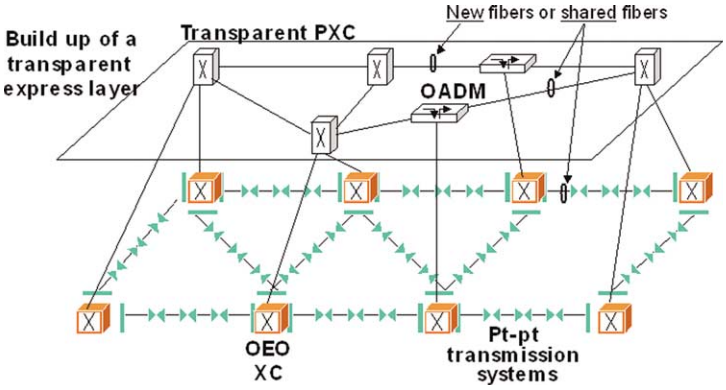

Fig. 10. 2-layer network (upgrade of legacy opaque network).

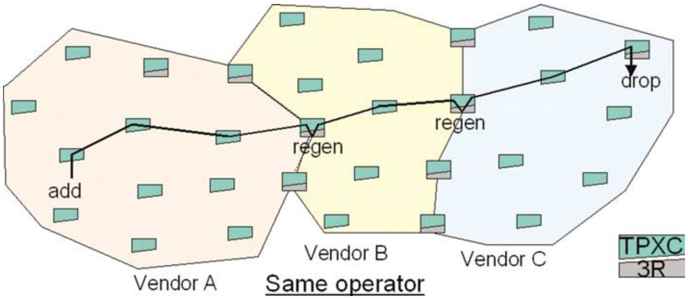

Fig. 11. Flat network, with opaque gateways between partitions.

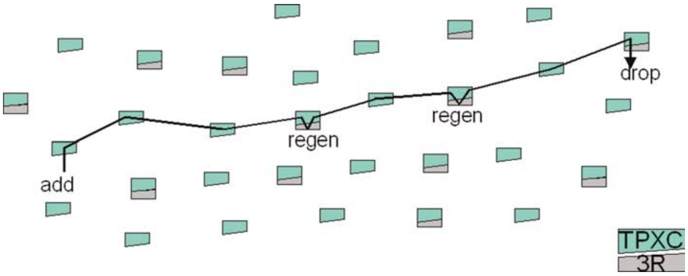

Fig. 12. Flat network, with sparsely distributed regeneration means.

In each case, the possible (cost) benefits of introducing transparency in each layer or partition must be assessed and must drive the architecture choices.

Protection schemes that can be supported may also drive towards one out of meshed- or ring-based fiber topology to be used to route the traffic, depending on the target network availability requirements. Depending upon protection schemes, the possibility to regenerate and convert wavelengths at some NEs will be helpful to reduce the contention in the network, to reduce the amount of fibers and associated transmission equipment, and for instance to better fill both fibers and wavebands between two regenerator points (waveband grooming, in case of band switching).

3.3. Optical engineering

Unlike in a point-to-point system which is designed to guarantee the correct operation of wavelengths having experienced the *same* path in a *same* transmission line, the design of transparent networks brings other issues due to the variability of paths through the network (experiencing different lengths, i.e., different CD compensation unmatch, OSNR, PMD ranges, ...): the architecture of the TPXC and the characteristics of compensation devices must fit the required ranges derived from these constraints.

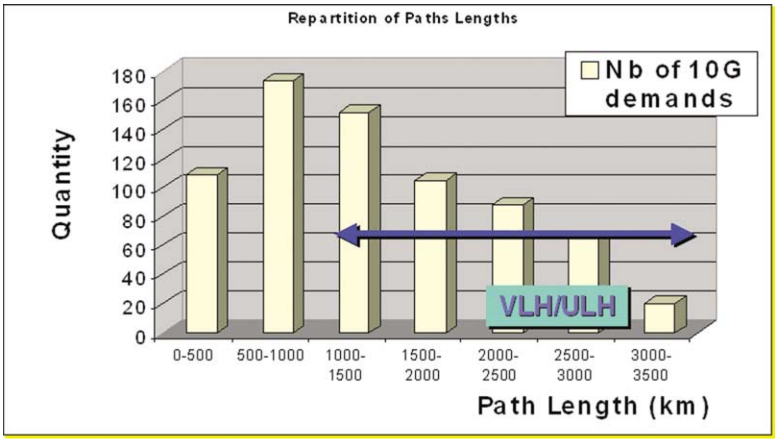

Fig. 13. Connections length distribution in pan-American network (impact on transmission performance requirement).

Secondly, events (failures, reconfiguration, especially in dynamic allocation scheme) from one link propagate to other links and impact other channels carried by the link, thus bringing the need for channel-power stabilisation means to prevent transient effects from impacting unchanged connections. Such means need to be fast enough to avoid/minimize transient degradations of unaffected or protected connections.

Additionally, degradations such as filtering cascades and crosstalk accumulation set cascadability limitations that need to be kept sufficiently low in the network design, through the enhanced performance specification of the building blocks.

To build transparent networks, the requirements imposed on transmission performance should fit (at most) the connections lengths (Fig. 13), and no longer the link lengths (case of opaque networks). While not critical for the design of metro networks, this requirement has much more impact on core networks: transmission performance requirement usually below 1000 km in an opaque USA backbone needs to reach several thousands of km in a wavelength-transparent backbone, but less in a band-switched network in which periodic band grooming at regeneration points is more cost-effective.

3.3.1. Line design issues

These observations result in both more powerful TPXC architectures (which need to support CD compensation with increased tunability range, clever and fast power stabilization techniques, etc.), and tighten performance specification (PMD, CD, noise contribution) to allow the cascading of TPXCs along an all-optical path.

3.3.1.1. Power management. Like dispersion, power management is crucial to maintain performances of the different channels and to avoid OEO regeneration. Indeed, OSNR and nonlinear impairments are directly linked to fluctuations of the power along the link.

Moreover, line aging, external perturbations or routing operations can dynamically change the optimal power repartition among channels. This equalization must be performed regularly along the line by *active gain equalization*. And for transparent optical network, *power equalization* should be done at each TPXC node (Fig. 14). Indeed, channels arrive with different origins and must be emitted with different powers potentially on different fibers.

3.3.1.2. Integrated software. With the TPXC nodes, commissioning and provisioning become very complex and time-consuming for network operators. Manual installation requires expert training. Then distributed software implementations are needed to turn up, upgrade and optimise the performance the systems and also to route the wavelengths.

The turn-up of DWDM systems can be easily done by adjusting the output power of amplifiers and the powers of the transponders.

3.3.1.3. Performance equalization. Due to different routes, wavelength channels have different performance. But to avoid regeneration, it is mandatory to equalize the different performances over all the wavelengths (Fig. 15). Bit error rate (BER) monitoring linked with power balancing enable to maximize performance.

3.3.1.4. Loading, protection and reconfigurability management. For complete flexibility, channels can be added and dropped everywhere in the transparent network (OADM). The scope is to maintain the performance of the channels during loading, reconfiguration phases. The solution is to keep constant the total power of the comb by using dummy channels.

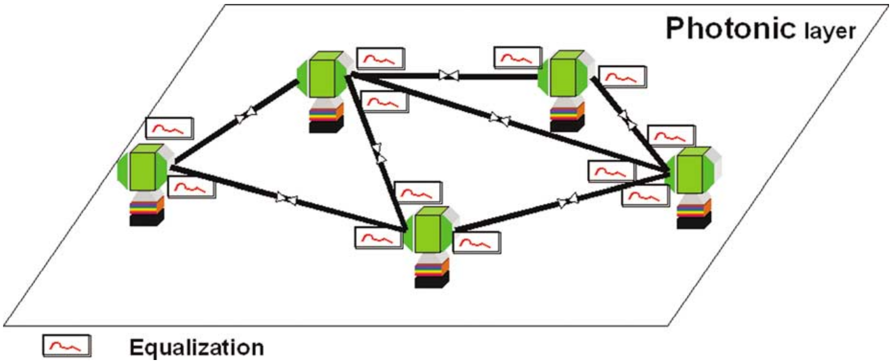

Fig. 14. Power management at photonic layer.

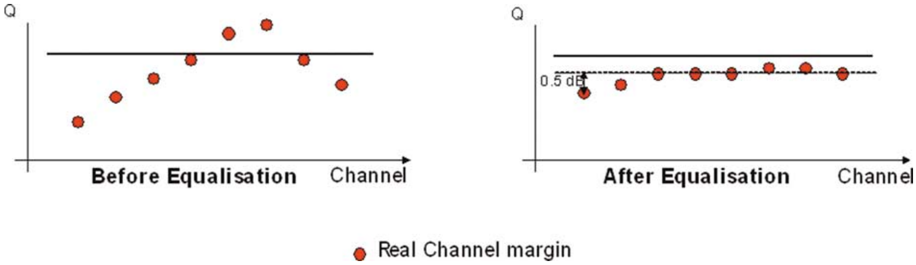

Fig. 15. Performance equalization.

3.3.2. *OADMs and TPXC functionality*

Considering the alterations to be experienced by the various signal routes across the network as described above, these OADMs and TPXCs must provide further functionality set than their basic logical functions of add/drop and routing. To an extent, they should include functions already available in line terminals of point-to-point transmission systems. These include:

- CD compensation, suited to the variability of residual dispersion among all paths that can be dropped or switched;
- internal amplification, with minimum noise contributions, not to set poor limits on the end-to-end connection transmission performance;
- equipment and network protection means;
- performance monitoring and fault detection, as well as connectivity monitoring to detect any misconnection/bad routing;
- adaptive loading schemes to allow for the proper operation of the network whatever the channel count.

3.4. *Network management and control issues*

Two main parameters will define the possible management scenarios to be supported, which are:

- Control scheme: centralised *transmission management network* (TMN [16]) approach versus *distributed control* (GMPLS [7]);
- Legacy: green-field network design versus upgrade of legacy network.

As previously described, it is likely that transparent networks will often be deployed as the upgrade of a first generation (opaque) optical network. In this case, interoperability constraints are a major requirement for managing the upgraded network. On the other hand, deploying a brand-new network allows one to consider integrated-management schemes, whether centralized or distributed. These cases are described in the two following sections, but as a preamble, transparency constraints in management schemes are first described.

The optical engineering rules taken for planning are applicable also for management of the network, should management be distributed (e.g., GMPLS) or centralized. The relevant parameters will be of the following type: OSNR, PMD, nonlinear phase, CD parameter, for instance. The provisioning of a working or protection transparent route includes feasibility calculation checks to ensure a route can be successfully provisioned. Ideally, this check should be based on live parameters of the network (if available) or possibly with parameters measured at installation or fixed parameters. In the case of a centralized management system, these parameters need to go through the TMN layers to reach the network management layer for processing. In a GMPLS control scheme, such data need to be exchanged between the nodes and processed in a de-centralized manner, which requires increased signaling bandwidth between network nodes (e.g., via the supervisory channels).

Because the measurement only concerns analogue optical parameters, it is not sufficient so far to guarantee signal quality, then complementary monitoring strategies can be proposed. Optical performance monitors (power, OSNR) at each node can poll several routes for diagnostic, fault localisation and performance only, but only BER measurements at egress or regenerators can trigger fast alarms in 3R regenerators or transponders.

3.4.1. Centralized management

In the traditional network management approach, the key information is grouped on a same decision point. For example, the provisioning performed at the *network management layer* (NML) exploits the complete and logical description of the network configuration provided by the *element Management Layer* (EML). In case of restoration schemes, the faults are also treated at the NML after alarm propagation before calculation of restoration routes.

The preferred and more secure way to transport the Management information is the signal overhead. The *digital wrapper* [5] of the optical channel has been defined for this very purpose. The key information and associated Management functions in the *optical channel overhead* (OCH-OH) can be divided into three elements (Fig. 16).

The '*OCH-Link Section*' applies the management functions related to the transport of the OCH on the optical transmission link. That includes especially the performance management functions of the OCH according to the OCH-link section definition (between two 3R-regeneration points). The performance management is mainly based on the 'OCH Signal Fail', 'FEC Corrected Errors' and 'FEC Uncorrected Blocks'. Several protection schemes can also be based on the OCH-Link Section management as *sub-network connection protection* (SNCP) schemes.

The '*OCH-connection monitoring section*' is involved in the configuration, fault and performance management aspects. These functions are applied for the OCH belonging to the same 'administrative domain'. The relevant data for the performance functions are the 'defect indication' and the 'code violation' or 'errored blocks'. For the fault function, an *alarm indication signal* (AIS) and a trace identifier were included for the configuration functions. Protection schemes, such as for example the OCH-SPRING (Optical Channel Shared Protection Ring), are applied on a restricted administrative domain and are managed from the OCH-connection monitoring section.

The '*OCH-Trail Section*' proposes all the management functions, which allow informing on the end-to-end OCH trail connection. These functions are similar to the functions on the OCH-connection monitoring excepted that they considered the complete trail connection without restrictions on the administrative domain. Protection schemes can also be managed by using OCH trail section overhead as for example to implement a dual ended scheme.

3.4.2. Distributed control plane

A distributed control plane can be introduced in either opaque, transparent or hybrid photonic networks.

In this scenario, some of the management functions can be maintained in the management plane (e.g., monitoring) whereas the control functions can be supported by the distributed control plane. In this context, some of the notions described in the previous paragraph can remain applicable in the management plane only.

The next generation optical networks will use transparent photonic cross-connects to route the light paths, i.e., the paths completely made by the same optical beam without being converted to electrical signal. However, physical constraints limit the range to which the beam can propagate. For example, when the OSNR becomes less than the limit which guarantees sufficient

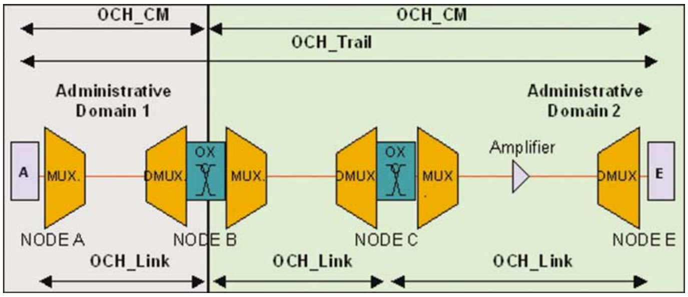

Fig. 16. Optical channel management view.

receiver BER, one cannot re-amplify the signal to go to further. For this purpose, an additional state information is required by the routing algorithm for each type of impairment [15] that has the potential of being a limitation for some routes. Moreover, it is likely that the physical parameters do not change value rapidly and could be stored in some database; however these are physical-layer parameters that today are often unknown at the required granularity. If the ingress node of a lightpath calculates a path, these parameters would need to be available at this node.

The transparency introduction requires the GMPLS protocols enhancements in order to cover this emerging trend and fulfil its role of a generalized control plane. Different topologies can be defined for this all-optical transport layer using GMPLS suite protocols for control plane.

3.4.2.1. Green-field network. This scenario assumes the new deployment/design of a network starting from scratch. The network can be composed of TPXC nodes, which are basically composed of demultiplexers/optical-matrix/multiplexers. The TPXC is associated to transponder resources for Add/Drop and potentially for transit traffic regeneration.

In such an all-optical, transparent network (Fig. 17), the traffic demands are routed individually and transparently from the source node, until transmission limit is reached. The signal is then regenerated (thanks to the associated 3R means of *re-amplifying, reshaping and retiming*) at the further reachable TPXC node and keeps on propagating transparently (or possibly via additional regeneration points) up to the final destination node.

Using this model, the regeneration resources are then dispatched at every network node. This architecture which is referred to in [17] as *hybrid photonic networks* could use only one control plane that is able to master both devices (All-optical [TPXC], regenerating [3R] switches). In such an architecture (Fig. 17), the GMPLS *routing engine* (GMRE) has the possibility to use proprietary protocol to carry out the inter-working between these devices.

Another approach for introducing transparency, discussed by IETF, is based on '*network partitioning*'. A partition (or domain) is defined as an all-optical transparent portion of the network, delimited by fully regenerative nodes. Within each area, any pair of nodes can exchange traffic fully transparently (no regeneration will be required), but paths spanning two domains will be regenerated at opaque gateways.

For these two alternatives, the GMPLS can be easily adapted for the transparent network. Thus, the shared protection scheme can be also introduced because the network operates as a single layer.

3.4.2.2. Network upgrade case. In this scenario, the introduction of transparency consists in upgrading a legacy-opaque network by creating new links, and potentially new nodes, or determining some existing node in order to build transparent network as an express layer (or 'super-backbone'). This multi-layer approach implies some issues introduction such as GMPLS functionality and protection implementation. As the existing opaque network could operate with GMPLS in limited domain, the transparent network could belong to another domain from the routing point of view, and operate with GMPLS taking into account the physical parameters to establish the lightpath. For this purpose, some protocols are required to allow the inter-working (UNI) between the two layers. This overlay model uses the transparent network as a master for light path establishing request, but as a slave for regeneration demand. This interface requires a definition of some parameters (like regeneration availability) to be flooded between the opaque and the transparent layers. On the other hand, an important question is in which layer the recovery actions are made. It is preferable to launch these recovery actions at the transparent layer because the recovery operates likely at a coarser granularity.

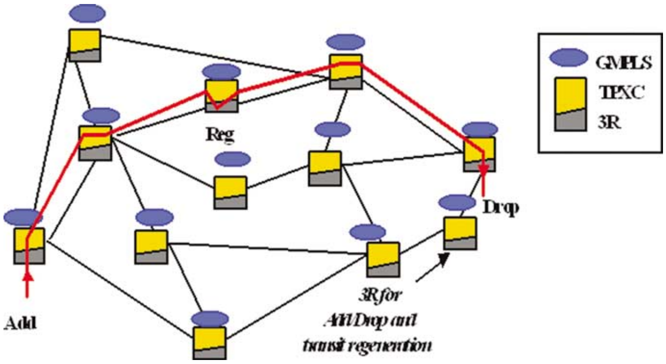

Fig. 17. Flat network design with single control plane at each node.

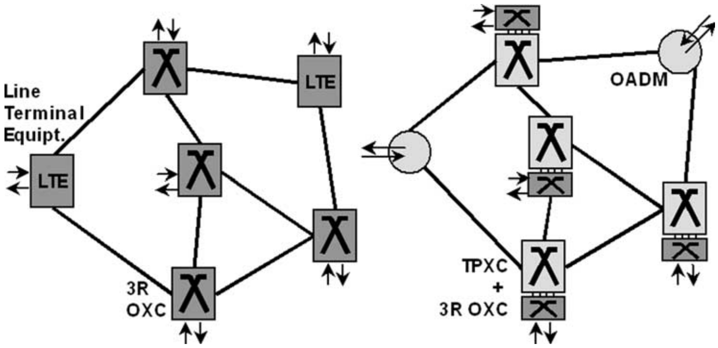

Fig. 18. Models for opaque (left) and transparent (right) networks.

4. Next-generation core networks

In the evaluation of optical network performance, design and planning activities, as well as simulation studies, become mandatory for a consistent evaluation of the real impact of equipment and behavior of tailored network protocols/algorithms. Since transponders are still fairly-expensive devices, an opaque long-haul network is a costly approach. Alternatively, transponders can be allocated only in these places where required with regards to signal degradation. In that case, planning of the locations where such regeneration should take place is also part of the network-design process.

The transparent network could be operated with wavelength, waveband or even fiber granularities. In the waveband case, a band path is defined as a path between two 3R regeneration points which follows its path completely in an optically transparent manner. Consequently, wavelengths channels in a band are not changed along this band path, neither multiplexed or de-multiplexed. An intermediate, cost-effective grooming strategy, is based on wavelength grouping in the regenerative nodes. At the node, the band structure changes and new band path is created. With band-grooming at intermediate regeneration points, bands are better filled, but the drawback is that the network management and protection becomes somewhat more complex. In the opposite, in the case of end-to-end path grooming, only wavelengths which have the same source and the same destination can be groomed into the band. In that case, the band are less filled, especially in networks with a light traffic load.

4.1. Case studies and conclusions

The analysis of different representative networks with real characteristics (traffic demands, fiber topologies, protection needs), spanning from pan-American (meshed or composed of interconnected rings) to pan-European backbone networks and national backbones has been very instructive for deriving useful conclusions. Various hypotheses of network element functionality were considered (all opaque NEs, opaque cross-connects with OADMs, wavelength TPXCs with wavelength OADMs, band TPXCs with band OADMs, with various levels of flexibility), including the suited protection schemes in each case, as depicted in Fig. 18.

Several transmission systems have been considered on 1.5 µm fiber (SMF) (among other): either LH or VLH links with EDFA amplifiers achieving distances without Raman amplification up to 1500 km, or ULH links thanks to Raman amplifiers and automatic gain equalisation (AGE) spanning 4000 km, both for 80 channels at 10 Gbit/s with 50 GHz spacing. The results presented here focus on SMF-based systems.

Although only lambda routing is relevant in an opaque context, transparent routing can benefit from band granularity. Fig. 19 represents the network cost, in one of the network example studied. Three cases are represented and compared: opaque network, and transparent Networks using different granularities of TPXC-lambda, bands of optimum number of channels. The opaque network cost is considered for comparison reference. Numerous analyses run on different networks showed however mainly the same trend, with a superior cost saving with band-switching versus transparent lambda-switching, especially with bands of 7–8 channels (in backbones with channel spacing of 50 GHz). The higher cost-effectiveness of band switching is explained by the improved cost-sharing of the optical switches by channels within same band, whereas this is not true when single channels are switched separately. It also shows that transparency benefits vary a lot depending on many network parameters such as the traffic load, the type of transmission system (performance/cost ratio), and other very sensitive cost hypotheses. Analysing the details of the cost breakdown in each case allows to observe that:

- 75% of the opaque network cost is due to transponders only;
- transparent networks bring this cost down to 1/3 of total, whereas other costs increase (line transmission equipment and switching nodes) when moving to transparency, keeping total cost below that of the opaque case. Indeed, the less optimised

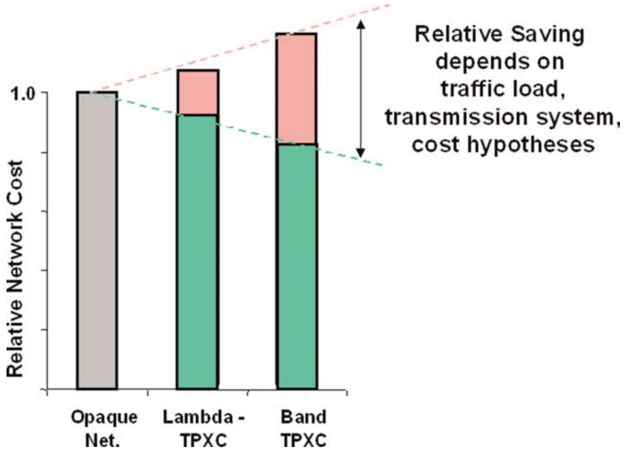

Fig. 19. Typical trend of network costs distributions (LH Transmission System on SMF).

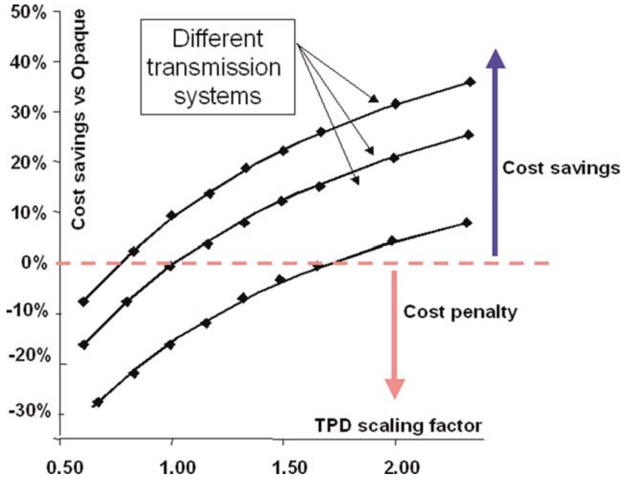

Fig. 20. Transparency cost savings variation range.

fiber filling pushes for an increased amount of fibers to be used, although more than compensated by the transponders reductions;

– regenerative WXC sizes are significantly reduced in the case of a transparent network, versus the opaque network case.

One may believe that the most efficient transmission system leads to the most cost-effective solution, as more OEO conversions are avoided. But if we compare the cost of ‘*band-switched*’ transparent networks associated with LH or ULH transmission capabilities, it can surprisingly be observed that the lower network cost comes from the more standard transmission system, i.e., the LH one. The higher cost of the network with ULH transmission is mainly due to the difficulties in grooming traffic into bands or converting wavelength when regeneration points become rare, whereas regenerating more often allows to better fill the bands and fibers, thus optimising the amount of transmission equipment. This conclusion on the transmission performance requirement for band-switched transparent networks is highly relevant and strategic.

It is all the more so interesting to observe that band switching allows the optimum cost, since band cascadability will be drastically relaxed compared to lambda-switching. Nevertheless, the conclusion could be refined if we consider more advanced, potentially cost-effective technologies, such as integrated wavelength switches [14], for wavelength-TPXC.

It is relevant to investigate the impact of the transponder relative cost on transparency benefits. Fig. 20 shows a typical variation range of transparency benefits, as a function of the transponder's cost scaling factor. As expected, the transponder cost indeed has a strong impact on transparency benefits, but it is more relevant to observe that in some cases it can be reached values as high as 30% to 40% network cost savings, provided the optimum transmission system is chosen. Conversely, this figure also shows that an unsuited transmission system (performance/cost ratio) can lead to negligible or ‘negative cost savings’ versus the opaque reference case. We also observed that the conclusion is very dependent on many parameters of the network: traffic load, traffic distribution, fiber topology, line versus terminals cost ratio, network partitioning, etc. so that networks should be analysed on a case by case basis before the winner scenario can be identified for each network.

5. Next-generation metropolitan networks

The context of metropolitan ('metro') networks is somewhat different from the backbone, for several reasons. First, the capacities and aggregation levels are lower because the traffic processing is closer to end users and applications. As a result, we observe a much wider range of signal formats to be transported than we could observe in backbone networks in which SDH/SONET was dominant: Ethernet, Gigabit Ethernet, TCP/IP, ATM, ESCON (*entreprise systems connection*), Fibre Channel and other formats are to be transported, with a diversity of related bit rates (from Mb/s to 10 Gb/s). These client formats are to be groomed onto wavelengths and the grooming capabilities of the transport equipment in dynamic conditions will be a key factor for the network performance. To assess this, network planning analyses under either dynamic traffic conditions or under variable/random traffic upgrade steps are required with new, specific, dedicated tools.

A main characteristics of metro optical networks is that rings are largely the most common topology, whereas ring interconnections and meshed networks can also be encountered but remain so far more rare. It is however expected that mesh topologies will become more frequent in the future through the increase of capacities to be transported and through network size extensions to further/better cover traffic-generating areas, rather than through the inefficient addition of more nodes in single rings. It remains that in metro optical networks, we can currently observe (Fig. 21) that the optical routes are traveling through very few nodes, fewer than in backbone networks, with paths including in average 2 intermediate transit nodes (versus 6 in backbones), which suggests that transparency benefit might be smaller. Also, transmission distance requirements currently target one (or two) hundred kilometers, with in average much shorter connection lengths, and short span lengths (<20 km in average, up to 80–90 km max).

Another characteristics of metro networks is the specificity of their traffic distribution, which has moved from almost fully-hubbed to a balanced sharing between hubbed and logically meshed traffic demands. Additionally, it is likely that the greater proximity to end applications, less groomed and averaged among larger capacities, increases the 'burstiness' of the traffic to be transported, thus creating a larger variability of the traffic. Because of this, it is commonly believed that distributed control schemes might bring higher benefits in metropolitan optical networks than in core backbones, although such a statement remains still very prospective and not based on any real traffic dynamic behavior observed in live networks. Simultaneously, it can be expected that most of the dynamic behavior of client applications will affect the sub-lambda grooming layers more than the optical layer itself, so that the efficiency of sub-lambda grooming effectiveness (again!) in '*dynamic*' traffic conditions will be one of the key factors to network cost-effectiveness and performance. In this context, we observe today several more or less competing trends:

- additional optical functionality set are being added to SDH/SONET multi-service grooming platforms;
- additional edge grooming functions (SDH, Ethernet, ATM, TCP/IP) are being progressively introduced in optical layer networking solutions;
- additional optical functionality set are being added to edge IP routers and switches. These new optical functions can extend to advanced optical packet and burst switching as a long term possible evolution.

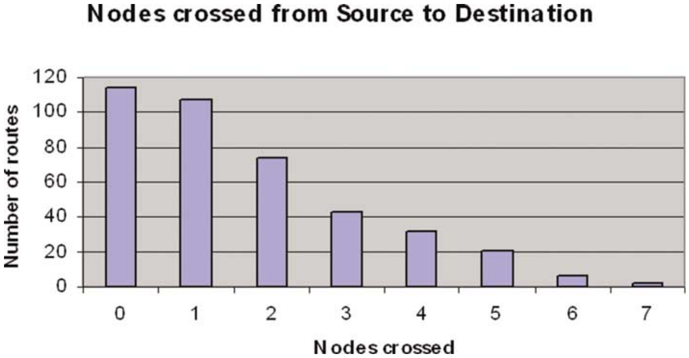

Fig. 21. Typical number of hops in a meshed optical metro network.

As of today the convergence or emergence of any major trend among these is not clear, but as far as optical functions are concerned, the emergence of ‘coarse’ WDM technologies (up to 16 channels spaced by 20 nm across the 1300–1600 nm window) for very low-cost applications at 2.5 and 10 Gb/s is clear in the metro access area [18].

6. Conclusions

Various aspects of network design have been discussed, both for ‘*opaque*’ and ‘*transparent*’ optical networks (‘*first*’ and ‘*next*’ generation networks, respectively). New optical technologies and control schemes will soon allow to build dynamically-flexible and more cost-effective photonic backbones and metropolitan networks. These could also later support interworking between transparent network elements from different vendors, but there is still clearly a significant effort and time before multi-vendor transparent interworking comes to a reality: this will be a long process. However, the more cost-effective networking solutions are yet not so obvious between electrically-switched (or regenerated) and transparent scenarios, and as we discussed, transparency expectable benefits are still very unsure and variable depending on network cases and optical technologies costs. Considering the present visibility we have, photonic technologies are not yet sufficiently ‘cost-killing’to make it obvious moving up to transparent networks. But increasing traffic loads in the networks and cost ratio evolutions between electronics and optics might change this present view.

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