

# Impairment-Aware Routing and Wavelength Assignment in Translucent Networks: State of the Art

Maurice Gagnaire and Sawsan Al Zahr, *Télécom ParisTech (ENST)*

## ABSTRACT

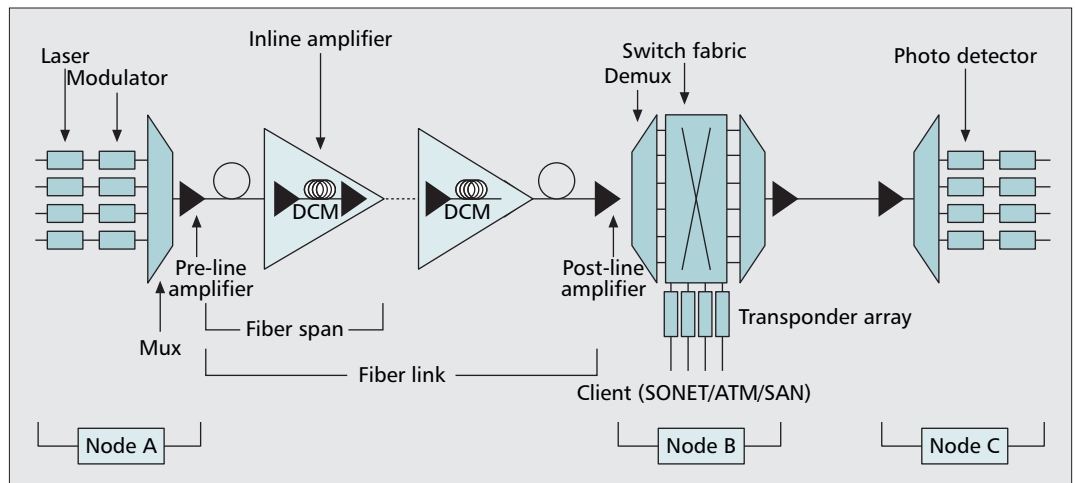
In the last 15 years, numerous investigations by both academia and industry have been carried out in the field of all-optical WDM networks' design. In all-optical — or transparent — WDM networks, data is transmitted from its source to its destination in optical form, switching/routing operations being performed in the optical domain without undergoing any optical-to-electrical conversion. Optical transparency may considerably reduce network infrastructures' cost and extend the range of services offered by the carriers. Designing an all-optical network consists of assigning to each traffic demand an end-to-end optical circuit, also called "lightpath." In such networks, the problem of routing and wavelength assignment (RWA) aims to find an adequate route and an adequate wavelength for each traffic demand subject to the wavelength continuity constraint and limited network resources. The feasibility of the obtained lightpaths in terms of admissible quality of transmission (QoT) presents another difficulty. Indeed, according to the state of technology, various physical impairments degrade the quality of the optical signal along its propagation. Optical fibers and optical amplifiers as well as optical switching/routing nodes impact on end-to-end QoT. In this context only translucent networks are achievable, for instance, at a pan-European or pan-American scale. A translucent network uses electrical regenerators at intermediate nodes only when it is necessary to improve the signal budget. The cost of a network is roughly proportional to average number of input/output ports of a node. Knowing that today an optical port is five times less expensive than an electrical one, sparse regeneration allows translucent WDM networks to meet the QoT requirements and achieve performance measures close to those obtained by fully opaque networks at much lower cost. In this article we propose a state of the art in the field of impairment-aware RWA (IA-RWA), starting from the case of predictable traffic demands to the open problem of stochastic traffic demands. An economic analysis of the IA-RWA problem is proposed to justify the concept of translucent networks. The case of multi-

domain lightpath establishment is also considered. Several examples of still open problems are mentioned in the article. Most of the concepts and results presented in this article refer to the FP7 DICONET European project in which the authors are involved.

## INTRODUCTION

The emergence of wavelength-division multiplexing (WDM) multiplexers in the 1990s enabled a strong boost in the capacity of optical fibers, while electrical regenerators that were used roughly every 70 km (43 mi) have been replaced by optical amplifiers. In parallel, numerous advances have been achieved in the field of optical switching and quality of transmission (QoT) monitoring. The feasibility of optical cross-connects (OXC), optical circuit switches (OCS), and optical packet switches (OPS) has been demonstrated in the last decade. Hardware technologies for OXC and OCS are mature. Studies like those carried out within the Dynamic Impairment Constraint Networking for Transparent Mesh Optical Networks (DICONET) project are dedicated to the specification of a control/management plane for dynamic lightpath establishment (see the article of our colleagues included in this issue). In this context two types of traffic demands, either static or dynamic must be considered. In the first case traffic demands are semi-permanent, with routing and wavelength assignment (RWA) mainly used for network planning. In the latter case the lifetime of a traffic demand is finite while remaining larger than network round-trip time. The specification of a signaling channel is necessary for automatic dynamic lightpath establishment. Either predictable or stochastic traffic demands are considered in the case of dynamic traffic. It has been shown that solving the RWA problem under dynamic and predictable traffic demands, referred in the literature to as scheduled traffic demands (STD), may be carried out offline. In that case RWA is one of the main functionalities of the management plane. When assuming dynamic and predictable traffic demands, RWA consists of a global optimization tool that compares the costs of all feasible RWA solutions for

The analog optical signal is subject to two main types of attenuation: intrinsic and extrinsic. Intrinsic attenuation is due to the absorption of the optical power in silica. Extrinsic attenuation is due to irregularities in the section of the cylindrical geometry of the fiber.



■ Figure 1. Configuration of a WDM transmission system.

the whole set of traffic demands. A solution's cost is expressed in terms of required optical and electrical ports. Dynamic and stochastic traffic demands are characterized by an unknown arrival time and a random lifetime. This unpredictability of the traffic imposes on-the-fly RWA applied to individual demands. This task must be done in real time and is the main functionality of the control plane. Although all-optical wavelength converters are technically feasible, their cost remains prohibitive for carriers. This is the reason two main constraints must be considered when solving the RWA problem: wavelength continuity and the limited number of optical channels that may be multiplexed onto the same fiber.

Only since 2000 has real attention been paid to the impact of transmission impairments on the feasibility of solutions provided by RWA [1]. According to the state of the technology, various factors degrade the quality of an analog optical signal along its route due to propagation itself, multiplexing, amplification, and switching. Many investigations have tried to include QoT constraints in RWA strategies; these constraints may be classified into linear and nonlinear impairments. Linear impairments are such that their impact on QoT is independent of the power of each of the optical channels transported on the same fiber. At the opposite, nonlinear impairments are strongly dependent on the accumulated power and on the individual power of the optical channels transported in parallel on the same fiber. The higher the bit rate of the data transported by a lightpath or the larger the length of the route adopted for a lightpath, the higher the required optical power at the transmitter. In other terms, under linear impairments QoT can be evaluated individually for the different optical channels sharing the same fiber. This is not the case under nonlinear impairments, wherein the QoT of each optical channel transported on a fiber depends on the number, value, and power of the other channels transported simultaneously on the same fiber. Impairment-aware RWA (IA-RWA) consists of solving the RWA problem while taking into account QoT constraints. Today, the great majority of the investigations

on IA-RWA are dedicated to static traffic. The case of IA-RWA with dynamic traffic remains widely open to further study; it is a key objective of the DICONET project.

The aim of this article is to provide an overview of the state of the art of IA-RWA. We recall the main physical layer impairments to be considered for QoT evaluation. As mentioned in the abstract, full optical transparency is in practice not achievable with the state of the technology. This is why the concept of a translucent network has been introduced. We discuss the necessary economical trade-off for carriers between opacity and transparency. Numerous technologies enable the impact of physical layer impairments on QoT to be reduced. Meanwhile, beyond a certain distance, electrical regeneration becomes mandatory if QoT at intermediate nodes degrades beyond an admissible limit. This limit is referred to as the Q-factor threshold. We also dedicate a section to static IA-RWA. The main task of static IA-RWA is to determine the most judicious locations for electrical regeneration in the network. We then deal with the more prospective problem of dynamic IA-RWA. We propose an introductory analysis of IA-RWA in the context of multidomain lightpath establishment. We then conclude this article.

## PHYSICAL LAYER IMPAIRMENTS

Figure 1 recalls the typical configuration of a point-to-point WDM transmission system. In carriers' networks optical fibers are set in pairs between adjacent nodes, a fiber for each direction of transmission. At the source node, parallel optical channels generated by fixed transceivers are multiplexed onto a standard single-mode fiber (SMF). An optical pre-amplifier (post-amplifier) is used at the input (output) of each switching node. The WDM multiplex is regularly re-amplified at amplification sites spaced on average 80 km apart. A span corresponds to the section of fiber separating two adjacent amplification sites. An optical link is the set of spans used between two adjacent switching nodes. A lightpath generally overlaps several links; intermediate nodes (electrical cross-connects [EXCs] or OCSs) are in charge of lightpath routing.

QoT is evaluated at the destination node of a lightpath by computing the Q-factor, which is directly linked to the bit error rate (BER) and optical signal-to-noise ratio (OSNR). As an indication, a Q-factor of 12.5 dB corresponding to a BER of  $10^{-5}$  is frequently considered the Q-factor admissibility threshold when forward error correction (FEC) is applied.

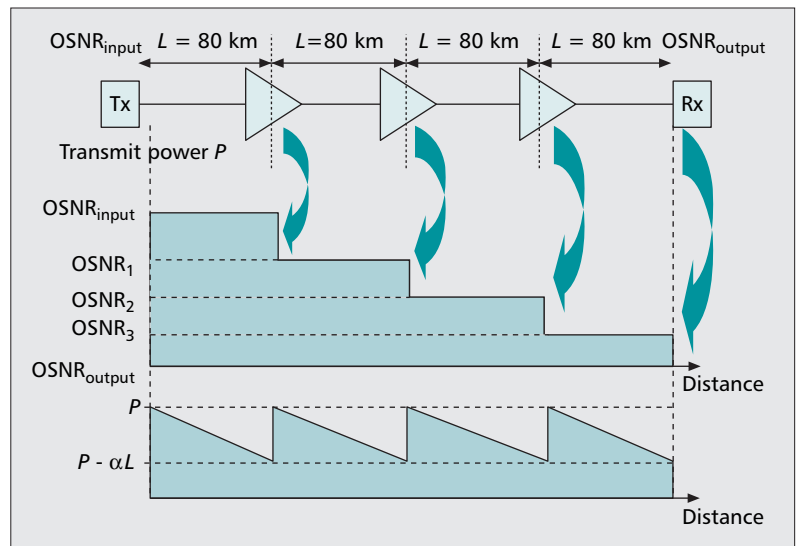
### LINEAR IMPAIRMENTS

**Attenuation ( $\alpha$ ):** The analog optical signal is subject to two main types of attenuation: intrinsic and extrinsic. Intrinsic attenuation is due to the absorption of the optical power in silica. Rayleigh scattering due to the interaction between photons and silica molecules causes scattering in multiple directions. Attenuation due to Rayleigh scattering is more sensitive for short wavelengths (in nanometers) than longer ones. Extrinsic attenuation is due to irregularities in the section of the cylindrical geometry of the fiber. Both attenuations are expressed in dB per kilometer. Global attenuation  $\alpha$  of SMF fibers (other types of fiber can be used for very long-haul transmission systems) is about 0.2 dB/km

**Amplified spontaneous emission:** Erbium doped fiber amplifiers (EDFAs) are subject to spontaneous emission that corresponds to photons generated by the non-controlled return of excited electrons in Erbium ions to their stable state. Such photons do not coincide in time and phase with those belonging to the incoming optical signal. The impact of amplified spontaneous emission (ASE) is expressed in terms of OSNR. Even if one assumes perfect compensation for the attenuation of a span by an EDFA, the inverse of OSNR at the output of an EDFA is equal to the summation of the inverse of OSNR at its input and the ratio of the ASE power to the input power. ASE is related to the noise figure (NF) of the amplifier. Figure 2 illustrates the typical evolution of OSNR over multiple spans.

**Chromatic dispersion:** CD is due to the fact the various spectral components of a modulated analog optical signal do not propagate with the same speed in the fiber. This propagation speed disparity induces intersymbol interference (ISI) at destination. CD depends on wavelength and increases with distance. It is expressed in picoseconds per nanometer or kilometer. CD is considered as one of the most penalizing linear impairments on QoT. CD of SMF fibers is about +17 ps/nm.km.

**Polarization mode dispersion:** PMD is due to unpredictable birefringence in the fiber, this birefringence being due itself to the non-circularity of the core of the fiber. The fact the two orthogonal polarization directivities of the electro-magnetic field do not propagate at the same speed induces a phenomenon similar to ISI at the destination. Being expressed in ps per square root of km, the square of PMD value is additive with distance. As an indication, the International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) recommends, for a 2 Gb/s (10 Gb/s) channel, a limited cumulated PMD of 40 ps (10 ps) after 400 km of propagation. Unlike CD, PMD is wavelength-independent. PMD of SMF fibers is about 0.1 ps per square root of km.



■ Figure 2. Impact of EDFA's ASE on OSNR.

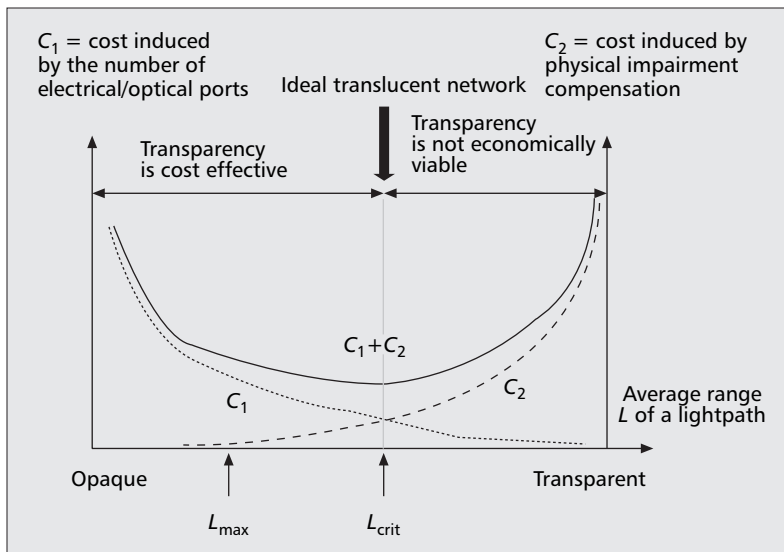
**Insertion loss:** IL corresponds to the difference between the power of the optical signal at the input and output of an opto-electronic device. IL expressed in dB is considered in the calculation of the power budget (OSNR) of a lightpath. The penalty induced by the transit through an OXC or OCS strongly depends on the hardware architecture of the switching fabric; it is evaluated in terms of IL.

### NONLINEAR IMPAIRMENTS

Nonlinear impairments may be classified into two categories. The first category refers to the impact of optical power on the fiber's refractive index. Such an impact is known as a Kerr effect. Three Kerr effects are distinguished: self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM). SPM induces a phase shift of the optical pulses. The other category refers to scattering effects between silica and optical signal. Stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) are the two scattering effects. In practice, the impact of SRS and of SBS on OSNR is negligible compared to SPM, XPM and FWM. FWM is the most penalizing impairment among Kerr effects. The cumulated impact of the various nonlinear impairments is in general expressed as a nonlinear phase shift ( $\Phi_{NL}$ ) expressed in rad/s.  $\Phi_{NL}$  depends on the value of the wavelength and is cumulative with distance.

### IMPAIRMENT COMPENSATION TECHNIQUES

In order to compensate for cumulated CD, each amplification site uses a dispersion compensation fiber (DCF) section with a strong negative CD of about -90 ps/nm.km. This DCF section is inserted between the two amplification stages of an amplification site. In current carrier networks, EDFAs operate in the C-band (1530–1560 nm) where attenuation is minimal. An EDFA enables up to 60 optical channels to be amplified simultaneously with a 40 dB global gain and a noise figure around 5 dB.



■ **Figure 3.** Opaque, translucent, and transparent networks.

### FLAT VS. NON-FLAT BEHAVIOR ASSUMPTION

In most studies optical fibers' CD and EDFA's penalty on OSNR are assumed to be flat, that is, independent of the wavelength used by the considered lightpath. In practice, this assumption is not valid. Hence, CD is wavelength-dependent. Similarly, the gain of an EDFA is not flat in the C-band. Wavelength allocation strategies may then have a strong impact on system performance [2]. Dynamic gain equalization (DGE) enables compensation for non-flat gain and wavelength-dependent NF of EDFAs.

### TRANSLUCENT OPTICAL NETWORKS

The amount and complexity of the equipment required in the network to compensate for QoT degradation increases with distance and bit rate. Thus, ultra long haul (ULH) equipment covering ranges from 880 mi (1500 km) to 1800 mi (3000 km) are much more costly than long haul (LH) transmission equipment operating from 90 mi (90 km) to 430 mi (700 km). The STM-16 and STM-64 standardized data rates at 2.5 Gb/s and 10 Gb/s, respectively, are currently widely deployed in LH systems. The first STM-256 equipment operating at 40 Gb/s more specifically dedicated to ULH systems are complex to design, mainly because of their sensitivity to nonlinear impairments. CD compensation and DGE are more complex and costly to deploy in ULH systems than in LH systems. In general, FEC techniques are strongly recommended in ULH or with STM-256 to prevent excessive BER at the destination. As an indication, current FEC enables BER to be reduced from  $10^{-5}$  to  $10^{-12}$ .

Figure 3 illustrates the principle of the necessary trade-off for a carrier between full opacity and full transparency. The horizontal axis refers to the average range  $L$  of the lightpaths on the considered network. The left side vertical axis corresponds to the cost  $C_1$  of the required optical and electrical ports provided by a solution of the RWA problem for a given set of traffic demands and a given physical infrastructure. The right side vertical axis corresponds to the cost  $C_2$

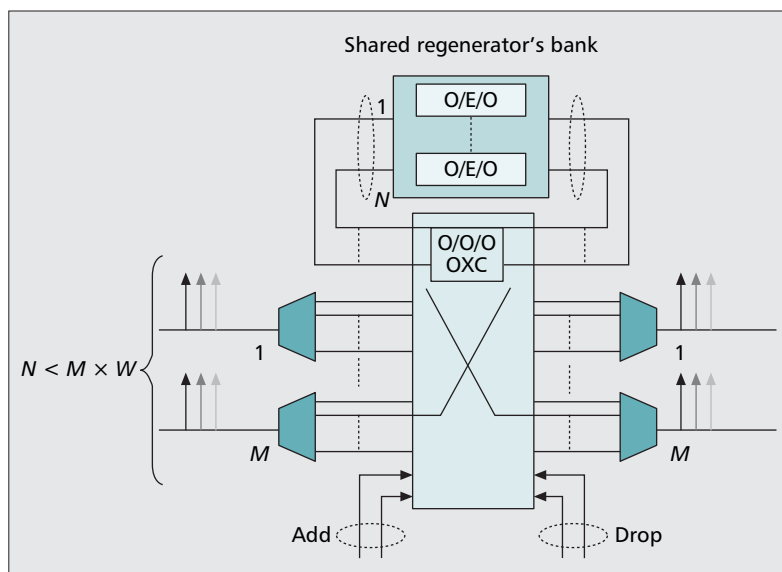
of the equipment to be used in the network to compensate for QoT degradation of the obtained lightpaths in order to get an admissible BER at the destination. In the case of a fully opaque network, electrical regeneration is systematically applied at intermediate nodes. Opaque networks correspond to current networks made of EXCs (e.g., a synchronous digital hierarchy [SDH] cross-connect) or electrical switches (asynchronous transfer mode [ATM], Ethernet, frame relay switches). Let us recall that in existing core networks, IP routers are interfaced with layer 2 switches in order to benefit from multiprotocol label switching (MPLS) constraint-based routing and traffic engineering. As mentioned in our introduction, the cost of an RWA solution is expressed as the cumulated cost of electrical and optical ports required in the network, the cost of an electrical port being around five times higher than the cost of an optical port. If the average range of the lightpaths is extended in order to overlap at least two hops, a fraction of the electrical ports initially required by the opaque architecture is replaced by optical ports, leading to a reduction of  $C_1$ . On one hand, we can say that the higher the lightpath range, the lower  $C_1$ . At the limit, full transparency reduces the number of electrical ports to a minimum corresponding to the transceivers used at the source and destination nodes. On the other hand, the larger the range of a lightpath, the higher the cost of the compensation techniques necessary to guarantee an admissible Q-factor at the destination. We see from Fig. 3 that for any network configuration there is a maximum distance  $L_{max}$  for a lightpath to operate without QoT compensation techniques. We can assume that QoT is at least acceptable on any single hop of the physical topology. Beyond  $L_{max}$ ,  $C_2$  increases progressively. In practice, in wide transport networks such as the North American backbone, full transparency is not achievable. As described later, various configurations are considered in the literature for translucent networks. In this section we consider the case for which all the nodes are transparent (e.g., OXCs or OCSs) and equipped with a pool of electrical regenerators. Figure 4 illustrates the architecture of a translucent node. The main problem of IA-RWA is then to determine the ideal sites where electrical regeneration is necessary in order to minimize the global cost  $C_1 + C_2$ . It has to be noted that electrical regeneration indirectly relaxes the wavelength continuity constraint, which then impacts on network congestion.

The right side of Fig. 3 corresponds to transparent networks. In existing LH networks, transparency may not be achievable for all traffic requests, as some demands are rejected by the management/control plane. We can conclude from Fig. 3 that theoretically, assuming translucent nodes, there is a critical length  $L_{crit}$  for which  $(C_1 + C_2)$  is minimal. As long as  $L$  remains under  $L_{crit}$ , transparency is cost effective. Beyond this value, transparency is economically not viable. The next sections show that determining the ideal location of electrical regenerator placement to reach this minimum is a complex objective because of the amount and nature of the parameters to take into account.

## STATIC IA-RWA

We have distinguished in our introduction three types of traffic: semi-permanent, dynamic and predictable, and dynamic and random. Adding to the complexity of the RWA problem the complexity of QoT management has driven most studies to investigate in a first step static IA-RWA [3–5]. In general, only the impact of linear impairments ( $\alpha$ , CD, PMD, IL) is considered. Few recent investigations take into account FWM in proposing suited wavelength assignment strategies [6]. For a given set of traffic demands and infrastructure, two main approaches are considered. The first consists of minimizing the global number of electrical regenerators; the second aims to minimize the number of regeneration sites. From the operator's perspective, we can say that the first approach is capital expenditure (CAPEX) driven, the second operational expenditure (OPEX) driven. The CAPEX-driven approach is intuitive. In this case with electrical regenerators placed sparsely in the network, we may expect that a certain number of nodes do not need a bank of electrical regenerators. Figure 5 depicts an example of results obtained with a CAPEX-driven IA-RWA [5] applied to the 18-node NSFNET backbone described in Fig. 6. In this network the average distance between adjacent nodes is 980 km, with the shortest/longest fiber link equal to 300 km/2400 km, respectively. We have generated 10 random matrices with 400 lightpath demands. The histogram of Fig. 5a depicts the mean number of regenerators at each node as well as the mean number of lightpaths transiting through each node. Although confidence intervals are not plotted in this figure, we have noticed that different traffic matrices with the same density result in light fluctuations in regenerator placement. This drives us to suggest that network topology rather than traffic distribution affects regenerator's placement. It seems that the nodes with the highest physical degree and highest average distance to their first neighbors should be equipped a priori with an electrical regenerator's pool. Thus, nodes 6 and 7 are good candidates to be equipped with the largest regenerator banks. Figure 5b illustrates the evolution of the global amount of regenerators vs. the Q-threshold. Intuitively, the higher this threshold, the higher the number of required regenerators.

We see that node 6 requires 23 regenerators, while nodes 2, 4, 16 and 17 need none. The CAPEX-driven approach is intellectually satisfying since it aims to minimize the global amount of electrical regenerators in the network. Meanwhile, it partially suits the operator's expectations in terms of OPEX. Indeed, electrical regenerators are not sold by the unit but in pools (e.g., cards with four regenerators may be found on the market). In addition, electrical regenerators need supervision by technicians of the operator since they are electrically powered. In general, technicians are not based at each node of the network, only at the most important ones. In that sense the OPEX-driven approach cannot be neglected, with the number

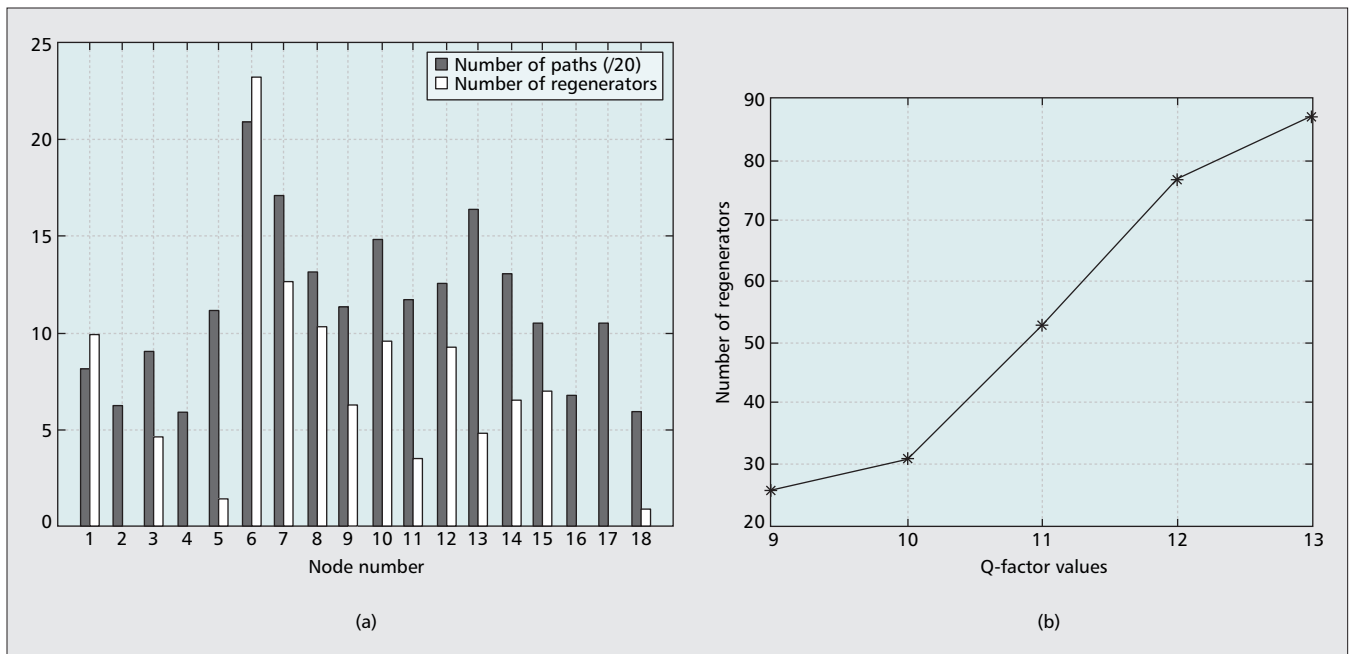


■ Figure 4. Architecture of a translucent node.

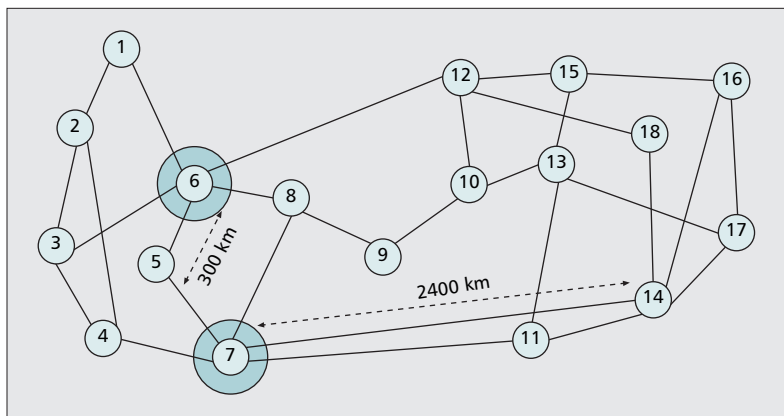
of sites to be supervised reduced in comparison to a spare electrical regenerator placement strategy. Ideally, both CAPEX- and OPEX-driven approaches are necessary. To the best of our knowledge, no investigation has been done from this perspective. Our laboratory works on this topic by considering Pareto optimization techniques.

## DYNAMIC IA-RWA

The problem of IA-RWA under dynamic traffic must distinguish between dynamic predictable traffic and dynamic stochastic traffic. As underlined in our introduction, predictable traffic may use IA-RWA algorithms comparable to those proposed for semi-permanent traffic since in both cases lightpath provisioning is computed offline. In this context time-space correlation between traffic demands can be exploited in order to optimize network resource utilization. IA-RWA under dynamic and stochastic traffic is of a different nature. In that case IA-RWA relies on dynamic lightpath establishment (DLE) for which the route and wavelength of an individual demand are computed on the fly at the instant of demand arrival [11]. Basically, a shortest path approach is adopted in considering the available resources at the instant the demand arrives. In practice we can consider that a carrier requires that its clients declare at the instant of generation of a stochastic demand the expected duration and capacity of this demand. Unlike static IA-RWA, dynamic IA-RWA does not have to solve the problem of electrical regenerator placement, but to decide which pre-installed regenerators must be used to guarantee an acceptable Q-factor at the destination. In other terms, during the network planning phase, the nodes susceptible to hosting the largest regenerator's banks after static IA-RWA could benefit from an overdimensioning factor to deal with future dynamic and stochastic traffic. In our example of Figs. 5 and 6, nodes 6 and 7



■ Figure 5. Electrical regenerator placement under a CAPEX-driven IA-RWA: impact of the  $Q$ -threshold.



■ Figure 6. The NSFNET network with 18 nodes.

could benefit from this overdimensioning. Judicious rules must be used to update the cost of the links when we apply the shortest path algorithm to a new incoming demand in order to favor the utilization of the available regenerators. In practice updating of the link cost needs an extended version of generalized MPLS (GMPLS) signaling. In [7, 8] two approaches are compared: the signaling and path computation element (PCE) approaches. It has been shown in the context of realistic traffic scenarios that the first approach is well suited to DLE. Meanwhile, it requires GMPLS control plane extensions. The second approach is apparently better suited to traffic engineering and does not require GMPLS control plane extensions. Nevertheless, it does not seem easily scalable to large backbone networks with high arrival rates of dynamic and stochastic traffic demands. In the context of the DICONET project, the impact of opto-electronic devices' ageing is viewed as a cause of traffic rerouting by means of dynamic IA-RWA.

## MULTIDOMAIN IA-RWA

The concept of island of transparency [9] is a first approach to facilitate multidomain IA-RWA in translucent networks. In this case the nodes at the border between two domains managed by two distinct operators are systematically opaque. Each carrier knows precisely the QoT inherent to each lightpath entering its network and arriving from a different domain. All the nodes of one domain except those located at the border are transparent and eventually equipped with a pool of electrical regenerators. Thus, any pair of nodes within an island of transparency may communicate transparently if it is physically possible. At the opposite end, any traffic demand from a source to a destination located on two different sides of the border is systematically subject to electrical regeneration at the border. A second approach authorizes transparent connections across a border between two domains. In this context the evaluation of end-to-end QoT may be a problem if the two operators are not equipped by the same vendors. Indeed, QoT thresholds may differ from one side of the border to the other. A third approach for multidomain IA-RWA could be based on traffic grooming. In [10] the  $k$ -center concept has been proposed as a clustering algorithm for hierarchical traffic grooming. The basic idea of this approach consists of positioning EXC/OXC multilayer nodes within a domain for both purposes: electrical traffic grooming and electrical regeneration.

## CONCLUSION AND OPEN PROBLEMS

IA-RWA may be seen as a form of cross-layer design associating QoT considerations from physics with advanced RWA optimization techniques. We have outlined the important progress

obtained in recent years in the field of static IA-RWA. Advances must be carried out in order to determine a reliable analytical expression of a global Q-factor, including the largest amount of linear and nonlinear impairments. This objective was partially achieved at the end of the RYTHME national research program funded by the French Ministry of Industry. Much work remains to be done in the domain of dynamic IA-RWA. The DICONET European project is focused on this problem. It also considers for the first time the impact of aging devices and systems in terms of QoT fluctuations. For that purpose, dynamic and nonintrusive optical network monitoring strategies have to be specified and evaluated both theoretically and experimentally.

## REFERENCES

- [1] B. Ramamurthy *et al.*, "Impact of Transmission Impairments on the Teletraffic Performance of Wavelength-Routed Optical Networks," *IEEE-OSA J. Lightwave Tech.*, vol. 17, no. 10, Oct. 1999, pp. 1713–23.
- [2] S. Al Zahr, M. Gagnaire, and N. Puech, "Impact of Wavelength Assignment Strategies on Hybrid WDM Network Planning," *IEEE DRCN Conf.*, La Rochelle, France, Oct. 2007.
- [3] S. Subramanian, M. Azizoglu, and A. Somani, "On Optimal Converter Placement in Wavelength Routed Networks," *IEEE INFOCOM*, vol. 1, Apr. 1997, pp. 500–07.
- [4] X. Chu, B. Li, and I. Chlamtac, "Wavelength Converter Placement under Different RWA Algorithms in Wavelength Routed All-Optical Networks," *IEEE Trans. Commun.*, no. 51, Apr. 2003, pp. 607–17.
- [5] M. A. Ezzahdi *et al.*, "LERP: A Quality of Transmission Dependent Heuristic for Routing and Wavelength Assignment in Hybrid WDM Optical Networks," *IEEE ICCCN Conf.*, Arlington, VA, Oct. 2006.

- [6] A. Bogoni and L. Potì, "Effective Channel Allocation to Reduce Inband FWM Crosstalk in DWDM Transmission Systems," *IEEE J. Sel. Topics in Quantum Elect.*, vol. 10, no. 2, Mar.–Apr. 2004.
- [7] E. Salvadori *et al.*, "A Study of Connection Management Approaches for An Impairment Aware Optical Control Plane," *Opt. Net. Design and Modeling Conf.*, Athens, Greece, May 2007.
- [8] P. Castoldi *et al.*, "Centralized Versus Distributed Approaches for Encompassing Physical Impairments in Transparent Optical Networks," *Opt. Net. Design and Modeling Conf.*, Athens, Greece, May 2007.
- [9] E. Karasan and M. Arisolu, "Impact of Wavelength Assignment Strategies on Hybrid WDM Network Planning," *J. Photonic Network Commun.*, vol. 3, no. 2, Feb. 2004.
- [10] B. Chen, R. Dutta, and G. Rouskas, "Clustering for Hierarchical Traffic Grooming in Large Scale Mesh WDM Networks," *J. Photonic Network Commun.*, vol. 3, no. 2, Feb. 2004.
- [11] Y. Pointurier *et al.*, "Cross-Layer Adaptive Routing and Wavelength Assignment in All-Optical Networks," *IEEE JSAC*, vol. 26, no. 6, Aug. 2008, pp. 32–44.

## BIOGRAPHIES

MAURICE GAGNAIRE (maurice.gagnaire@telecom-paristech.fr) is a professor at TELECOM ParisTech, France, where he leads a team working on grid networks, optical wireless access systems, and IA-RWA. He has authored and co-authored several books and numerous papers in these domains. He is involved in various European and national research projects. He graduated from INT Evry. He received his Ph.D. from ENST-Paris and his Habilitation from the University of Versailles in 1992 and 1999, respectively.

SAWSAN AL ZAHR (sawsan.alzahr@telecom-paristech.fr) is working as a research engineer in the optical networks research group at TELECOM ParisTech. She graduated from Damascus University, Syria. She received her M.Sc. and Ph.D. degrees from TELECOM ParisTech in 2004 and 2007, respectively. She is mainly working on translucent network planning with guaranteed quality of transmission.

*Much work remains to be done in the domain of dynamic IA-RWA. The DICONET European project is focused on this problem. It also considers for the first time the impact of devices and systems ageing in terms of QoT fluctuations.*