

# Physical Layer Impairment Aware Routing (PLIAR) In WDM Optical Networks: Issues and Challenges

Chava Vijaya Saradhi, *Member, IEEE*, and Suresh Subramaniam, *Senior Member, IEEE*

**Abstract**—In WDM optical networks, the physical layer impairments (PLIs) and their significance depend on network type—opaque, translucent, or transparent; the reach—access, metro, or core/long-haul; the number and type of network elements—fiber, wavelengths, amplifiers, switching elements, etc.; and the type of applications—real-time, non-real time, mission-critical, etc. In transparent optical networks, PLIs incurred by non-ideal optical transmission media accumulate along an optical path, and the overall effect determines the feasibility of the lightpaths. If the received signal quality is not within the receiver sensitivity threshold, the receiver may not be able to correctly detect the optical signal and this may result in high bit-error rates. Hence, it is important to understand various PLIs and their effect on optical feasibility, analytical models, and monitoring and mitigation techniques. Introducing optical transparency in the physical layer on one hand leads to a dynamic, flexible optical layer with the possibility of adding intelligence such as optical performance monitoring, fault management, etc. On the other hand, transparency reduces the possibility of client layer interaction with the optical layer at intermediate nodes along the path. This has an impact on network design, planning, control, and management.

Hence, it is important to understand the techniques that provide PLI information to the control plane protocols and that use this information efficiently to compute feasible routes and wavelengths. The purpose of this article is to provide a comprehensive survey of various PLIs, their effects, and the available modeling and mitigation techniques. We then present a comprehensive survey of various PLI-aware network design techniques, regenerator placement algorithms, routing and wavelength assignment algorithms, and PLI-aware failure recovery algorithms. Furthermore, we identify several important research issues that need to be addressed to realize dynamically reconfigurable next-generation optical networks. We also argue the need for PLI-aware control plane protocol extensions and present several interesting issues that need to be considered in order for these extensions to be deployed in real-world networks.

**Index Terms**—Wavelength division multiplexing, wavelength-routed optical networks, routing and wavelength assignment, optical performance monitoring, optical layer service level agreements, transmission impairments, quality of transmission, physical layer impairment aware routing, impairment constraint-based routing, regenerator placement algorithms, physical layer impairment aware control plane, GMPLS-based WDM networks, and IP over WDM networks.

Manuscript received 21 December 2007; revised September 2008.

Chava Vijaya Saradhi is with the Department of Broadband & Wireless Communications, Create-Net, Trento 38100, Italy (e-mail: saradhi@ieee.org).

Suresh Subramaniam is with the Department of Electrical & Computer Engineering, The George Washington University, Washington DC, USA (e-mail: suresh@gwu.edu).

Digital Object Identifier 10.1109/SURV.2009.090407.

## I. INTRODUCTION

**O**PTICAL networks employing dense wavelength division multiplexing (DWDM) and wavelength routing are potential candidates for future wide-area backbone networks. These networks provide high throughputs of the order of terabits per second, low error rates, low delays, and can satisfy emerging applications such as supercomputer visualization, medical imaging, and distributed CPU interconnect. Optical fiber transmission and communication systems have evolved tremendously over the past few years. In first-generation optical networks, fiber is used purely as a transmission medium, serving as a replacement for copper cable. These networks provide point-to-point transmission service. In these networks all switching and processing of the data is handled by electronics. The key evolutions within the optical networking space over the last several years, e.g. DWDM techniques and DWDM component technologies—such as amplifiers, lasers, filters, optical switches, etc.—have yielded unprecedented levels of bandwidth capacity over single mode fiber (SMF). These advances in turn have led to profound transformations at the networking layer, ushering in revamped, highly-scalable *on-demand* bandwidth provisioning paradigms. As a result, in second generation optical networks the switching, routing, and restoration functionalities are moved to the optical part of the network.

DWDM technology provides several wavelengths per fiber as logical channels. Present DWDM technology can allow transmission rates of up to  $10 \text{ Gb/s}$  per channel  $\times 40$  ( $80$ ) channels @  $100 \text{ GHz}$  ( $50 \text{ GHz}$ ) spacing and standard link distances up to  $600 \text{ km}$  with optical amplifiers placed every  $80 \text{ km}$ . A DWDM network consists of optical cross-connects (OXC) interconnected by point-to-point fiber links in an arbitrary mesh topology as shown in Fig. 1. In these networks a connection is referred to as a *lightpath*, and is established between any two nodes by allocating the same wavelength (if there are no wavelength converters available in the network) on all the links along the chosen route. The requirement that the same wavelength be used on all the links along the chosen route is known as the *wavelength continuity constraint*.

In a transparent optical network, if a lightpath is established between any two nodes, traffic between these nodes can be routed without requiring any intermediate optical-electrical-optical (OEO) conversion and buffering. For example, in Fig. 1, no buffering or OEO conversion is required at OXC 2 for the lightpath identified by  $(P_1, \lambda_1)$ , where  $P_1$  is the route

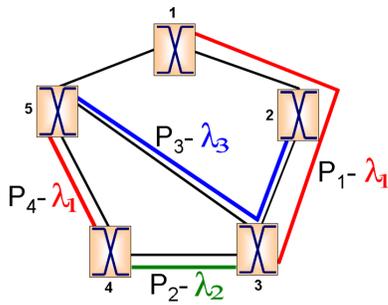


Fig. 1. An example of a transparent optical network with 3 wavelengths ( $\lambda_1 - \lambda_3$ ) and 4 lightpaths ( $P_1 - P_4$ ). The fiber-link between two OXCs is composed as shown in Fig. 2 assuming that the pre- and post-amplifiers are located at OXCs.

(1, 2, 3) and  $\lambda_1$  is the wavelength of the lightpath. In these networks, physical layer impairments (PLIs) incurred by non-ideal optical transmission medium accumulate along an optical path, and determine the feasibility or transmission quality of the lightpaths [1-4]. If the received signal quality is not within the receiver sensitivity threshold, the receiver may not be able to correctly detect the optical signal, causing the lightpath (and the corresponding reserved resources) to be useless. Hence, it is important for network designers and operators to know 1) various important PLIs; 2) their effects on lightpath feasibility; 3) PLI analytical modeling, and monitoring and mitigation techniques; 4) various techniques to communicate PLI information to network layer and control plane protocols; and 5) finally, how to use all these techniques in conjunction with control and management plane protocols to dynamically set up and manage optically feasible lightpaths. The purpose of this article is to provide a tutorial introduction to PLIs and survey the various related techniques (as discussed above) that are important to realize dynamically reconfigurable next-generation optical networks.

The PLIs and their significance depend on network type, reach, and the type of network applications. The network type could be opaque wherein an optical signal undergoes OEO conversion at all intermediate nodes along its path, translucent wherein an optical signal undergoes OEO conversion at some intermediate nodes along its path, or transparent wherein lightpaths are switched completely in the optical domain. The reach could be access, metro, or core/long-haul network, and the type of network applications could be real-time, non-real time, mission-critical, etc. In general, WDM links (see Fig. 2), which may introduce impairments into the signal path and consequently determine the maximum transparency length (the maximum distance or number of hops an optical signal can travel and be detected by a receiver without requiring OEO conversion) of an optical path depend on the following parameters: 1) the optical signal power, 2) the fiber distance, 3) type of fiber and design of links (e.g. dispersion compensation), 4) the number of wavelengths on a single fiber, 5) the bit-rate per wavelength, 6) the amplification mechanism and the number of amplifiers, and 7) the number and type of switching elements (nodes) through which the signals pass before reaching the egress node or before regeneration.

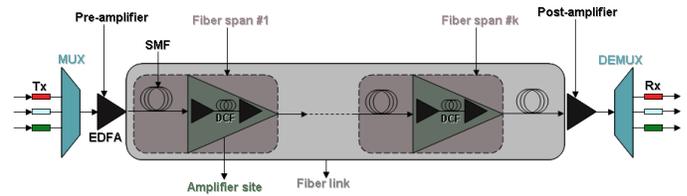


Fig. 2. Typical configuration of a WDM point-to-point system.

Some PLIs are unique to transparent networks (such as the filter cascading and crosstalk, etc.) and others may be present in all kinds of optical networks (such as dispersion). The impairments incurred by non-ideal physical layer elements accumulate along the path as the optical signal progresses toward the destination. The overall effect of individual PLIs determines the feasibility of an optical path; the received bit-error rate (BER) at the destination node might become unacceptably high. The lack of OEO conversion makes it necessary to consider impairment accumulation along the path. If OEO converters are present along the path, they can be used to clean up the signal, thus eliminating the need for considering the impairments. Introducing optical transparency in the physical layer on one hand leads to a dynamic, flexible optical layer with the possibility to add intelligence such as optical performance monitoring, fault management, etc. On the other hand, transparency reduces the possibility of client (electrical) layer interaction with the optical layer at intermediate nodes along the path. This has an impact [5] on:

- **Network design:** by adapting the size of the transparent domains to WDM system reach in such a way that there is no impact of PLIs in the design process;
- **Network planning:** for example, measurement and PLI databases, regenerator placement algorithms, PLI-aware network design algorithms;
- **Network management and control plane:** for example, dynamic provisioning of lightpaths with physical layer service level agreements (SLAs) or fault management.

In most routing and wavelength assignment (RWA) algorithms [6], the optical layer is considered as an ideal black box and it is presumed that lightpaths are feasible as long as wavelengths are available. However, this is not a reasonable assumption and may not be valid, particularly for longer hop connections in large core transparent networks. Therefore, it is necessary that RWA algorithms consider the physical layer limitations of the path to guarantee that the optical signal will reach the receiver with the desirable signal quality. In order to overcome the problems, several new RWA algorithms known as physical layer impairment aware routing (PLIAR) algorithms or impairment constraint-based routing (ICBR) algorithms are proposed and are discussed later in this article.

The rest of the article is organized as follows. Section II presents a detailed overview of various PLIs, their importance, and techniques to mitigate their effects. In Section III, we discuss issues in modeling, real-time measurement, and monitoring of PLIs and how these techniques help dynamic lightpath setup, their advantages and disadvantages. We discuss several optical component technological advances that

are required to achieve dynamically reconfigurable PLI-aware lightpath setup in Section IV. Several optical layer SLAs that are important in assuring the received optical signal quality are defined in Section V. Section VI provides a detailed PLI-aware static network design methodology and issues. We present several issues in dynamic routing for single and multi-domain networks in Section VII and Section VIII, respectively. In Section IX, we provide a brief overview of various PLI-aware wavelength assignment algorithms and discuss their benefits. We discuss the urgent need for standard control plane extensions, and present several possible alternatives and issues in Section X. We discuss the importance of PLI-aware fast failure recovery techniques and present several protection/restoration algorithms in Section XI. Other important issues such as efficient regenerator placement algorithms, effect of PLIs on increase in network capacity, physical layer security threats, optical grooming, etc., are discussed in Section XII. Finally, we conclude this article in Section XIII and provide directions for future research.

## II. OVERVIEW OF PHYSICAL LAYER IMPAIRMENTS (PLIs)

In this section we describe various PLIs, their effects, and mitigation techniques. PLIs are broadly classified into two categories: linear and non-linear impairments [1-4]. The terms linear and non-linear in fiber optics mean intensity-independent and intensity-dependent, respectively. The linear impairments are static in nature and non-linear impairments are dynamic in nature. The non-linear impairments strongly depend on the current allocation of route and wavelength, i.e., on the current status of allocated lightpaths. Moreover, the allocation of route and wavelength for a new lightpath request affects the existing lightpaths in the network.

### A. Linear Impairments (LIs)

**A) Power Losses:** Power loss can be defined as the optical loss that is accumulated from source to destination along fiber-links and is normally made up of intrinsic fiber losses and extrinsic bending losses [1, 7]. Intrinsic fiber losses are due to attenuation, absorption, reflections, refractions, Rayleigh scattering, optical component insertion losses, etc. Let  $P_{in}$  be the power launched at the input of a fiber of length  $L$ ; then the output power  $P_{out}$  is given by  $P_{out} = P_{in} \cdot e^{-\alpha L}$ , where  $\alpha$  is the fiber attenuation coefficient. The loss introduced by the insertion of optical components, such as couplers, filters, multiplexers/demultiplexers, and switches, into the optical communications system is called insertion loss and is usually independent of wavelength. The extrinsic losses are due to micro and macro bending losses. Additional losses occur due to the combined effects of dispersion resulting from inter-symbol interference (ISI), mode-partition noise, and laser chirp as discussed later in this section.

**B) Chromatic Dispersion (CD):** The degradation of an optical signal caused by the various spectral components traveling at their own different velocities is called *dispersion*. CD causes an optical pulse to broaden such that it spreads into the time slots of the other pulses. It is considered as the most serious linear impairment for systems operating at bit-rates higher

than 2.5 Gb/s. CD depends on bit-rate, modulation format, type of fiber, and the use of dispersion compensation fiber (DCF) modules. The total dispersion at the end of a lightpath is the sum of dispersions on each fiber-link of the considered lightpath, where the dispersion on a fiber-link is the sum of dispersions on the fiber-spans that compose the link (see Fig. 2). Most commonly deployed compensation techniques are based on DCF. Dispersion compensation techniques are useful in long-haul as well as metro networks. A fiber of length  $L_f$  and dispersion  $D_f$  can be compensated by using a spool of DCF of length  $L_c$  and dispersion parameter  $D_c$  such that the dispersion at the end of the fiber is close to zero and satisfies  $D_f L_f + D_c L_c = 0$ . Due to imperfect matching between the dispersion slopes of CD and DCF, some wavelengths may be over-compensated and some others may be under-compensated. Moreover DCF modules may only be available in fixed lengths of compensating fiber. Hence, sometimes it may be difficult to find a DCF that exactly compensates the CD introduced by the fiber, leading to residual CD. A typical value of dispersion compensation tolerance in commercial receivers is around  $\pm 800$  ps/nm for non-return-to-zero (NRZ) 10 Gb/s, while it is  $\pm 160$  ps/nm for optical duobinary (ODB) 40 Gb/s [7].

**C) Polarization Mode Dispersion (PMD):** Anywhere along a fiber-span, fiber could be non-circular, contain impurities, or be subject to environmental stress such as local heating or movement. These irregularities present obstacles to an optical pulse along its path. These obstacles cause different polarizations of the optical signal to travel with different group velocities resulting in pulse spread in the frequency domain, known as PMD. The differential group delay (DGD) is proportional to the square root of fiber length  $L$ , i.e.,  $\Delta\tau = D_{PMD} \cdot \sqrt{L}$ , where  $D_{PMD}$  is the PMD parameter of the fiber and typically measured in ps/ $\sqrt{km}$ . Because of the  $\sqrt{L}$  dependence, the PMD-induced pulse broadening is relatively small compared to CD. The PMD on a fiber-link is a function of PMD on each fiber-span and is given by  $PMD_{fiber-link} = \sqrt{\sum_{fiber-spans} PMD(f)^2}$  (see Fig. 2). The PMD at the end of a lightpath is  $PMD_{lightpath} = \sqrt{\sum_{fiber\ links\ along\ the\ route} (PMD(f))^2}$ .

The PMD values vary from fiber to fiber in the range of 0.01-10 ps/ $\sqrt{km}$  [7]. PMD becomes a major limiting factor for WDM systems designed for longer distances at higher bit-rates. The effect of second and higher order PMD becomes prominent at high-bit rates exceeding 40 Gb/s. PMD-induced problems can be reduced by shortening the optical transmission distance by placing OEO regenerators between two optical nodes. However, as most long-haul DWDM systems are multi-wavelength, the transmission link must first be demultiplexed, then regenerated, and then multiplexed again, which is a very expensive operation. Another alternative is to use dispersion compensation modules (DCM) at optical add/drop multiplexers (OADMs), optical cross-connects (OXC), or amplifier sites to compensate for accumulated PMD on an optical path. Because PMD effects are random and time-dependent, this requires an adaptive/active PMD compensator that responds to feedback over time. Hence, the most reliable and efficient PMD compensation technology is

the use of adaptive optics to realign and correct the pulses of dispersed optical bits.

**D) Polarization Dependent Loss (PDL):** The two polarization components along the two axes of a circular fiber suffer different rates of loss due to irregularities in the fiber, thereby degrading signal quality in an uncontrolled and unpredictable manner and introducing fluctuations in optical signal to noise ratio (OSNR). The combined effect of PMD and PDL can further degrade the optical signal quality. PDL is a measure of the peak-to-peak difference in transmission of an optical component/system w.r.t. all possible states of polarization and is given by  $PDL_{dB} = 10 \cdot \log(P_{Max}/P_{Min})$ , where  $P_{Max}$  and  $P_{Min}$  are the maximum and minimum output power, respectively. PDL mainly occurs in passive optical components. The most common passive optical components that exhibit PDL include couplers, isolators, multiplexers/demultiplexers, and photodetectors. The polarization scanning technique (PST) and the Mueller matrix method (MMM) are suitable methods for measuring the PDL [8]. While the PST is preferable for determining PDL at a specific wavelength, the MMM has clear advantages when PDL must be characterized at numerous wavelength points with equal spacing.

**E) Amplifier Spontaneous Emission Noise (ASE):** The primary source of additive noise in optically amplified systems is due to the ASE produced by the optical amplifiers used as intermediate repeaters and as preamplifiers at the receiver end. This noise is often quantified with noise figure (NF). The NF is a factor which says how much higher the noise power spectral density of the amplified output is compared with the input noise power spectral density times the amplification factor and is often specified in decibels (dB). ASE is emitted by the amplifier in both the forward and reverse directions, but only the forward ASE is a direct concern to system performance since that noise will co-propagate with the signal to the receiver where it degrades system performance. Counter-propagating ASE can, however, lead to degradation of the amplifier's performance since the ASE can deplete the inversion level and thereby reduce the gain of the amplifier. Excess ASE is an unwanted effect in lasers, since it dissipates some of the laser's power. In optical amplifiers, ASE limits the achievable gain of the amplifier and increases its noise level. The ASE noise mixes with the optical signal and produces beat noise components at the square-law receiver. The ASE noise is very broadband ( $\sim 40$  nm) and needs to be carefully analyzed to evaluate its degrading effect on system performance. ASE effects may be mitigated by increasing the input laser intensity, decreasing the amplifier facet reflectivities, or tuning the master oscillator so that it is resonant with the amplifier.

**F) Crosstalk (CT):** Linear crosstalk arises due to incomplete isolation of WDM channels by optical components such as OADMs, OXCs, multiplexers/demultiplexers, and optical switches, i.e., the effect of signal power leakage from other WDM channels on the desired channel. It is different from non-linear crosstalk involving non-linear fiber interaction (such as cross-phase modulation, stimulated Raman scattering, etc.). Linear crosstalk depends on the ratio of the optical powers of two channels, whereas non-linear crosstalk (discussed in Section II.B) depends on absolute powers. Linear crosstalk can be either incoherent (i.e., heterowavelength or out-of-band) or

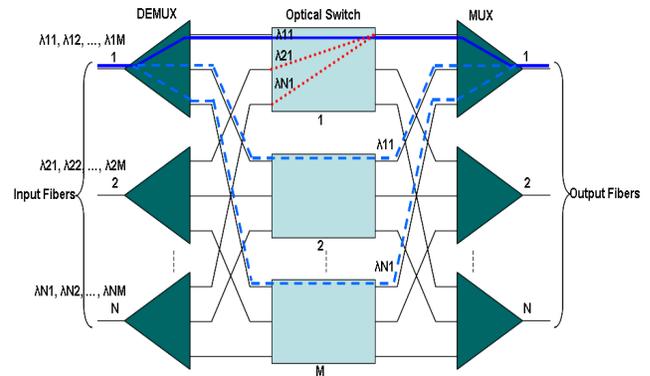


Fig. 3. Typical OXC structure with  $N$  ports and  $M$  wavelengths.

coherent (i.e., homowavelength or in-band). Consider a case in which a tunable optical filter is used to select a single channel among the  $W$  channels incident on it. If the optical filter is set to pass the  $k^{th}$  channel, the optical power reaching the output of the filter can be written as  $P = P_k + \sum_{w \neq k}^W T_{kj} P_j$  where  $P_k$  is the power in the  $k^{th}$  channel and  $T_{kj}$  is the filter transmittivity for channel  $j$  when the channel  $k$  is selected. For an ideal filter  $T_{kj}$  should be zero. Crosstalk occurs if  $T_{kj} \neq 0$  for  $j \neq k$ . This is out-of-band crosstalk because it belongs to the channels lying outside the spectral band occupied by the channel selected. It is incoherent because it depends only on the power of the neighboring channels.

The in-band crosstalk can be easily understood by considering a typical structure of an OXC without in-built amplifiers as shown in Fig. 3. The OXC consists of  $N$  fiber ports and  $M$  optical switches. Wavelength 1 in input fiber 1, denoted by  $\lambda_{11}$ , is affected by the  $N - 1$  crosstalk components due to the leakage from the  $N - 1$  signals with wavelength 1 on the other  $N - 1$  input fibers,  $\lambda_{21}, \lambda_{31}, \dots, \lambda_{N1}$ , when passing through the optical switch 1 (shown in red dotted lines). Similarly, when wavelength 1 is demultiplexed to one path, there will be a fraction of it in each of the other  $M - 1$  outputs of the corresponding demultiplexer. Passed through the optical switches, the main signal is multiplexed with  $M - 1$  signals with different wavelengths. At the same time, the  $M - 1$  crosstalk contributions of wavelength 1 in these  $M - 1$  paths are combined with the main signal (shown in blue dashed lines). Assume  $\varepsilon$  is the isolation of multiplexers/demultiplexers,  $P$  is power of the input signal, and then the crosstalk contributions are  $\varepsilon^2(M - 1)P$ . The computation of crosstalk becomes quite complicated as the number of crosstalk elements which the signal passes through increases, and should be considered in the design of WDM networks. Crosstalk effects can be mitigated by the use of intelligent wavelength assignment techniques as discussed in Section IX.

**G) Filter Concatenation and Amplifier Tilt Effects:** The narrowing of spectral width of the signal as it traverses through a set of filters along a path is called filter concatenation (FC) effect. The penalty induced by FC depends on the route, the modulation type used, and the number of network elements the signal traverses before it reaches the destination. Low-pass filter-based duobinary (LPF-DB) modulation offers greater

tolerance to FC effects than NRZ modulation [9]. The main limitation of Erbium doped fiber amplifier (EDFA) stems from the spectral non-uniformity of the amplifier gain. As a result, different wavelengths of a WDM signal are amplified by different amounts causing lambda-dependent effects known as amplifier tilt effects. The problem becomes quite severe in long-haul WDM networks, where the signal undergoes amplification over a chain of in-line amplifiers. Tilt effects can be reduced with the application of gain-flattening techniques using optical filters that have gain profiles that are the inverse of the gain profiles of the amplifiers. Alternatively, gain-clamped EDFAs may be used.

### B. Non-linear Impairments (NLIs)

The worries that plagued optical fiber communication in the early days were fiber attenuation and, sometimes, fiber dispersion; however, these issues are dealt with using a variety of dispersion compensation techniques. However, fiber non-linearities present a new realm of obstacles that must be overcome. Effects of non-linear impairments become crucial as data transmission rates, transmission lengths, number of wavelengths, and optical power levels increase in addition to reduction in channel spacing [2]. Network designers must be aware of these limitations and of the steps that can be taken to minimize the detrimental effects of these fiber non-linearities.

The response of any dielectric medium to light becomes non-linear under intense electromagnetic field, and optical fibers are no exception. Due to anharmonic motion of bound electrons the total polarization  $P$  induced by electric dipoles is not linear in the electric field  $E$ , but satisfies a more general relation as  $P = \epsilon_0(\chi^{(1)}.E + \chi^{(2)}.E^2 + \chi^{(3)}.E^3 + \dots)$ , where  $\epsilon_0$  is the permittivity of vacuum and  $\chi^{(k)}$  is the  $k^{th}$  order susceptibility. The predominant contribution to  $P$  is from linear susceptibility  $\chi^{(1)}$ . For a medium like fiber with symmetric molecules,  $\chi^{(2)}$  vanishes. Therefore optical fibers do not exhibit second order nonlinear refractive effects. Hence, the third order susceptibility  $\chi^{(3)}$  is responsible for the lowest-order non-linear effects such as non-linear refraction (Section II.B.A), third order harmonic generation (Section II.B.B), and four-wave mixing (Section II.B.C) as discussed later.

The non-linear effects in optical fiber occur either due to change in the refractive index of the medium with optical intensity (power) or due to inelastic-scattering phenomenon. A general classification of non-linear effects in fiber medium is shown in Fig. 4 [2]. The dependence of refractive index on power is responsible for Kerr effect which produces three different kinds of effects—self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM), depending on the type of input signal. At high power levels, the lightwaves (optical signals) interact with the phonons of the fiber medium resulting in scattering phenomenon. The intensity of scattered light grows exponentially if the incident power exceeds a certain threshold value. The inelastic scattering phenomenon can induce stimulated effects such as stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). The Brillouin generated phonons (acoustic) are coherent and give rise to a macroscopic acoustic wave in the fiber, whereas, in Raman scattering, the phonons (optical)

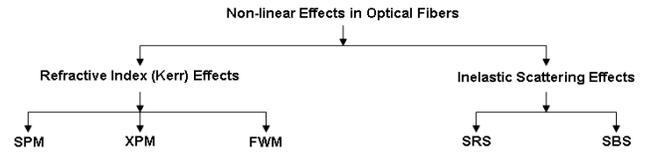


Fig. 4. Classification of non-linear effects in fiber medium.

are incoherent and no macroscopic wave is generated. All non-linear effects, except SPM and XPM, provide gains to some channel at the expense of depleting power from other channels. SPM and XPM affect only the phase of the optical signal and can cause spectral broadening, which leads to increased dispersion. A comparison of various non-linear effects in fiber medium is presented in Table I [2, 10].

The importance of non-linear effects is growing due to 1) increase in optical power levels to increase the optical reach, 2) recent developments in optical components such as EDFA and DWDM systems to build more flexible networks, 3) increase in channel bit-rate to increase the traffic carrying capacity of wavelengths, and 4) decrease in channel spacing to increase the number of wavelengths and overall network capacity. Although the individual power in each channel may be below the one needed to produce non-linearities, the total power summed over all channels in a multi-wavelength WDM system can become significant. The combination of high total optical power and a large number of channels at closely spaced wavelengths is ideal for many kinds of non-linear effects. For all these reasons it is important to understand and be able to accurately measure fiber non-linearities. In the following, we briefly explain the reasons behind each of these non-linear effects and discuss some possible solutions to overcome these effects.

**A) Self-Phase Modulation (SPM):** The non-linear phase modulation of an optical pulse caused by its own intensity in an optical medium is called SPM. An ultra-short optical pulse, when traveling in a medium, will induce a time varying refractive index of the medium, i.e., the higher intensity portions of an optical pulse encounter a higher refractive index of the fiber compared with the lower intensity portions. This results in a positive refractive index gradient ( $dn/dt$ ) at the leading edge of the pulse and a negative refractive index gradient ( $-dn/dt$ ) at its trailing edge. This temporally varying refractive index change results in a temporally varying phase change leading to frequency chirping, i.e., the leading edge of the pulse finds frequency shift towards the higher side whereas the trailing edge experiences shift towards the lower side. Hence, the primary effect of SPM is to broaden the pulse in the frequency domain, keeping the temporal shape unaltered. As the chirping effect is proportional to the transmitted signal power, the SPM effects are more pronounced in systems with high transmitted power. SPM is the strongest among the Kerr effects for DWDM systems working at 100 GHz spacing. The chirp also depends on the input pulse shape. The appropriate chirping of input signals using chirped RZ (CRZ) modulation can reduce the SPM effects [11]. The effects produced by non-linear SPM and linear dispersion are opposite in nature. By proper choice of pulse shape and input power, one effect will

compensate for another, leading to undistorted pulse in both time and frequency domains. Such a pulse is called a soliton pulse and is useful in high-bandwidth optical communication systems.

**B) Cross-Phase Modulation (XPM):** The non-linear refractive index seen by an optical pulse depends not only on the intensity of the pulse but also on the intensity of the other co-propagating optical pulses, i.e., the non-linear phase modulation of an optical pulse caused by fluctuations in intensity of other optical pulses is called XPM. The result of XPM may be asymmetric spectral broadening and distortion of the pulse shape. XPM hinders the system performance through the same mechanism as SPM: chirping frequency and chromatic dispersion. XPM damages the system performance even more than SPM and influences it severely when the number of channels is large. The XPM-induced phase shift can occur only when two pulses overlap in time. Due to this overlap, the intensity-dependent phase shift and consequent chirping is enhanced, leading to enhanced pulse broadening. The effects of XPM can be reduced by increasing the wavelength spacing between individual channels. Another way to reduce XPM effects is by careful selection of bit-rates for adjacent channels that are not equal to the present channel's. For increased wavelength spacing, the pulses overlap for such a short time that XPM effects are virtually negligible. XPM is more important at 50 (or less) GHz spacing compared to 100 GHz spacing.

**C) Four Wave Mixing (FWM):** FWM originates from third order non-linear susceptibility ( $\chi^{(3)}$ ) in optical links. If three optical signals with carrier frequencies  $\omega_1$ ,  $\omega_2$  and  $\omega_3$ , co-propagate inside a fiber simultaneously, ( $\chi^{(3)}$ ) generates a fourth signal with frequency  $\omega_4$ , which is related to the other frequencies by  $\omega_4 = \omega_1 \pm \omega_2 \pm \omega_3$ . In general for  $W$  wavelengths launched into a fiber, the number of FWM channels produced is  $M = W^2(W - 1)/2$ . The FWM effect is independent of the bit-rate and is critically dependent on the channel spacing and fiber dispersion. Decreasing the channel spacing increases the four-wave mixing effect. FWM has severe effects in a WDM system, which uses dispersion-shifted fiber. If there is some dispersion in the fiber, then the effect of FWM is reduced. This is why non-zero dispersion-shifted fibers are normally used in WDM systems. Another way to reduce FWM effect is to employ unequal channel spacing in such a way that the generated signals do not interfere with the original signals.

**D) Stimulated Brillouin Scattering (SBS):** SBS occurs when an optical signal in fiber interacts with the density variations such as acoustic phonons and changes its path. In SBS, the scattering process is stimulated by photons with a wavelength higher than the wavelength of the incident signal. SBS is recognized as the most dominant fiber non-linear scattering effect. SBS sets an upper limit on the amount of optical power that can be launched into an optical fiber. When input optical power exceeds the SBS threshold, a significant amount of the transmitted light is redirected back to the transmitter leading to saturation of optical power in the receiver, and introducing noise that degrades the BER performance. The SBS threshold depends on the line-width of the optical source, with narrow line-width sources having

TABLE I  
A COMPARISON OF NON-LINEAR EFFECTS IN FIBER MEDIUM.

Characteristic	Non-linear Refractive Effects		
	SPM	XPM	FWM
Bit-rate	Dependent	Dependent	Independent
Origin	$\chi^{(3)}$	$\chi^{(3)}$	$\chi^{(3)}$
Effect	Phase shift due to pulse itself	Phase shift due to co-propagating signal	New waves are generated
Shape of broadening	Symmetrical	Asymmetrical	No shape change
Energy transfer between medium and pulse	No	No	No
Effect of channel spacing	No	Increases as channel spacing decreases	Increases as channel spacing decreases

considerably lower SBS thresholds. The back-scattered signals can be measured using a Fabry-Perot interferometer or pump probe or self-heterodyne techniques. Externally modulating the transmitter provides one way to broaden the line-width of the optical source. Hence, it is particularly important to control SBS in high-speed transmission systems that use external modulators and continuous wave (CW) laser sources.

**E) Stimulated Raman Scattering (SRS):** In WDM systems, if two or more optical signals at different wavelengths are injected into a fiber, the SRS effect causes optical signal power from lower wavelength optical channels to be transferred to the higher wavelength optical channels. This can skew the power distribution among the WDM channels—reducing the signal-to-noise ratio of the lower wavelength channels and introducing crosstalk on the higher wavelength channels. Both of these effects can lower the information-carrying capacity of the optical transmission system. SRS occurs at significantly higher optical powers than SBS, with threshold powers of the order of watts for SRS compared to milliwatts for SBS. Unlike SBS, SRS scatters in both forward and reverse directions. The effect of SRS, i.e., Raman gain coefficient, can be measured using relative cross-section method or pulse-scanning technique or Raman amplification method. Several optical filtering techniques are proposed to suppress SRS interactions in optical fiber systems. The filters, when inserted appropriately into the transmission link, can effectively suppress the SRS power flow from the WDM channels to lower frequency noise. Furthermore, usage of a high-pass filter can enhance the SRS threshold in an optical fiber.

### III. PLI MODELING, REAL-TIME MEASUREMENT, AND MONITORING

Physical layer monitoring in WDM networks could be implemented at the impairment level (OIM—optical impairment monitoring) or at the aggregate level where the overall performance is monitored (OPM—optical performance monitoring). In the first approach, every network element should report its status in terms of input/output power, noise figure, dispersion, etc. In the second approach, optical monitoring systems

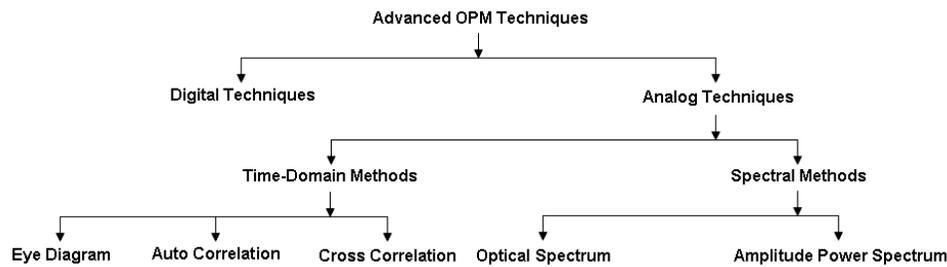


Fig. 5. A broad classification of advanced OPM techniques.

are located at each node for assessing the overall impact of degradation caused by impairments; for example, use of photonic path tracers for lightpath feasibility verification and to monitor the lightpath performance at various intermediate nodes along the path. A suitable OIM/OPM strategy would support the network control plane in lightpath establishment or rerouting—using a limited number of parameters associated with the link which indicate whether a link is operational or not. This *link performance indicator* could then be calculated based on estimated optical performance parameters provided by the transport plane.

It should be noted that, from the network design and deployment, there is *a-priori* knowledge about the topology, (e.g. fiber types, dispersion maps, etc.), some basic parameters of network elements (e.g. power levels, EDFA noise figure, etc.), and the design rules (e.g. associated margins and level of confidence). However, a more precise and timely estimation of some optical performance parameters may be relevant to better predict and adapt transparent network performance. PLI variations arise due to two reasons: (a) aging or environmental conditions (such as temperature, seasons, stress, bending, etc.) which cause slow variations and are not network state-dependent, and (b) linear and nonlinear effects that are network-state dependent. In dynamic lightpath establishment scenarios, where lightpaths arrive to and depart from the network randomly, the average setup time is very small (in the order of msec); PLI changes in this time period due to aging or environmental conditions can be considered negligible. However, network state-dependent impairments such as non-linear impairments and linear crosstalk may be significant. Hence, whenever there is a change in network status (either due to lightpath setup or teardown), it may need to be communicated to all the nodes in the network.

The various important link performance parameters that should be monitored can be grouped together with reference to their static or dynamic features, the underlying network characteristics, and the means of communicating and collecting them. In the following we provide an example of important parameters: a) residual or total dispersion which directly or indirectly affects crosstalk, SPM, etc., b) total EDFA input/output powers which determines ASE, crosstalk, amplifier tilt and concatenation effects, etc., c) channel optical power and bit rate which determine non-linear impairments, d) OSNR, e) BER, and f) quality-factor (Q-factor)—as an estimator of the overall system performance. The importance of OSNR, BER, and Q-factor and the corresponding estimation techniques are discussed in Section V. The two most common techniques to measure Q-factor are the voltage-histogram

method and the variable optical-threshold method. The first technique estimates Q-factor by using a digital sampling scope to measure both voltage histograms at the center of the eye diagram and the standard deviation of the noise at both signal levels. The second technique uses a receiver with a variable-decision threshold to measure the BER at different decision thresholds. The Q-factor is the ultimate performance measure that could be estimated fast but questions remain regarding the actual accuracy of the performance estimation obtained with this technique, especially when non-linear effects come into play. Because of strong correlation between Q-factor and BER, this measurement is highly effective for fault management.

A broad classification of advanced OPM techniques is shown in Fig. 5 [12] and briefly discussed in the following. The digital techniques commonly use high-speed logic to process digital information encoded in the optical waveform and have strong correlation with BER, but are less effective in isolating individual impairments. Analog techniques measure specific characteristics (such as CD, PMD, optical noise, optical power, etc.) of the optical waveform and are protocol independent. Optical spectrum techniques provide optical noise information; however, the optical spectrum and signal quality are not strongly correlated. The amplitude power spectrum is a better measure of signal quality as these techniques measure the spectrum of the superimposed narrowband monitor signal (RF spectral tones) on the optical data signal. Noise and distortion on the amplitude power spectrum usually directly translate to impairments on the signal. The monitoring of RF tones can be used for measuring the accumulation of CD and PMD on a digital signal. The advantage of these spectral methods is that they can be implemented with narrowband electronics. In the following we provide a brief overview of various OSNR, dispersion (CD and PMD), and Q-factor/BER monitoring techniques.

OSNR of individual wavelengths in a multi-wavelength DWDM system can be monitored using various tunable filters such as PZT-tuned Fabry-Perot filter, acoustic-optic tunable filter, and temperature-tuned etalon filter. These techniques require elaborate tuning mechanisms and suffer from insufficient resolution. To overcome these problems, fiber gratings such as fiber Bragg grating (FBG) or arrayed waveguide grating (AWG) with a photodiode array is proposed [13]. However, these techniques are expensive due to the requirement of a large number of photodetectors. OSNR can be measured by linearly interpolating the ASE noise level at carrier wavelength. However, in dynamically reconfigurable WDM networks, each lightpath may traverse different routes and different numbers of amplifiers. Hence, in these networks

OSNR cannot be accurately monitored using conventional linear interpolation techniques. Recent methods based on receiver noise characteristics and polarization extinction ratio of WDM signal can overcome these disadvantages. For proper management of WDM networks, it is essential to monitor the optical path of a WDM signal and this can be achieved by using pilot tone techniques. The low frequency pilot tones usually propagate to neighboring nodes and accumulate in the amplified WDM network, generating *ghost tones*. To avoid these problems, dual high-frequency tones can be used to monitor the optical paths in optical nodes or OXCs.

Several techniques have been proposed for real-time dispersion monitoring such as 1) detection of the conversion of a phase-modulated signal into an amplitude-modulated signal, 2) subcarrier or RF-tone based approach, 3) extraction of clock from photo-detected data and monitoring of its RF power, and 4) detection of relative group delay between upper and lower vestigial sideband (VSB) signals in transmitted data. The first two methods require modifications to a WDM transmitter, while the latter two methods do not need any modifications. The VSB technique seems to be highly sensitive to fiber non-linearity and transmitter chirp. It can be applied to WDM signals by sweeping the optical filter. PMD can be monitored based on spectral analysis of RF tones, but these techniques cannot isolate individual impairments. The PMD monitoring techniques based on measurement of degree of polarization (DOP) of the signal using optical filters at either the central frequency or one of the signal sidebands have the advantage of not requiring high-speed circuits and are also insensitive to other degrading effects. Q-factor can be measured using asynchronous histograms by recording the amplitude histogram without any regard to timing. The literature on various OPM techniques to monitor OSNR, dispersion (CD and PMD), BER, Q-factor, timing jitter, etc., is quite extensive and readers are directed towards several review articles for a comprehensive treatment of the subject (see [13] and references therein). The general requirements of various OPM techniques are summarized in Fig. 6.

The various PLI monitoring techniques mentioned above have different effects on the performance of the RWA algorithms. For this reason, an accurate modeling of various PLIs is essential in order to estimate the level of performance degradation and consequently the importance of including these PLIs in the design of algorithms. The dynamic channel modeling of various optical channel distortions including linear and non-linear effects, inter- and intra-channel types, and power-dependent and wavelength-dependent interactions is a challenging task. The main purpose of these analytical models is to identify critical network paths and set optimization criteria for conducting network simulations including the efficiency evaluation of the RWA algorithms.

#### IV. PLI-AWARE OPTICAL COMPONENT TECHNOLOGIES AND ADVANCES

Development of optical components and sub-systems, which are aware of PLIs, is of paramount importance for on-demand lightpath provisioning in dynamically reconfigurable optical networks. To realize these functionalities, the present optical networks resort to expensive OEO regeneration techniques

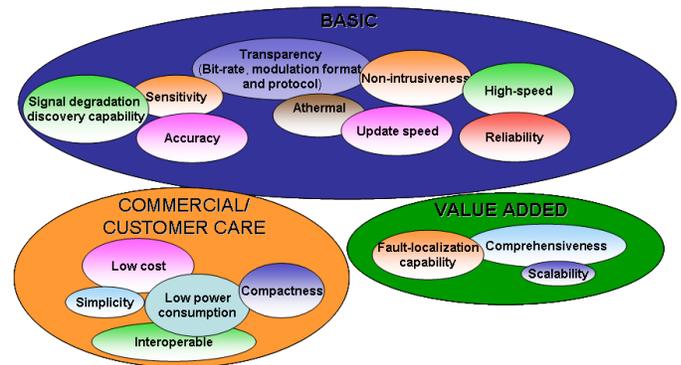


Fig. 6. General requirements of OPM techniques.

(depending on technique used, for example, 1R-simple retransmission, 2R-regeneration with reshaping, and 3R-regeneration with reshaping and retiming) which may not be suitable for future networks. The research on emerging optical component technologies such as advanced dynamic electronic dispersion compensation techniques, all-optical regeneration and wavelength conversion, advanced dynamic sampling and processing techniques, and photonic integrated circuits will help in the deployment of reconfigurable optical networks and their evolution and are discussed briefly in the following:

**A) Dynamic Electronic Dispersion Compensation (EDC):** The capacity of current single-mode fiber (SMF)-based long-haul optical networks is mainly limited by CD and PMD, though the influence of PMD is not severe for data rates less than  $10\text{ Gb/s}$ . Apart from CD and PMD, the non-linear properties of the fiber result in SPM, XPM, and FWM, which further limit the transmission capacity. The present real-world optical transport networks mainly have a static optical layer with fixed length spans and OEO conversion after a specified distance. In such a static environment where the reconfiguration is very slow, the optical channel parameters such as CD, PMD, power, etc., can be calculated in advance and adjusted accordingly. By contrast, in dynamically reconfigurable optical networks the optical transmission/channel parameters change dynamically, requiring online computation and adaptive channel impairment adjustment/mitigation techniques and adaptive electronic signal processing techniques in the receiver. EDC techniques using electrical equalization such as linear equalizer (LE), decision feedback equalizer (DFE) and maximum likelihood sequence estimation (MLSE) are considered as the most cost-effective solutions to mitigate the inter-symbol interference (ISI) resulting from CD as well as PMD. Several such techniques need to be investigated in order to improve the EDC performance in the presence of the non-linear direct detection process.

**B) Tunable Dispersion Compensation:** The dispersion compensation fiber (DCF) which is used to compensate CD is very expensive and has several disadvantages such as high attenuation, high PMD, and large physical dimensions. Furthermore, it is difficult to provide tunable compensation and to compensate the dispersion slope of advanced fibers such as G.655. In order to be dynamically reconfigurable, future optical networks require fast, dynamic and tunable dispersion compensation techniques based on fiber Bragg gratings (FBG), Etalon filters [14], virtually imaged phased

arrays (VIPA), etc. The Etalon filter and VIPA suffer from relatively high insertion loss compared to DCF. However, the channelized nature of these tunable dispersion technologies introduces several limitations, leaving room for more specialized research. Specifically, 1) the cascading limitations of these technologies; 2) the influence of dispersion ripples on system penalties, particularly when the bit-rate is close to the ripple frequency; and 3) the modeling for dynamic dispersion component technologies, need further investigation.

**C) All-Optical Regeneration and Wavelength Conversion:** In WDM optical networks, a connection request may be rejected because of non-availability of a common wavelength on all the links along the chosen route. Wavelength-continuity constraint leads to inefficient utilization of wavelength channels. Wavelength conversion is one of the possible approaches for improving the resource utilization and average call acceptance ratio. Wavelength conversion in today's optical networks is achieved using OEO conversion which regenerates electrically and retransmits at the new desired wavelength. Signal regeneration also cleans all the PLIs. However, OEO conversion techniques are complex, expensive, and are not transparent to bit-rate, making them not suitable for future optical networks. In recent years, all-optical wavelength conversion is considered as an alternative because of several advantages such as bit-rate and protocol transparency and fast and hitless wavelength conversion. However, these techniques are still in research laboratories and need a method for cost-effective mass production. The characterization and modeling of these new all-optical wavelength conversion and all-optical 2R/3R regeneration techniques [15] for different bit-rates need further investigation.

**D) Photonic Integrated Circuits (PICs):** Several vendors, many of them startups [16], are working hard to put multiple optical functions on a single optical chip called photonic integrated circuit. PICs can be used to develop high-performance optical systems that could accelerate the deployment of optical networks by reducing cost, space, power consumption, time to market, and improving reliability. The basic aim of photonic integration is to eliminate the fibers among individually packaged components. Fibers are undesirable as each fiber-to-component interface is a source of loss and a potential point of failure. PICs can employ hybrid or monolithic integration. In a hybrid PIC, multiple single function optical devices and (sometimes associated electronics) are inter-connected by electronic and/or optical couplings and assembled into a single package. In contrast, monolithic integration consolidates many optical devices and/or functions into a photonic substrate so that all photonic couplings are consolidated into a single, physically unique device. The PICs available today utilize hybrid integration to consolidate the package. Photonic integration is in its infancy relative to the electronics industry. If it succeeds, the impact on telecom equipment and networks could be just as massive as the impact of electronic chips on virtually everything.

## V. PLI-AWARE SERVICE LEVEL AGREEMENTS (SLAs)

In addition to SLAs that are common to conventional circuit-switched networks such as setup time, bandwidth,

availability, reliability, recovery time, mean service downtime, end-to-end delay, jitter, packet/burst loss, etc., RWA algorithms need to consider SLAs that are specific to the optical layer in order to realize dynamically reconfigurable generalized multi-protocol label switching (GMPLS)-based WDM optical networks [17] (see Section X). These SLA parameters are discussed below [18]:

**A) Optical Power:** The optical power at the end of a lightpath has to be within the dynamic range of the receiver. An optical receiver needs a minimum power, called receiver sensitivity, to distinguish between 1's and 0's. If the optical power at the receiver is more than the maximum value, then it damages the receiver. In addition to the receiver sensitivity, the minimum optical power required also depends on the type of forward error correction (FEC) used. The final optical power (in dB) at the end of a lightpath with wavelength  $i$  can be calculated using  $P_{out}(\lambda_i) = P_{in}(\lambda_i) + \sum_j G_j(\lambda_i) - \sum_j \alpha_i$ , where  $P_{in}$  is the input power of the lightpath at wavelength  $\lambda_i$ ,  $G_i$  is the gain of wavelength  $\lambda_i$  at  $j^{th}$  amplifier (in dB), and  $\alpha_i$  is the loss of wavelength  $\lambda_i$  at  $j^{th}$  component (in dB).

**B) Minimum Optical Signal to Noise Ratio (OSNR):** To correctly decode and interpret the received signal, it is important for the received signal to be above the minimum OSNR level. It depends on the span of the physical link(s) and the number and type of links/nodes which the optical signal traverses before regeneration. The requirement can be estimated based on the type of transponder, the bit-rate, FEC, the channel power, and the PLIs. The OSNR of the signal before the receiver can be obtained using  $1/OSNR_{Out} = 1/OSNR_1 + 1/OSNR_2 + \dots + 1/OSNR_N$ , where  $OSNR_1$  is OSNR of the output signal from the transmitter and  $OSNR_j$  ( $j = 2, \dots, N$ ) is the OSNR of the output signal from the  $j^{th}$  component along the path and depends on several impairments such as ASE, CD, PMD, etc.

**C) Bit-Error Rate (BER):** BER is a measure of service degradation in optical networks and should be below some threshold level; otherwise false alarms may be sent to higher layers indicating a failure which eventually may lead to setup of alternate lightpaths or rerouting of traffic. The BER of an optical path depends on the span of physical links and the number and type of links/nodes which the optical signal traverses before regeneration. The requirement can be estimated based on the type of transponder, the bit-rate, modulation format, FEC, the channel power, and the PLIs. Industry-wide BER requirements range from  $10^{-12}$  to  $10^{-15}$ . The major disadvantage of BER measurement is that, at line rates of 2.5 Gb/s and 10 Gb/s, a BER test takes a considerable amount of time to achieve statistically valid results for error ratios of  $10^{-15}$  for financial transactions and banking or  $10^{-12}$  as specified by the ITU-T and for Gigabit Ethernet.

**D) Q-factor:** This method can determine error ratios faster than the traditional BER test. Q-factor measures the quality of an analog transmission signal in terms of its signal-to-noise ratio (SNR). As such, it takes into account physical impairments to the signal—for example, noise, chromatic dispersion and any polarization or non-linear effects—which can degrade the signal and ultimately cause bit errors. In other words, the higher the value of Q-factor, the better the OSNR and therefore the lower the probability of bit errors. The advantages of Q-

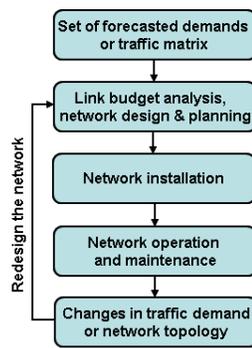


Fig. 7. Traditional optical network design.

factor include rate transparency and in-service performance monitoring in addition to fast and complete performance analysis. Q-factor is the difference between the mean values of the signal levels for a ‘1’ and a ‘0’ ( $\mu_1$  and  $\mu_0$ ), divided by the sum of the noise standard deviation values ( $\sigma_1$  and  $\sigma_0$ ) at those two signal levels assuming Gaussian noise and the probability of a ‘1’ and ‘0’ transmission being equal, i.e.,  $Q = (\mu_1 - \mu_0) / (\sigma_1 + \sigma_0)$ . Industry-wide Q-factor requirements can range from 6 to 8 corresponding to BERs of  $10^{-9}$  to  $10^{-15}$ .

Furthermore, parameters such as CD, PMD, type of FEC, regeneration technique, e.g. 1R or 2R or 3R, etc., can be defined and considered in SLAs. Ideally SLAs should specify the parameters involved in optical services, so that they can be mapped into control-plane protocol parameters for optical connectivity establishment at different scales. Other SLAs that are of importance to end users, their values for a set of classes, and mechanisms to provision the connections which meet these SLAs need further investigation. In addition, the cross-border negotiation of optical SLAs is an important issue. In multi-domain multi-granularity networks (discussed in Section VIII), based on the network topology, the definition of border nodes (e.g. OEO or all-optical) and on physical characteristics, the overall SLAs may need to be mapped on to SLAs for each domain.

## VI. PLI-AWARE STATIC NETWORK DESIGN AND ROUTING

In general, the present real-world optical transport networks mainly have a static optical layer with fixed point-to-point fiber-links (as shown in Fig. 1). Traditional network design procedures (shown in Fig. 7) used by many service providers/network operators work as follows: 1) Plan the required resources (number of nodes, wavelengths, and fibers, etc.) for predicted/forecasted traffic requirement; 2) Design and run the network for a certain time; 3) Upgrade the network with increase in traffic demand/capacity requirement by repeating the first step. However, introduction of nodes in the network (and their removal) might cause serious problems since the properties of optical components, e.g. optical transponders and amplifiers, were carefully designed for a specific situation. It means that, for each upgrade or maintenance, the network needs to be designed as a new one, which makes it time consuming and costly.

Hence, the optical nodes need *plug-and-play* (PnP) capability in which the nodes can automatically identify their own

optical transparency islands—the subset of nodes that can be reached all-optically from one node—and make their wavelength routing decisions based on the collected data. These PnP nodes should be able to support an ad hoc optical topology. Recently, there are some studies on PnP node architectures [19]. When a PnP node is plugged into the network, it can automatically learn about the optical propagation properties of its neighboring fibers and nodes, and therefore it has the capabilities of topology auto-discovery, node self-configuration, and fiber parameter monitoring. In order to achieve these capabilities, a PnP node has a miniature on-board optical transmission laboratory (mini-lab) module for signal quality monitoring and processing [19]. The function of the mini-lab is to collect information regarding fiber parameters and impairments and to disseminate it to the neighboring nodes to achieve the plug-and-play capabilities. In the following, we provide a brief discussion on static network design algorithms that represent different categories, for example, algorithms that consider 1) only linear impairments, 2) both linear and non-linear impairments, 3) the presence of regenerators/wavelength converters, and 4) the power levels of optical amplifiers.

In static network design (step 2 of the traditional network design procedure shown in Fig. 7), the traffic demand between node pairs is known *a priori* and the goal is to design a virtual or logical topology so as to optimize a certain objective function such as the minimization of total capacity required, maximization of single-hop traffic, congestion minimization, and minimization of average weighted hop count. Although designing an optical network and a logical topology on top of a physical topology is studied extensively, these algorithms assume ideal optical components; however these assumptions are not valid as we discussed earlier in the article. A heuristic algorithm to set up a collection of lightpaths in a multi-hop manner when its estimated BER is higher than the required BER, so that lightpath requests with a higher estimated BER can be established with OEO conversions at some intermediate nodes is presented in [20]. After finding a route for a lightpath request, BER is estimated on the route. If the estimated BER is higher than the required threshold, the lightpath request is blocked or established in a multi-hop manner with OEO conversion at intermediate nodes. In such cases, transmitters and receivers are required at intermediate nodes where OEO conversion takes place and some connection requests might be blocked due to the lack of free transmitters or receivers. Therefore, locations of intermediate nodes for signal regeneration are important and have considerable effect on request blocking. Hence, apart from lightpath routing, the algorithm also finds best locations for OEO conversions, so that the effect on the establishment of other lightpaths is minimized.

The impact of PMD on the design of wavelength-routed optical networks is considered in [21]. An ILP formulation to optimize the cost of the network comprising a number of regenerators and additional installed fiber is developed. Here, given the physical network topology and traffic demand, for each source-destination pair, the route is optimally partitioned into the minimum number of transparent segments by introducing a new segment whenever the accumulated PMD exceeds the acceptable threshold. A heuristic search technique called hill-climbing with random restarts is presented to reduce

the complexity of the optimal solution and evaluated on networks with non-homogeneous fiber quality.

For designing optical networks, three kinds of strategies are proposed: the wavelength path (WP)—same wavelength is assigned on all the links along the path, the virtual wavelength path (VWP)—the wavelengths are assigned link-by-link and wavelengths can be changed at all intermediate OXCs, the partial virtual wavelength path (PVWP)—only a limited number of converters are placed in the OXCs. A very detailed comparison of these three methods on Italian and Belgian networks with coherent wavelength converters in OXCs under PLIs is presented in [22] with a traffic matrix as input. In this study, only ASE and in-band crosstalk are considered with the assumption that there are no non-linear effects. Three performance metrics are considered for evaluating different routing methods: *system scale* ( $\sigma$ )—average number of OXC ports which is the sum of average number of ports directed toward other OXCs ( $\sigma_1$ ) and the average number of ports connecting an OXC to the higher client layers of the network ( $\sigma_2$ ), *wavelength conversion percentage amount* (WCPA)— $K/(\sigma_1 W)$  where  $K$  is the average number of converters in the OXC and  $W$  is the number of wavelengths in a fiber, and the *average unacceptable paths number* (UPN)—after finding a route for a lightpath request, the  $Q$ -factor is estimated on the route and the number of paths that do not assure acceptable  $Q$ -factor is considered as a metric. The results show that UPN is quite large in the case of VWP due to the large number of wavelength converters crossed by each path. In addition, it is shown that the PVWP scheme achieves the same routing performance as the VWP scheme, but with simpler OXCs and with much better transmission performance.

In [23] a simple impairment model is developed to estimate the goodness of a lightpath as given by  $OSNR = OSNR_{ASE} - OSNR_{pen,lin} - OSNR_{pen,nl}$  [dB], where  $OSNR_{ASE}$  is the OSNR penalty due to ASE noise, and  $OSNR_{pen,lin}$  and  $OSNR_{pen,nl}$  are OSNR penalties due to linear and non-linear PLIs, respectively. The penalties  $OSNR_{ASE}$  and  $OSNR_{pen,lin}$  are estimated using models available in the literature. The  $OSNR_{pen,nl}$  depends on the number of wavelengths used in the fiber (i.e., logical network configuration) and is estimated considering XPM. However, both SPM and FWM are neglected. A series of Monte-Carlo simulations are performed on a test-link and an empirical function for noise standard deviation  $\sigma_{XPM} = [P_{TX} L_{eff} \gamma K \log(N_w) / \Delta f d_{min}]$  is deduced, where  $P_{TX}$  is the channels power,  $L_{eff}$  is the effective length of the link,  $\Delta f$  is the minimum channel spacing,  $N_w$  is the total number of established channels in the fiber,  $\gamma$  is the fiber non-linear coefficient,  $d_{min}$  is the minimum distance between the channel under consideration and the used wavelengths, and  $K$  is a constant used to fit the values given by XPM. Given a physical topology and a set of lightpath requests, the RWA is posed as an optimization problem with the objective to maximize the minimum OSNR among the lightpath requests. As the optimization problem is NP-complete, two greedy algorithms—first-fit minimum hop (FF-MH), in which shortest path and first available wavelength is used, and best-optical signal to noise ratio (B-OSNR)—which jointly chooses a path and a wavelength solution which provides maximum OSNR;

and two metaheuristic algorithms—simulated annealing (SA) and Tabu search (TS) are developed. It is shown that FF-MH does not meet the minimum OSNR requirement and gives the worst results; B-OSNR improves the solution by 1 dB but does not meet the minimum OSNR requirement in all scenarios, whereas SA improves the solution by 2 dB and always meets the minimum OSNR requirement.

The gain of an optical amplifier depends on the total power of all the established channels on a fiber and gets saturated when it exceeds a certain threshold. One individual lightpath with high signal power might saturate the amplifier and reduce the gain for other lightpaths that are sharing the same amplifier. Hence, for proper operation of lightpaths in the network, the power level of individual lightpaths needs to be maintained such that total aggregated power of all the channels on a fiber is maintained below a certain threshold. Given a physical network topology, set of amplifier locations, set of available wavelengths on each link, traffic matrix, and system parameter triple  $(P_{sen}, P_{max}, SSG)$ , where  $P_{sen}$  is the threshold for power below which a signal cannot be detected;  $P_{max}$  is the maximum aggregate power on a link, and SSG is the maximum small-signal gain for an inline EDFA amplifier; the RWA with power constraints (RWA-P) is formulated as a mixed integer non-linear program (MINLP) with the objective of maximizing the number of established connections without violating  $(P_{sen}, P_{max}, SSG)$ , while determining the transmitted powers of lightpaths [24]. Since RWA-P is NP-complete, a two phase solution is proposed: in the first phase, RWA without power constraints using a fixed set of routes is formulated as an ILP problem and solved, and in the second phase, power assignment to the source nodes is done using either a heuristic algorithm called smallest-gain first (SGF) or a genetic algorithm (GA). The results from simulation experiments show that though GA takes more time to find a good solution, it performs well for a wide choice of network parameters compared to SSG.

## VII. PLI-AWARE DYNAMIC ROUTING: SINGLE-DOMAIN CASE

Recently, there has been a lot of interest in the research community in addressing the issues raised by the optical layer transparency and PLIs that are discussed earlier. Most of the studies on PLIs have considered a subset of linear impairments and their effects, as it is difficult to consider both linear and non-linear PLIs and their dependencies. The PLI-aware RWA algorithms available in the literature can be classified based on 1) the constraints used to verify the feasibility of a lightpath, such as OSNR, BER,  $Q$ -factor, 2) the impairments considered in the feasibility evaluation, 3) the type of RWA algorithm such as integrated—where route and wavelength are calculated jointly in a single step — or two-step—where network route and wavelength are computed in two different steps one after the other, 4) the network scope such as centralized or distributed RWA, and 5) PLI scope—whether PLIs are estimated using analytical models either in a centralized server or in a distributed manner; or measured in real-time using monitors.

A more general flowchart of dynamic PLI-aware RWA algorithms is shown in Fig. 8. Note that in Fig. 8, 1) the RWA

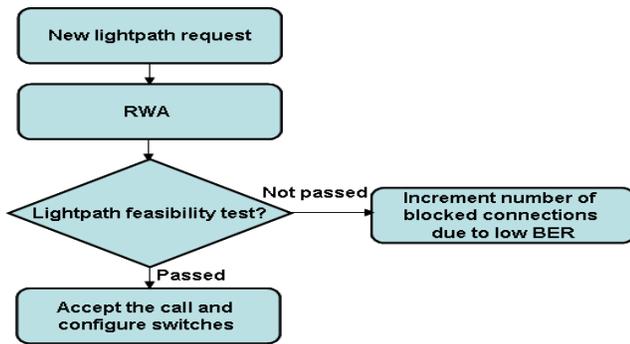


Fig. 8. A general flow chart for PLI-aware RWA algorithms.

*block* is responsible for either integrated or two-step RWA and 2) the *lightpath feasibility test block* is responsible for optical feasibility evaluation for a set of PLIs collected using either centralized or distributed approaches, wherein the PLIs may be obtained using either analytical models or real-time monitors against some feasibility metric (e.g. OSNR, BER, etc.). Here, for each connection request a route and wavelength are found using a well-known RWA algorithm and then the lightpath is tested for its feasibility. The RWA can be a two-step or single-step procedure. Then the OSNR/BER/Q-factor is estimated on the selected lightpath using the PLI-modeling techniques presented in Sections II-V. If the estimated OSNR/BER/Q-factor satisfies the threshold requirement, the lightpath is feasible and is admitted into the network. Otherwise, RWA may select an alternate route and/or wavelength and repeat the procedure to check the feasibility of the selected route and/or wavelength. For simplicity, trying alternate route and/or wavelength is not shown in Fig. 8.

A few studies considered the route computation first and then the verification of the optical feasibility of the path [25-27]. In [25] an online BER calculation mechanism is proposed and integrated into existing RWA algorithms. For each requested call, the network layer finds a route and then the BER is estimated on free wavelengths using the physical layer models and online BER calculation mechanism. A simulation study was conducted on ring and mesh networks and it was found that employing BER-based call admission algorithms has a significant impact on the performance of real networks. In [26] two algorithms, namely, impairment-aware best-path (IABP) and impairment-aware first-fit (IAFF) algorithms are proposed. The network layer finds a shortest path and then uses either best-fit or first-fit wavelength assignment technique to find a free wavelength. Once the route and wavelength are found, both PMD and OSNR are estimated. If the estimated PMD and OSNR both meet the requirement, then the lightpath is established and the request is accepted.

The study in [27] considered non-linear impairments together with linear impairments and proposed two RWA algorithms based on two step procedure, namely, first-fit minimum hop (FF-MH), first-fit least-congested (FF-LC) and one integrated algorithm called best optical signal to noise ratio (B-OSNR). In FF-MH, the shortest path is selected and first-fit wavelength assignment technique is used to find a lightpath. But in FF-LC, a pre-ordered list of available paths is

dynamically sorted based on the wavelength usage information and the least congested path is selected. The B-OSNR finds both route and wavelength simultaneously but the complexity grows linearly with number of routes and wavelengths.

Some other studies have considered the estimated impairments during the path computation and then the verification of optical feasibility [28], i.e., the link costs are assigned based on analytically computed Q-factors (based on the impairment information collected from the network design phase) and then  $k$ -shortest paths are computed to solve a linear optimization problem to find the minimum cost lightpath. The lightpath is established if the Q-factor of the lightpath is above the required threshold. Yet some other studies have considered the impairments during the network design phase [20-24, 29]. In [29], CD and filter concatenation effects are considered apart from PMD, ASE, and CT and an ILP formulation is developed based on the three-step procedure in [28] for design of metro area networks. These studies assumed that the PLIs are static and are used to compute optical feasibility of the path whereas, in fact, PLIs such as crosstalk and non-linear impairments change dynamically based on the status of the network. A rigorous analysis of all PLIs and their effects on WDM optical network performance should require simulation of the entire network for every possible configuration that the RWA algorithms may take into account, which might require millions of hours of computation time. Hence, most of the studies have considered a subset of impairments separately without considering their combined effects.

In [30] a PLI-aware architecture based on GMPLS control plane is developed. The extensions required to GMPLS control plane are discussed in Section X. Table II presents a survey of relevant work in the literature. The various definitions and categories are as follows: the network scope—whether the RWA procedure is centralized or distributed; PLI scope—can be centralized where the impairments are assumed to be available at a central server using analytical models or distributed in which impairments are either disseminated using OSPF-TE or collected using RSVP-TE or online monitors; feasibility constraints—can be one of the optical parameters used to measure the quality of transmission at the receiving end of lightpath such as BER, Q-factor, OSNR, etc; PLIs considered—the PLIs considered and their complexity, e.g. linear impairments or non-linear impairments, or both; RWA algorithms—can be PLI-aware RWA using joint RWA or step-by-step RWA or normal RWA followed by feasibility evaluation. To the best of our knowledge almost all these studies concentrate on RWA in single domain optical networks with implicit assumption of homogeneous and single granularity optical networks, i.e., all links carry same number of wavelengths and all wavelengths support the same bit rate. In the next section, we discuss the issues of PLI-aware dynamic routing in multi-domain and multi-granularity (MDMG) networks.

## VIII. PLI-AWARE DYNAMIC ROUTING: MULTI-DOMAIN AND MULTI-GRANULARITY CASE

All-optical networks are capable of switching traffic at various granularities other than a wavelength, for example,

TABLE II  
A CLASSIFICATION OF PLI-AWARE RWA TECHNIQUES.

Author and Reference	PLIs Considered	Feasibility Constraints	RWA Algorithms	PLI Scope	Network Scope	Remarks
Ramamurthy <i>et al.</i> [25]	ASE, XT	BER	2-steps: 1) Network layer; 2) Optical feasibility	Centralized	Centralized	Models are presented for EDFA and OXC. Only homowavelength crosstalk is considered
Huang <i>et al.</i> [26]	ASE, XT, PMD	OSNR, PMD separately				ASE noise and noise due to multipath interference is considered
Cardillo <i>et al.</i> [27]	PMD, ASE, SPM, XPM, FWM	OSNR				Offline computation of NL PLI impact
Martins-Filho <i>et al.</i> [32]	ASE, amplifier gain saturation, and wavelength dependent gain and loss	BER	2-steps: 1) Route based on lowest PLIs [32]/Q-factor [33]; 2) BER feasibility			The order of two steps is different from [25-27]
Markidis <i>et al.</i> [33]	SPM, XPM, FWM, GVD, optical filtering, and jitter degradation					Extension of [28] considering 2R regeneration and non-linear impairments for ultra long-haul networks
Kulkarni <i>et al.</i> [28], Tomkos <i>et al.</i> [29]	ASE, CD, PMD, XT, Filter concatenation	Q-factor	3-steps: 1) Link cost computation; 2) Shortest path; 3) Optical feasibility			Traffic matrix is known a priori
Duhovnikov <i>et al.</i> [31]	ASE, PMD, CD SRS, SPM, XPM, FWM	Q-factor	3-steps: 1) Q-factor for $\lambda$ ; 2) Linear constraints; 3) Modified shortest path algorithm			Impact of LI+NLI computed offline. Fixed span only
Martnez <i>et al.</i> [30]	ASE, CD, PMD	Not Specified	1-step: distributed route and wavelength computation based on updated PLI information	Collected on-line	Distributed	Routing-based approach is used to carry impairment related information.
Li <i>et al.</i> [34]	ASE, fiber dispersion, and PMD	Q-factor	3-steps: 1) Link metric using estimated ECP; 2) Shortest path using Bellman-Ford; 3) Optical feasibility based on Q-factor	Collected on-line	Distributed	Proposed and evaluated an algorithm in the context of ASON
Pinart <i>et al.</i> [35]	ASE, PMD	OSNR, PMD, and OSNR-PMD	2-steps: 1) Optical-layer link parameter monitoring; 2) PLIAR computation	Collected on-line	Distributed	Proposed a technique to aggregate PLIs to reduce routing information
Pavani <i>et al.</i> [36]	ASE	Min/max signal power	3-steps: 1) Routing based on fixed-alternate routing; 2) First-fit wavelength assignment; 3) Min/max power constraint check	Centralized	Centralized	Maximum (minimum) power constraint is used to limit the non-linear PLIs (to assure minimum OSNR)
Papadimitriou <i>et al.</i> [37]	SPM, XPM, FWM	Non-Linear Phase Shift	OSPF-TE used to distribute non-linear phase shift and compute routes. RSVP-TE is used to set up lightpaths	Distributed	Distributed	SBS and SRS are assumed to be handled at design phase
McNeill <i>et al.</i> [38]	ASE, CD, PMD, SPM, XPM, FWM	Q-factor	2-Step process: 1) Route selection; 2) Wavelength selection	Distributed	Distributed	Architecture and various databases required to implement continuous OPM, feedback, and ICBR are presented. Effect of impairments on various modulation formats is studied
Tomkos <i>et al.</i> [39]	ASE, XT, FWM, XPM	Q-factor	3-Step process: 1) Pre-processing phase collects all the information about the network/traffic demands and assigns Q-factor as link cost; 2) A joint optimization problem with k-shortest paths is solved; 3) Feasibility constraint on Q-factor is checked	Centralized	Centralized	For calculating Q-factor of a k-link path, an empirical formula is presented
Politi <i>et al.</i> [40]	FWM, XPM, OSNR	Q-factor	2-Step process: 1) Path selection based on least congestion; 2) Wavelength selection based on best physical performance	Centralized	Centralized	An analytical model is presented to compute Q-factor based on several impairments

TABLE II (cont.)  
A CLASSIFICATION OF PLI-AWARE RWA TECHNIQUES.

Author and Reference	PLIs Considered	Feasibility Constraints	RWA Algorithms	PLI Scope	Network Scope	Remarks
Politi <i>et al.</i> [41]	FWM, XPM, OSNR	Q-factor	2-Step process: 1) For each wavelength compute shortest cost path; 2) Select shortest cost path and see if the Q-factor is above certain threshold for the current and existing light-paths	Centralized	Centralized	Three cost metrics are considered 1) length of the path, 2) congestion of the path, and 3) noise of the channel in the path
Castoldi <i>et al.</i> [42]	ASE, PMD, CD, SPM using non-linear phase shift	BER + Q-factor with a relation to OSNR	Two different methods: Signaling based distributed method and PCE based centralized method.	Centralized and Distributed	Centralized and Distributed	A comparison of centralized vs distributed RWA. The conclusion is signaling approach may require extensions while PCE based approach may suffer from scalability problems
Deng <i>et al.</i> [43]	ASE, fiber attenuation, OXC insertion loss and OSNR degradation, receiver noise, and amplifier gain fluctuations	Received power, OSNR, BER	Dynamic source power assignment algorithm is proposed. Fixed shortest path routing is used. Upon call arrival 1) Assign minimum power to the source and accept the connection, if $OSNR_{r,x} \geq OSNR_{th}$ and $P_{s,r,x} \geq P_{sen}$ ; 2) Otherwise central server initiates the source power adjustment algorithm	Centralized	Centralized	Infinite number of wavelengths is assumed. It requires all OXCs in the network to report their equalization status to central server $OSNR_{r,x} - OSNR$ at the receiver where $OSNR_{th}$ - OSNR threshold; $P_{s,r,x}$ - Received power; $P_{sen}$ - Receiver sensitivity; Note that the power assignment is different from RWA.
Deng <i>et al.</i> [44]	ASE, linear in-band crosstalk in OXC, OSNR penalty due to fiber non-linear effects	Q-factor and BER	Two adaptive routing algorithms proposed: 1) Q-measurement method (QM); 2) Adaptive QoS algorithm based on QM	Q-factor is collected on-line	Centralized	Standard control plane protocols such as OSPF-TE is assumed to be present to disseminate Q-factor information
Pointurier <i>et al.</i> [45]	ASE, crosstalk, non-linear penalty, CD	Q-factor	Compute the shortest path for each wavelength and check if Q-factor of current and existing lightpaths is above threshold. Select one path that satisfies the above constraint using one of the four proposed heuristics	Q-factor is collected on-line	Centralized	Fairness is the main concern and to achieve fairness among blocking probability and BER four heuristics are proposed

packet/burst, waveband, fiber, and furthermore different wavelengths may operate at different bitrates. Thus, it is likely that future all-optical networks consist of multiple granularities. So, it is very important to examine the interfaces between the different granularity layers within the all-optical network, for example, would a wavelength layer and a waveband layer operate in a peer-to-peer arrangement or in a client-server mode? Even if the switching granularity is the same, it may be the case that different links have different physical layer technologies making them heterogeneous networks, for example some links may employ DWDM technology and some others may use CWDM technology. The spacing between the wavelengths may be different or the type of transceivers used may be different. Furthermore, future optical networks most likely will have several domains each controlled by a different service provider and the granularity within each domain may be different.

Given all these, it is natural that in the future, all-optical networks will be multi-domain multi-granular (MDMG) and it is important to understand how various PLIs affect service

provisioning in these networks. Though there are many definitions of domain and granularity, in this article we restrict the definition of domain and granularity to the following. We define a domain as an independently managed network cloud exposing a set of ingress and egress nodes and links. Inside a domain the paths from a node to any other node may or may not be optically feasible. The separation between neighboring domains can be either OEO nodes or all-optical switches with a few ports shared between different domains. We call these switches (irrespective of whether the switch is optical or O-E-O) as border switches. Ports on border switches can terminate links of multiple different domains. Every border switch needs a globally unique address or name for addressing purposes.

Based on the design of the optical network and the type of border switches, there is a possibility of having several kinds of MDMG networks. For example, we can design all-optical sub-networks (optical islands) such that any route is physically feasible and the border switch is equipped with transponder interfaces, where the signal undergoes electrical conversion [46-51]. This design is simple and straightforward and can

be used for static and dynamic optical networks, but is sub-optimal. The connection set-up algorithm is also very simple, since it does not consider physical constraints. In the second type of design, the border switch may not be OEO capable; instead it is an optical switch some ports of which are owned by one domain and some other ports are owned by other domain(s). In the third alternative, a network domain could have been designed without considering any impairments at all, but could have provisions for OEO conversion at some points in the network. In this case, the control plane should be intelligent enough to consider impairments when selecting routes and wavelengths. Other types of network design could be such that some connections are physically feasible between every pair of nodes. In this case, we need to find a series of lightpaths to be cascaded between a source and destination.

The complexity of information exchanged between domains and RWA depends on the type of border switch, typically, OEO or all-optical switch. However, in general the border switches are OEO in order to reduce the overall complexity. The presence of all-optical border switches requires standardization of wavelength spacing, optical power, and may need efficient alien wavelength monitoring techniques as discussed in Section XII. The requirement for routing in a MDMG network (in case of OEO border switches) is that the RWA process needs to know the extent of each domain and the granularities on each link within the domains. There are several reasons for this [46, 47]:

- 1) When entering or leaving an all-optical domain, the regeneration process cleans up the optical impairments discussed in Section I. If the domain is not an all-optical domain, the routing process needs to compute a path which is physically feasible and also satisfies the bandwidth requirement considering the granularities of different links using some kind of constrained shortest path first (CSPF) algorithm.
- 2) Each domain may have its own bounds on each of the PLIs and inter-domain routing process needs to meet these requirements apart from meeting the overall PLI target.
- 3) The routing process needs to be sensitive to the costs associated in traversing through other domains with multiple granularities. Some domains may not support the higher granularities (for example, 40 G interfaces). In this scenario, though there may exist routes from the source to the destination through multiple domains, the interface granularities in various domains may not support the connection.

The issues raised above have some implications on standard GMPLS control plane and are discussed below:

- 1) Information about each domain and their boundaries needs to be advertised (PLI information may need to be advertised in some cases). Granularity information can be obtained using some directory services as it is more often static information.
- 2) The routing algorithm needs to be sensitive to domain transition and to the connectivity and granularity limitations and PLI constraints particular to each domain.
- 3) The cost function used in routing must allow the bal-

ancing of transponder costs, OXC and OADM costs, and fiber costs across the entire routing domain.

The topology and PLI information can be advertised in several ways. When a domain advertises its topology information to other collaborating domains, it is not necessary to include the details such as internal switches and internal links. Instead, it will just send out a topology summary of its own domain consisting of only border switches and abstract links. A peer-to-peer publish/subscribe based routing protocol to exchange topology summaries among different domains can be used. The peer-to-peer exchange mode may be more suitable than simple flooding because it is possible that some domains may want to selectively advertise different sets of resources to different domains.

In a second method, the routing process can advertise the internal topology including granularities and PLI constraints of each domain globally. This method allows the ingress node to compute an end-to-end strict explicit route considering constraints such as granularity, PLI, and wavelength availabilities. In this approach, the routing algorithm used by the ingress node must be able to deal with the details of routing within each domain.

In a third method, when a lightpath reservation request arrives, the local domain will compute a domain-level path based on its own view of global topology. This path includes only the border switches. Source routing will be used to compute the path. Then the border switches can be requested to get the route within the next domain, if the complete topology information of all the nodes is not present with the source node. In this method, impairment and granularity constraints are handled within each domain and are not required to be advertised outside of the domain. The methods discussed here are not extensively studied in literature. It needs an in-depth study to understand the issues involved and to arrive at efficient methods for routing in PLI-aware MDMG optical networks.

It is worth to note that disseminating a huge amount of information across the domain borders is either difficult or introduces a lot of overhead. The overhead can be reduced using TE aggregation or optical layer aggregation. However, the aggregation either requires huge processing and advertising overheads to keep it up-to-date, or results in the loss of information that may result in path computation based on the aggregation useless. Recently, the Internet engineering task force (IETF) standardization body proposed a path computation element (PCE) [52, 53] based approach to solve multi-domain path computation issues. PCE is an entity/application that can run on network node/component or on out-of-network server and is capable of computing a constrained route for an incoming connection request based on a network graph obtained through Traffic Engineering Database (TED). PCE-based path computation is applicable in intra-domain, inter-domain, and inter-layer (e.g. IP over DWDM) contexts. Path computation can be realized via single PCE or through multiple PCE entities. The computational model used to compute a route can be centralized or distributed: in the first case, only a single PCE is involved in the path computation, while in the latter either single or multiple PCE path computations

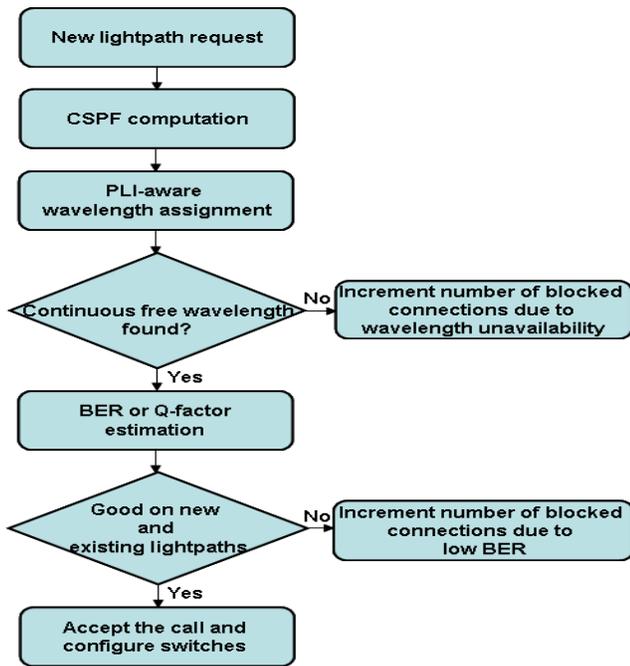


Fig. 9. Flow chart for PLI-aware wavelength assignment scheme.

can be performed. Though PCE is targeted to address several path computation issues in multi-domain networks, it is not aware of physical layer constraints that are specific to optical networks and needs corresponding techniques and extensions.

### IX. PLI-AWARE WAVELENGTH ASSIGNMENT

In optical networks, the lightpath setup is done either using integrated RWA considering PLIs or in two steps: calculate CSPF and assign a wavelength. In the earlier part of this article, we argued the need for the route computation part to be aware of the PLIs, however, careful selection of wavelengths during RWA process can also reduce the impact of PLIs. There exist a few studies on physical layer aware wavelength assignment [54-58] techniques. A general flow chart for PLI-aware wavelength assignment is shown in Fig. 9. For example, the in-band crosstalk has been considered as a major impairment that significantly affects BER. Such crosstalk usually occurs when multiple lightpaths occupying the same or adjacent wavelengths pass through an optical cross-connect. We can cleverly choose a wavelength based on the ongoing wavelength usage in a cross-connect, which can actually reduce the crosstalk (thereby BER) and hence the impact of impairments on optical feasibility [54-58].

Two wavelength assignment schemes considering the impact of FWM were proposed in [54], namely, *greedy allocation* and *global allocation*. In greedy allocation, the crosstalk generated by the calls in progress is considered only on the candidate wavelength. But in global allocation, in addition to the crosstalk generated on the candidate wavelength, the crosstalk generated on the active connections in the network is also considered. In [55], several wavelength assignment techniques, namely, crosstalk aware (CTA)-random pick, CTA-first-fit, CTA-most-used, CTA-least-used, based on traditional wavelength assignment schemes are developed. Here, all the

proposed schemes select a wavelength that creates as little in-band crosstalk on the new and existing lightpaths as possible to reduce the number of BER-related blocked calls. Based on simulation results, it is recommended that these algorithms be applied to moderate to large scale networks such as MAN and WAN networks, where BER performance is critical.

In [56], a wavelength ordering technique (FFWO, first-fit with wavelength ordering) to overcome the crosstalk introduced by adjacent channels is presented. FFWO uses the first available wavelength in a specific predefined order. The wavelength ordering is pre-computed offline once and stays static during network operation, and is explicitly designed to minimize the crosstalk due to adjacent wavelength usage. The algorithm for ordering wavelengths chooses wavelengths that are not adjacent to any previously used wavelengths. If such a wavelength does not exist, a wavelength that has one adjacent used wavelength is selected. Here, the route is computed using minimum shortest path algorithm. It is shown that the blocking probability using FFWO technique approaches that of PLI-aware wavelength assignment techniques [55], but with lower complexity.

A wavelength assignment technique based on first-fit wavelength spectrum separation (FFWSS) is presented in [57]; again, it ignores non-linear fiber crosstalk yet works well when PLIs are severe or moderate; if the PLIs are small, the blocking rate of FFWSS is worse than that of FFWO because it has a worse network-layer performance [57]. During the lightpath setup procedure, the FFWSS algorithm tries to find the least physically impaired (performance penalty factor) channel and hence spreads the traffic to all wavelengths. The idea behind FFWSS is that the channels with the smallest total penalty factor are the least likely to be blocked because of an unsatisfactory BER. However, it adds a small amount of calculation compared to the FFWO algorithm. An adaptive wavelength assignment technique based on wavelength spectrum separation integrating non-linear crosstalk into the model of [57] is presented in [58]. An adaptive switch function is integrated into FFWSS to choose between FFWO and FFWSS based on network PLI severity, to exploit the combined advantages, i.e., it exploits the strong node crosstalk rejection capability of FFWSS in times of heavy instantaneous network usage while enjoying the lower blocking rates of FFWO in times of light network usage.

### X. PLI-AWARE CONTROL PLANE EXTENSIONS AND STANDARDIZATION

A recent approach to network control and management using the GMPLS framework [17] developed by IETF seems to be emerging as the winning control plane solution for the next-generation optical network. One of the main applications of GMPLS in the context of optical networks is the dynamic establishment of lightpaths. However, it suffers from a lack of physical layer details such as PLI, transponder characteristics and availability, regenerator/wavelength converter availability information, etc. The availability of this information makes a GMPLS-capable node capable of evaluating the effects of PLIs and of deciding whether a proposed path is feasible in the optical domain. In addition, GMPLS also suffers from the lack of good techniques to disseminate and utilize physical layer

details. Hence, there is a strong need for the development of efficient techniques to address these issues, without which it would be impossible to automatically initiate a lightpath from client layers, for example, a router.

In addition, control plane protocols need several extensions to make them aware of PLIs. This can be done in one of three ways: the first option is to extend the routing protocol (for example some interior gateway protocol (IGP) protocols such as open shortest path first with traffic engineering extensions, OSPF-TE or intermediate-system to intermediate-system, IS-IS) to carry the wavelength availability and PLI information [59, 60]. In this case, the route is computed using a constrained shortest path first (CSPF) algorithm at the source node and a wavelength is selected as well. The constraints used in the CSPF algorithm can be extended to consider PLIs and hence no modifications are required for the signaling protocol (such as resource reservation protocol, RSVP-TE), to check optical feasibility. In order to consider this option, the PLIs at each node in the network need to be modeled considering several possible types of network elements and vendors. The important issues are: 1) to identify a subset of important parameters that are to be carried in the routing protocol, 2) how to represent and carry these linear/non-linear impairments, and 3) handling inaccurate wavelength availability/PLI information due to delays in link state advertisement (LSA) updates and non-zero convergence time, which may result in an infeasible lightpath. Hence, efficient techniques to handle network misalignments need to be explored. In addition, the stability of this method depends on the dynamics of traffic and the rate at which PLIs change.

The second option is to extend the signaling protocol such as RSVP-TE [60, 61]. In this method also, the route computation is done at the source node using a CSPF algorithm. Then RSVP-TE is used to select an optically/physically feasible wavelength before setting up a lightpath. In this method, there is no need to extend routing protocols (such as OSPF-TE or IS-IS), as RSVP-TE is used for physical/optical feasibility check. Hence, the impact of the dynamic traffic and the rate at which PLIs change do not matter. The issues here are: 1) optical feasibility checking of bi-directional paths and the asymmetric nature of non-linear impairments in both directions, and 2) the selection of a suitable wavelength that minimizes the blocking of future connections and also the interference with the existing lightpaths in the network.

The third option is to extend both the signaling (RSVP-TE) and routing protocols (OSPF-TE or IS-IS), where appropriate, depending on the complexity and feasibility considerations. For example, 1) the routing protocol can be extended to distribute wavelength availability information, while the signaling protocol can be extended to carry impairment-related information and check the feasibility of lightpath as in signaling-based approach, or 2) the routing protocol may be extended to carry both wavelength availability information and linear impairment information as these are relatively static in nature, while the signaling protocol carries non-linear impairment information and evaluates the feasibility of lightpath during the setup phase. There are also some arguments to extend the link management protocol (LMP) to carry and disseminate PLI information [62].

As discussed earlier in this section, the constraint-based path computation is a fundamental building block for traffic engineering in GMPLS-based optical networks. Path computation in large multi-domain, multi-region, or multi-layer networks may require special computation components, such as path computation element (PCE) and is emerging as a new standard from IETF [52, 53, 66-68]. In this approach the path computation can be either centralized or distributed. In [68] the centralized path computation approach together with distributed signaling to set up the paths is implemented and evaluated. In this approach, the PCE is aware of the complete network topology, resource availability, and physical parameters in a central repository termed the traffic engineering database (TED). Since all the paths within the domain are computed by the PCE, lightpath provisioning both optimizes the resource utilization and guarantees a required level of optical signal quality. In [34], an algorithm for path selection in automatically switched optical networks (ASON) based on eye closer penalty (ECP), Q-factor, and modified OSPF protocol is presented. Through simulations, it was shown that ECP caused by various impairments can be combined approximately linearly on dB scale. The estimated ECP is used as a cost metric in OSPF using Bellman-Ford algorithm. Then, the Q-factor is used as a measure of signal quality to decide on the feasibility of the computed lightpath.

Several common practical/deployment problems to all the protocol extensions discussed above are: 1) downward compatibility issues, i.e., what happens if there exist some nodes which are not aware of the proposed extensions? How to handle these kinds of situations; 2) migration path—what is the best strategy to replace or deploy the proposed extensions in real-world networks; 3) fragmentation—after extensions, the length of the control packets (for example LSA) should not exceed the maximum transfer unit (MTU) size leading to IP fragmentation, which is a challenging issue to tackle; 4) scalability—how the performance of these protocols varies with the number of wavelengths (which may go beyond a few hundreds) and size of the control plane network; 5) bi-directional lightpath setup—is important to consider in the presence of non-symmetrical PLIs and end components; 6) handling tunable components—how to handle the presence of tunable components such as, for example, tunable dispersion compensators, 7) how to deal with non-linear impairments which vary depending on network status and active adjacent channels, and 8) others—the routing protocols are basically designed to carry and disseminate only the routing information, which is much more static except in case of failures or node additions/deletions. The proposed protocol extensions may add the wavelength availability and optical signal quality or PLI information, making them dependent on the traffic pattern and thus more dynamic.

There is also a strong need to design and assess various control plane techniques/algorithms and extensions to handle the presence of regenerators/wavelength converters while considering both linear and non-linear PLIs as discussed in Section XII.A. In addition to the issues discussed above, how do we disseminate the routing and PLI information across the domains? The inter-domain routing protocol such as border gateway protocol (BGP) would need to be extended

to disseminate this information or the standardization bodies such as IETF should try to come up with new generalized multi-protocol label switching (GMPLS) protocols to support this functionality. There is some work on optical BGP (OBGP) and asynchronous transfer mode (ATM) private network to network interface (PNNI) for optical networks [63–65] without considering optical layer impairments.

**Control Plane API Standardization:** Recently, there are some discussions across various optical equipment vendors to run control plane software outside their equipment/hardware [69, 70]. In such cases, the control plane application program interfaces (APIs) to the hardware need to be standardized. Different vendors may have different proprietary internal switch architectures (for example, blocking or non-blocking, shared memory access, input buffer or output buffers, etc.), internal communication protocols, internal representations of switch configuration matrix, and modeling and representation of PLIs. In order to run the control plane outside the equipment/hardware, at least some of these also need to be standardized and need further investigation and research efforts.

#### XI. PLI-AWARE FAST FAILURE RECOVERY ALGORITHMS

Maintaining a high level of service availability at an acceptable level of overhead is an important issue in WDM optical networks due to the huge volume of traffic carried in such networks. Almost all protection/restoration mechanisms available in the literature assume the presence of an ideal physical layer, i.e., the existing methods did not consider the effect of PLIs. Usually, the protection paths are longer than the primary/working paths. Hence, the protection/backup path selection should introduce new constraints such as “impairments in the protection paths should be less than or equal to the threshold value”. Introducing new constraints will make it difficult to find an end-to-end protection path for a given working path, thereby leaving room for further research [71, 72]. Usually, fault detection and localization is handled at the optical layer, for example, by detecting the loss of light (LOL) on a WDM channel or an incoming fiber in an optical switch (i.e., OADM or OXC). When a connection traverses an excessive number of hops, the performance parameters such as OSNR and BER may be degraded, which could cause a false LOL alarm to higher layers. Hence, failure detection and localization algorithms need to be smart enough to distinguish between real failures and poor performance due to PLIs. In addition, failure recovery algorithms should consider what happens after a failure. For example, failure occurrences can cause rerouting of traffic, thereby introducing sudden changes in the channel load over the optical amplifiers along the relevant links forming the protection path. This, in turn, could affect the normal operation of lightpaths that are routed through the protection path before failure. Impact of these transient effects in an optical amplifier and the amplifier chain on the performance of the surviving channels needs further study.

In multi-layer networks, a failure event changes the configuration of the network, triggering recovery at multiple layers. For example, in GMPLS/DWDM networks a failure triggers recovery in both the optical domain and the GMPLS

control plane. The coordination or interworking aspects of single layer recovery mechanisms is a challenging problem, specifically, for high-bandwidth DWDM networks which may require guarantees on fast failure recovery, e.g. 50 msec. Failure recovery can be done either sequentially or in parallel. In the sequential case, failure recovery is handled at the optical layer first; if it is not successful then the failure is propagated (escalated) to the GMPLS control plane. In the parallel case, failure recovery is triggered by both the optical layer and the GMPLS control plane. The failure recovery at GMPLS control plane requires several details from optical layer, e.g. available wavelengths on links, the current network status in terms of active channels on each link to evaluate the optical feasibility, etc., and techniques to handle transient effects due to multiple concurrent restoration requests. These coordination and interworking aspects require a more in-depth study to understand the requirements and to develop possible solutions.

#### XII. OTHER IMPORTANT ISSUES IN PLI-AWARE ROUTING

In this section, we discuss the importance of considering PLIs in the development of various regenerator placement algorithms, techniques to identify and mitigate optical layer security threats, grooming algorithms, and consideration of policies and priorities in RWA algorithms.

**A) Regenerator Placement:** Translucent optical network design and placement of regenerators are particularly important in the context of IPoDWDM networks, due to increased demand for high-bandwidths from geographically distant locations. The high-bandwidth requirement makes optical networking vendors build high-bit-rate transponders and increase the number of wavelength channels by reducing wavelength spacing; both these activities lead to more vulnerability of lightpaths to PLIs and reduction of optical reach. In addition, transparent optical networks suffer from inefficient wavelength utilization, as a connection request may be rejected because of non-availability of a common wavelength on all the links along the chosen route. To increase optical reach, resource utilization, and average call acceptance ratio (and hence revenues), network operators resort to regenerators. However, as OEO regenerators are expensive, operators are forced to reduce the number of regenerators in the network, and hence CAPEX, without compromising network performance. To address these issues, recently there is a lot of interest in efficient regenerator placement [73–77].

Efficient heuristics based on  $K$ -connected  $K$ -dominant sets method is developed for placement of regenerators to guarantee  $K$ -connectivity [73]. In [74] the problem of establishing lightpaths in a multi-hop manner considering a subset of impairments is considered. A minimum cost solution using dynamic programming (DP) and heuristic algorithms are presented. These algorithms use BER for feasibility evaluation and try to reduce the overall cost of the network. In [75] the placement of regenerators in WDM ring networks under static traffic is considered and three heuristic techniques are proposed, namely, genetic algorithms (GA), simulated annealing (SA), and tabu search (TS) to solve the combinatorial optimization problem. In [76] the advantages of using regenerators in which the directionality can be changed dynamically, is studied and it is shown that the new architectures lead

to significant savings in overall cost. In [77] a heuristic to achieve a given blocking probability with a minimum number of regenerator nodes is proposed.

The development of optical control plane and optical components/sub-systems which are aware of PLIs, location and number of regenerators/wavelength converters, is of paramount importance for on-demand lightpath provisioning. Recently, handling regenerators using extended GMPLS control plane, specifically RSVP-TE, under a specific set of assumptions is addressed [78, 79]. However, [78, 79] does not consider the full set of PLIs and availability of transponders. The proposed distributed regenerator selection methods take a longer time to set up a lightpath due to the two-step process: in the first phase it attempts to use transparent paths and if it is not successful then the algorithm tries to use regenerators. Efficient distributed techniques/algorithms for selection of regenerators to reduce the cost of feasible connections, future blocking, and extensions based on real node/network models are required for deployment of GMPLS protocols.

**B) PLI-Aware Security:** There can be several kinds of physical-layer security threats in optical networks, such as service disruption, tapping, intrusion, injecting malicious wavelengths, etc., [80-82]. Rapid and sensitive attack detection, localization, and identification of an attack or intrusion is critical. This can be sometimes achieved with advanced and intelligent OPM techniques (power, spectrum, and optical time domain reflectometer). Service disruption (SD) prevents communication or degrades QoS. Optical amplifiers are particularly vulnerable to SD attacks, such as gain competition in EDFAs. To avoid this, all-Raman amplified systems can be used. Tapping compromises privacy by providing unauthorized access to data which may be used for eavesdropping or traffic analysis. Fiber non-linearities can be used for tapping, such as XPM or FWM. Advanced modulation formats such as polarization shift key (PLSK) can be used to avoid eavesdropping from neighboring channels. In addition, PLSK also reduces non-linear effects such as SPM, XPM, and FWM, but it is very sensitive to PMD and PDL.

Depending on the type of inter-domain switch (OEO or an optical switch without OEO), different kinds of security issues exist. These risks depend on the level of trust between nodes that exchange GMPLS control messages, as well as the realization and physical characteristics of the control channel. If the border switch is an optical switch without OEO conversion, then it is required to allow externally generated optical signals (called alien wavelengths) into the domain. The alien wavelengths may be improper wavelengths or with different wavelength spacings, may not meet the required power levels, or may have impairments inconsistent with those assumed by the domain. These alien wavelengths may create layer 1 (optical layer) security threats. Hence, there is an urgent need for efficient alien wavelength monitoring mechanisms [83]. If the border switch is an OEO node, then these threats may be controllable to some extent by signal regeneration, wavelength conversion and positioning in international telecommunication union (ITU-T) grid, and cleaning of PLIs. Another layer 1 security threat is resilience in case of physical attack. A possible solution could be to define all kinds of physical threats, and then, for each in-scope threat, shared risk link

groups (SRLGs) must be defined so that all the links that are vulnerable to the same threat are grouped together in a single SRLG [5]. The effectiveness of this solution depends on the definition of SRLGs and the characterization of physical layer parameters.

**C) Impact of Increase in Network Capacity:** There are two general ways of increasing network capacity: increase the number of wavelengths supported on a fiber or increase the bit rate of each wavelength [84]. The emergence of 40/100G systems over the next couple of years looks inevitable due to the rapidly growing number of broadband subscribers and the increased use of 10G Ethernet. Though  $4 \times 10G$  DWDM systems can be used to achieve the same transport capacity, carriers prefer 40/100G because of tradeoff between cost and flexibility. However, the leap from 10G to 40/100G poses interesting economical and technical challenges, most notably, how to cope with PLIs. In general, all kinds of PLIs which present at lower bit rates will tend increase on inverse square law, i.e., four fold increase in bit-rate reduces the tolerance to PLIs by a factor of 16. This leads to more rapid degradation of the optical signal for a given fiber length. These challenges result in a severe toll on the reach of the system, impact the complexity and economics of the solution, and require considerable advances in compensation techniques.

For example, at 40G the duration of an optical pulse is 25 picoseconds, which is more susceptible to CD (which distorts or stretches the optical signal) and increases the ISI compared to at 10G. However, as CD is largely time-invariant, depends on the fixed characteristics of the fiber, and CD compensation techniques are well known, it does not present a major problem. However, PMD (which largely depends on mechanical factors during fiber manufacturing and installation) is more significant and poses serious challenges at 40/100G due to its non-deterministic nature as it varies with both long-term factors such as seasons/temperature and short-term factors such as local vibrations and mechanical stress. PMD reduces the unregenerated span distance significantly. For example, assuming an equivalent 1 dB penalty and a PMD coefficient of  $0.5 \text{ ps}/\sqrt{\text{km}}$ , the unregenerated span distance is 400 km at 10G whereas it is 25 km at 40G, which is much less than the typical spacing between existing equipment (e.g. regenerators or amplifiers).

Overall, 40G systems can be deployed by replacing 10G line cards with 40G line cards which have spectrally efficient modulation formats, advanced error correcting codes, and variable dispersion compensation. Note that both 10G and 40G signals can co-exist in the same network. At 100G PLIs are more severe; for example CD tolerance decreases to a *hundredth* of 10G systems', PMD tolerance decreases to a *tenth* of that of 10G systems, and OSNR requirement increases by 10 dB. Consequently, 100G deployment requires several advances in multi-level modulation, adaptive CD compensation, advanced FEC, and coherent detection.

**D) PLI-Aware Traffic Grooming:** For the network provider, it is much more efficient and cost-effective to aggregate or multiplex lower-rate clients into a single, higher-capacity wavelength channel either in the time-domain [85] or in the optical-domain [86]. Electrical-domain aggregation techniques have been termed as traffic grooming, whereas optical-domain

techniques are called as optical time division multiplexing (OTDM). The PLIs dictate the physical span of an all-optical path and hence the placement of OEO and grooming-capable nodes in the network. OEO nodes allow for better traffic grooming and also reset PLIs. Therefore, the conventional traffic grooming techniques discussed in the literature [85] may not be very effective in the presence of PLIs. In [87, 88] traffic grooming in the presence of PLIs is considered. The effect of PLIs on grooming algorithms varies with the capacity of wavelengths under consideration, i.e., the effect of PLIs when grooming 10G wavelengths may be different than when grooming 40G or 100G wavelengths. As the trend in optical networking is moving from 10G to 40G or more, it is necessary to understand these effects before actual deployment.

**E) PLI-Aware Policies and Priorities:** In Section V, we defined some important optical layer SLAs. In order to find routes which meet these SLAs together with network layer SLAs, a cost metric which is a function of signal quality parameters corresponding to the PLIs and link metric (e.g. distance, delay, bandwidth, or number of wavelengths etc.) may have to be defined. Consider an example to understand the importance of policies and priorities—a traffic demand between node *A* and node *B* can be satisfied by two physical paths, say *X* and *Y*. Now consider two scenarios: 1) path *X* has lower hop count but higher BER; path *Y* has a slightly higher hop count but lower BER, and 2) path *X* has lower BER and hop count but has an OEO node along the path; path *Y* is all-optical path with lower BER, but higher hop count. In both the scenarios, the final path selection depends on the policies and priorities enforced within the domains.

In [89], RSVP-TE protocol is extended to handle the transponder parameters and availability at signaling time. It is argued that there is a need to intelligently select a transponder based on the sensitivity and availability; and then two PLI-aware transponder selection policies: worst-first and best-first are presented. The worst-first policy selects a less sensitive transponder among the available transponders leaving the best transponders to be used by the lightpaths that are affected worst by the PLIs (e.g. longer hop lightpaths). The best-first policy selects highly sensitive transponders among the available transponders. Simulation results show that the worst-first policy performs better w.r.t. blocking probability.

### XIII. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

In transparent optical networks, PLIs incurred by a non-ideal optical transmission medium accumulate along an optical path and determine the feasibility or transmission quality of the lightpaths. If the received signal quality is not within the receiver sensitivity threshold, the receiver may not be able to correctly detect the optical signal, and hence the reserved resources and lightpath become useless. Therefore, it is important to understand 1) various important PLIs, 2) their effect on optical feasibility, 3) analytical models, monitoring and mitigation techniques, 4) various techniques to communicate PLI information to network layer and control plane protocols, and 5) finally, how to use all these techniques in conjunction with control and management plane protocols

to dynamically set up and manage optically feasible lightpaths. In this article, we discussed the importance of PLIs and surveyed the related work. Efficient optical impairment and performance monitoring techniques are required to realize the design of dynamic PLIAR algorithms. We presented a survey of several PLI-aware RWA algorithms available in the literature. We discussed several important issues in static and dynamic routing scenarios and argued the importance of PLI-aware control plane extensions. The dissemination of the collected impairment information to all nodes in the network is important in computing and establishing optically feasible lightpaths. The routing and signaling protocols should be able to find and establish a feasible optical path (i.e., the route, fiber, wavelength, transponders, regenerators, etc.) which meets the required received signal quality, such as BER. In order to accomplish these, the standard GMPLS control plane protocols need extensions to make them aware of physical layer impairments. We also presented several security threats at the optical layer and argued the need for alien wavelength monitoring techniques. The importance of PLI-aware failure recovery algorithms, regenerator placement algorithms, traffic grooming algorithms, etc., was discussed.

Finally, this article identified several important and challenging issues which need more research by the community to understand, propose and evaluate efficient solutions, and to extend and standardize the control plane protocols, implementation, and deployment scenarios. Some of these open issues are as follows. As no existing work considers all PLIs in the RWA process, future research should consider both linear and non-linear impairments and at the same time should try to reduce the computational complexity due to PLI evaluation. Presence of regenerators/wavelength converters poses several new challenges and need to be studied in depth. Efficient placement of regenerators to increase the optical reach and average call acceptance ratio at minimum cost under dynamic traffic scenarios is a good problem to address. Efficient placement of monitors to perform online OPM/OIM and the techniques to integrate the measured values with RWA process is an emerging topic of interest. Rerouting of existing connections to satisfy feasibility constraints (e.g. BER, Q-factor, OSNR) and load balancing could be an important area. PLI-aware control plane protocol extensions and related algorithms considering the presence of regenerators/wavelength converters or tunable components is another important area of future research.

Several large scale research efforts, for example DICONET ([www.diconet.eu](http://www.diconet.eu)), DRAGON (<http://dragon.east.isi.edu>), CANARIE CANet4 ([www.canarie.ca](http://www.canarie.ca)), NOBEL2 ([www.ist-nobel.org](http://www.ist-nobel.org)), GEANT2 ([www.geant2.net](http://www.geant2.net)), FIND ([www.nets-find.net](http://www.nets-find.net)), GENI ([www.geni.net](http://www.geni.net)), EIFFEL ([www.fp7-eiffel.eu](http://www.fp7-eiffel.eu)), FIRE (<http://cordis.europa.eu/fp7/ict/fire>), etc., funded by leading government agencies across the world, are undertaken to address some of the issues discussed in this article and to provide a test environment for future Internet research. On the industry side, many carriers are actively deploying metro DWDM and plan to roll out several emerging services with the introduction of dynamically reconfigurable IPoD-WDM network architectures. In addition they are looking to develop novel interoperability mechanisms, through for

example IPSphere consortium, to develop a new business layer independent of control and data planes. Apart from IETF defining extensions for PLI-aware intra- and inter-domain routing, the optical internetworking forum (OIF) is playing a crucial role in interoperability trials and initiatives. Clearly, these newer research initiatives will play a crucial *prove-in* role for emergent dynamically reconfigurable next-generation optical network technologies, and their importance cannot be understated. Finally, the challenges identified in this article need further consideration in current and future research projects, without which it may be difficult to realize the deployment of dynamically reconfigurable optical networks.

#### ACKNOWLEDGMENT

Chava Vijaya Saradhi would like to thank his colleagues, Andrea Zanardi, Elio Salvadori, and EU-IST DICONET project partners for technical discussions and valuable inputs. His work was supported by EU-IST DICONET project funded by European Commission. Suresh Subramaniam was partially supported by NSF Grant 0519911. The authors would like to thank the anonymous reviewers for their valuable suggestions for improving the organization of this article.

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**Chava Vijaya Saradhi** (M'03) received his MS degree in computer science from the Indian Institute of Technology (IIT), Chennai, India and the Ph.D. degree from National University of Singapore, Singapore. He worked as a Project Associate at IIT, Chennai. He was with Phillips Innovation Center, Bangalore, India, as Software Engineer in 2002. He was with Institute for Infocomm Research (*I<sup>2</sup>R*), Singapore, from Sep 2002 to Dec 2006, as a senior research engineer. Where he is extensively involved in development of GMPLS-based optical network test-bed and field trail activities. Currently, he is working with Create-Net, Italy, on several industry and EU funded projects. He has over 55 journal/conference articles. In addition to the technical credentials, Dr. Saradhi has an extensive track record of service to the broader technical community. For example, he served as co-chair for IEEE/Create-Net GOSP 2005/2006/2008 workshops. He served as guest editor for well-received and timely three special issues of the IEEE Commun. Mag. and a special issue of IEEE Network Magazine. He has also served on TPC of many international conferences and as a reviewer for many leading journals/conferences. His research interests include optical networks, GMPLS networks, wireless sensor networks, and real-time systems.



**Suresh Subramaniam** (S'95-M'97-SM'07) received the Ph.D. degree in electrical engineering from the University of Washington, Seattle, in 1997. He is a Professor in the Department of Electrical and Computer Engineering at the George Washington University, Washington, DC. His research interests are in the architectural, algorithmic, and performance aspects of communication networks, with particular emphasis on optical and wireless ad hoc networks. Dr. Subramaniam is a co-editor of the books "Optical WDM Networks - Principles and Practice" and "Emerging Optical Network Technologies: Architectures, Protocols, and Performance". He has been on the program committees of several conferences including Infocom, ICC, Globecom, OFC, and Broadnets, and served as TPC Co-Chair for the optical networks symposia at Globecom 2006 and ICC 2007. He currently serves on the editorial boards of the IEEE/ACM Transactions on Networking, Optical Switching and Networking, and KICS Journal of Communications and Networks. He is a co-recipient of Best Paper Awards at the ICC 2006 Symposium on Optical Systems and Networks, and at the 1997 SPIE Conference on All-Optical Communication Systems.