Alternatives for in-service BER estimation in all-optical networks: towards minimum intrusion

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***Abstract*— Combining the existing approaches for optical intelligence and the speed and capacity of light is undoubtedly the only viable strategy for building future-proof, high-speed networks. Future optical networks are also expected to provide added value through service quality. However, the performance parameters included in current service level agreements (SLA) require the termination of a channel (wavelength) at an optical-electrical (O/E) conversion point to measure them. In all-optical networks, this is associated with higher cost. Therefore, the optimal monitoring solution for all-optical networks will be one that implements the minimum amount of O/E conversions required to measure or estimate the SLA parameters. This is very challenging due to the complex relations of electrical and optical parameters.**

Taking the bit error rate (BER) as the key performance parameter to quantify the reliability of a transmission system, this paper discusses the applicability of in-service BER estimation strategies used in current (opaque) optical networks to an all-optical framework. From this discussion, it is derived that link bit error checks are not cost-effective in an all-optical network. Then, we compare different alternatives for low-cost, real-time BER estimation with different levels of O/E conversions and apply the least intrusive of them to a use case consisting of an all-optical networking laboratory testbed. Through this example, we show that the combination non-intrusive monitoring of OSNR and packet statistics results in a viable estimation of the BER and at also provides additional, valuable information of packet metrics.

***Index Terms*— Performance monitoring, all-optical, WDM, physical impairments, service quality**

I. Introduction

Today, optical networks are based on the Synchronized Digital Hierarchy (SDH) architecture [1]. With the growth of bursty, packet-based Internet Protocol (IP) data traffic, this architecture is being used to deliver Internet content. However, SDH's core technologies were originally designed for voice and high-priority data traffic, which makes them difficult to adapt to the nature of IP traffic. SDH networks are opaque optical networks because they require O/E conversions at each node's input and output. This electrical regeneration may amount to 70-90% of the cost of lighting up a new wavelength [2]. In the last years, equipment for Wavelength Division Multiplexing (WDM), tunable lasers, reconfigurable optical cross-connects and optical add-drop multiplexers (ROADM), along with emerging approaches of optical intelligence, have matured sufficiently to move to all-optical. The removal of O/E conversions associated to this evolution will result in the efficient transportation of any type of data traffic, regardless of its payload or format. Figure 1 illustrates an all-optical connection from a source to a destination, which is also known as a lightpath. The Figure shows that core nodes have no electrical layers, only an optical physical layer.

The combination of these facts gives future optical networks the chance to provide new on-demand connectivity services in a transparent way (in contrast to opaqueness) and with different quality levels (QoS), but results in a major challenge for in-service performance monitoring, principally due to the lack of electrical regeneration in the core nodes, which limits the amount of monitoring information available. However, optical communications are essentially digital with analogue transmission, which means that optical signals are exposed to a set of linear and non-linear phenomena. Then, the main drawback of all-optical networks is that these phenomena are no longer overcome through electrical regeneration, that is, the impairments introduced by the elements along the route of an all-optical connection (lightpath) are accumulated. This degrades the quality of the signal at the destination, i.e., the Bit Error Rate (BER).

In the first deployment phase of all-optical networks, each WDM channel is expected to transport a single service, which is known as a wavelength-based or lambda service. Physical-layer quality measures will be crucial here in the sense that each service level will have to be defined by a set of parameters characterizing the quality of the optical signal transporting it; a wavelength-based Service Level Agreement (SLA). Such SLAs are expected to continue to include the BER as a key parameter, because it captures the overall performance of the physical layer. For example, the wavelength-based SLA proposal of the 'Next-generation Optical network for Broadband European Leadership' [3] project includes BER thresholds between 10^{-6} and 10^{-10}. Then, providing on-line moni-

This paper is based on "Minimum-intrusion approaches for in-service BER estimation in transparent WDM networks," by C. Pinart, which appeared in the Proceedings of the 17th IFIP/IEEE International Workshop on Distributed Systems: Operations and Management (DSOM), Lecture Notes in Computer Science, LNCS 4269, pp. 221-226. Dublin, Ireland, October 2006.

This work was partially funded by Spanish Ministry of Science and Education through the project RESPLANDOR under contract TEC2006-12910/TCM.

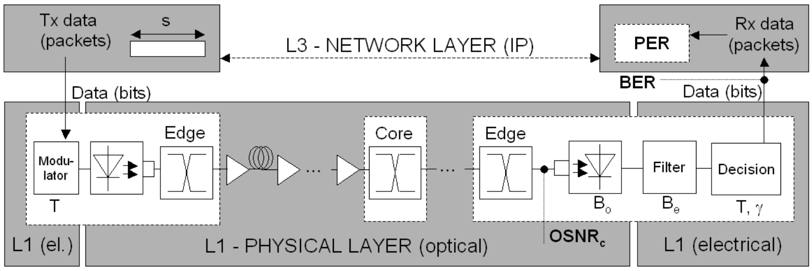

Figure 1. Connection from a source to a destination (physical and network layers).

toring capabilities and BER estimation methods adequate for all-optical networks is a critical element in making wavelength-based SLAs successful, because they would allow service providers to create SLAs per customer, service, link and/or wavelength. Monitoring capabilities inherent to the optical layer are especially interesting here.

On the other hand, the capabilities of optical intelligence will make it possible to support bandwidth on demand services, which require rapid, in-service guarantee of quality. The BER is defined as the ratio of errored bits to the number of transmitted bits, which means that, in practice, it takes long to calculate the BER in terms of received bits: for a BER of 10^{-12} and a line rate of 155 Mbps, there would be an error in about 10 days. Therefore, already in current SDH networks, the BER is estimated in real time by performing bit and block checks at each hop, that is, in the edge and core nodes. However, as mentioned before, in an all-optical environment, such checks are not possible in the core nodes, which makes on-line BER estimation a challenge.

This paper proposes scenarios with minimum or absence of extra O/E conversions to estimate the BER in all-optical networks using non-intrusive capabilities where possible and provides a practical example in the form of a laboratory testbed enabled with non-intrusive packet-level and spectral monitoring, as well as an accomodated wavelength-based SLA. The remainder of the paper is organized as follows. Section II sets the framework and assumptions of this work, and provides the background to service quality monitoring in current optical networks. In Section III we propose and discuss three monitoring scenarios for in-service estimation the BER in all-optical networks. Section IV provides a practical example of BER estimation according to the least-intrusive scenario of Section III, which is implemented in the ADRENALINE testbed, an all-optical network that supports QoS-enabled services. In Section V we draw conclusions.

II. Background and Related Work

An optical signal is influenced by two different kinds of degradations; noise and distortion, which are usually treated separately. Being the BER a fundamental signal quality measure in a digital communications system, the accuracy of the BER estimation is of fundamental importance, as any margins used to compensate inaccuracy are taken out of the system margins.

A. Framework

An optical transport network has at least one layer of the OSI architectural model (physical layer or layer 1, L1), with fiber optics as the communication medium. Additionally, SDH networks have a second layer (data link layer, L2). Note that, although SDH is usually considered as an L1 switching technology, since this paper falls within the scope of all-optical networks, SDH is only considered as a framing technology that allows L2 monitoring. The border routers interconnected to an optical network have (at least) layers 1 to 3 (network layer, L3). In this work, a WDM connection is an intensity-modulation, direct-detection (IM/DD) system, where an optical signal is either "0" or "1" (optical pulse of duration *T* carried on a wavelength), i.e. an amplitude shift keying (ASK) system. *T* (in s/bit) is the inverse of the line rate. For simplicity, no polarization dispersion is considered. Therefore, the dominant noise at the receiving end is the amplified spontaneous emission noise (ASE) of the amplifiers. We assume the standard features of optical receivers for IM/DD systems, as defined in [4] [5].

At the following we review the the most common service and signal quality measurement or estimation methods used in L1, L2 and L3 of current opaque networks, which are considered as IM/DD systems. To illustrate the functions of each layer, Figure 2 illustrates L1, 2 and 3 of an IP/Gigabit Ethernet optical network.

B. Service quality measures in opaque networks

1) L1: This layer deals with coding and transmission. The electrical L1 includes the physical coding sublayer and intensity modulation, whereas the optical L1 performs transmission. Assuming Gaussian probability density functions for the input voltage to the decision circuit (at the sampling time) for both the "0" and "1" levels, the Q factor can be calculated from the mean values μ_0 and μ_1 and the standard deviations σ_0 and σ_1 of the "0" and "1" levels respectively, according to:

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} \quad (1)$$

The BER can be related to the Q factor by using the decision-circuit method introduced by Personic in [6] and enhanced by Bergano *et al.* in [7], $BER = \frac{1}{2} erfc(\frac{Q}{\sqrt{2}})$, where *erfc(x)* is the complementary error function. The area of the tail portions of the probability distribution functions for "0" and "1" that fall on the wrong side of the γ threshold in the decision circuit of the receiver provide the error probability (P_e). The integration of this region denotes the complementary distribution function (CDF), *Q(x)*, which is determined by the distance between "0" and "1" and the variance of the noise component (eq. 1). The BER can also be related to the electrical Signal to Noise Ratio (SNR) through eq. 1, $Q = \frac{\sqrt{B_o T SNR}}{\sqrt{2SNR+1}}$, where B_o is the optical bandwidth of the photodetector, and can be analytically derived from the SNR without the need for the customary Gaussian approximation, as done by Marcuse in [5].

2) L2: SDH systems integrate frame-oriented error monitoring equipment that can perform BIP-*n* (Bit Interleaved Parity over *n* bits). *n* is chosen so that errors are detected with at least 90% probability ($n \geq 8$). Bit parity check is possible at intermediate nodes because SDH networks are formed by point-to-point optical links between electrical nodes. The SDH standard [1] defines synchronous transport modules (STM) for the fiber-optic based transmission hierarchy and segments the network into sections, the receiving end of a connection being a multiplex section (MS). SDH frames consist of rows and columns, with each location containing one byte, which can be used to transmit either payload or overhead data depending on its position within the frame. The SDH overhead is divided into sections, and includes bytes dedicated to parity checks for the line overhead and payload. In an MS node, parity bytes are labelled B2 and the BIP scheme verifies $n = 24$. For an STM-*N* frame, a BIP Nx24 code is used to determine if a transmission error has occurred over an MS. It is even parity, calculated over all bits of the MS overhead and the payload of the previous frame before scrambling. The BIP error count is used to determine the BER of the data received by an SDH device.

Apart from SDH, Asynchronous Transfer Mode (ATM) has served as traditional L2 framing method for optical networks. With the mass move to IP-based networking, the desire to eliminate the SDH and ATM layers of overhead, equipment, and their respective management systems have sparked new developments to get IP packets into optical wavelengths with a minimum of framing overhead. In Optical Transport Network (OTN) [8] compliant networks, the Generic Frame Procedure (GFP) encapsulation is a standard protocol that can be leveraged with the OTN payloads to transmit IP packets across optical wavelengths. Another example of L2 technology is Gigabit Ethernet (GigE) [9]. As with SDH framing, L2 monitoring in OTN and GigE involves partity and block checks.

3) L3: The most extended L3 technology is IP, which requires framing to be transported in L2 and be transmitted as bits over the optical physical medium. Intrusive L3 monitoring methods generate and inject test traffic into the network that shares the same network resources with the real traffic. An example of intrusive IP monitoring is the Gigabit core pan-European research network (GEANT), which integrates monitoring nodes that generate variable-bitrate traffic next to each IP border router - an overhead of less than 1% of each link's capacity [10]. Contrarily, non-intrusive IP monitoring methods are based on information collected by network nodes, usually dedicated packet capturing nodes, which receive diverted real traffic by using optical splitters.

C. Signal quality measures in all-optical networks: BER estimation

In all-optical networks, optical signals are not regenerated electrically, which makes monitoring functions that use the overhead information carried in optical signals (e.g. SDH or OTN), or packet metrics unfeasible in the core nodes. Some L1-based BER estimation methods can be found in the literature for the context of all-optical networks. For example, [11] proposes a BER estimation method for optical fiber transmission systems employing all-optical 2R regenerators. The method is based on the linearization of the nonlinear transfer function of the regenerators in three sections. In [12], the authors propose a method to monitor the bit error probability in all-optical optical networks based on the evaluation of signal histograms with synchronous and asynchronous sampling. All these methods are based on different parameters of L1 quality, which can be obtained intrusively (i.e., digital information) or non-intrusively. Examples of intrusive L1 monitoring techniques applied to optical networks are BER calculations and optical time-domain reflectometer measurements. Examples of L1 non-intrusive techniques are the spectral analysis (power, frequency drift, OSNR) and pilot-tone methods [13].

The existing methods of signal quality monitoring can be subdivided into error-detecting codes, sampling methods, spectral methods, and indirect methods. The error-detecting codes (as in the SDH frame and the digital wrapper, DW) are the best BER estimators, but they need access to the digital or electrical signal, which results in "intrusion" in the core nodes of an all-optical network. For analogue signals the sampling methods are the most accurate, but they are still complex and costly to use in every network element. The spectral, time-averaging methods ignore distortion aspects, and are thus less accurate, though simpler. In general, the desired simple and reliable monitoring method does not (yet) exist for optical signals. This is the reason why it is interesting to consider the combination of different monitoring alternatives to achieve a reasonably good estimation of the BER and other important SLA parameters with the minimum extra cost (i.e., minimum O/E conversions).

III. Proposed strategies for L1/2/3 BER estimation in all-optical networks

When offering an all-optical lambda service, traffic is mapped natively onto individual wavelengths. The service is logically and physically terminated directly

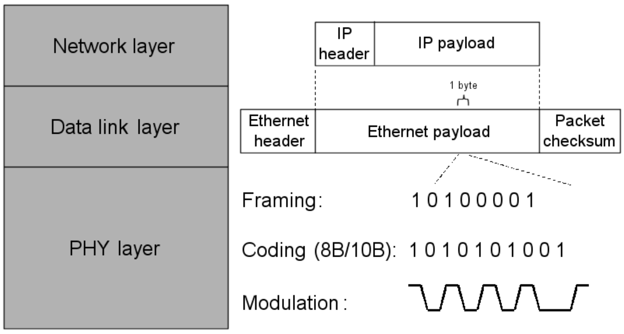

Figure 2. OSI layering of border IP routers in optical Gigabit Ethernet.

onto the end user's IP router or L2/L3 switch, and is transported across an individual wavelength over the all-optical network to be terminated on another IP router or L2/L3 switch. This transparency allows the delivery of the service to be more cost-effective but at the same time it makes the measurements of SLA metrics difficult to implement. Without optical-based monitoring capabilities, measurement of QoS in all-optical networks is reduced to measuring the physical connectivity. With SLA metrics being provided on a per-service basis, service monitoring and SLA measurements will have to be implemented on each individual wavelength. Two issues will be essential in this context: real-time performance monitoring and management. In other words, monitoring techniques will need to provide, regardless of protocols:

1) In-service monitoring of the raw bit stream (BER) in real time at multi-gigabit rates with accuracy.
2) Independence of the bit rate.
3) In-service monitoring of optical signal transmission, which can be used in systems with high number, dense-spaced, multiple-bitrate WDM channels.
4) Rapid detection of degradation.
5) Limited latency and/or overhead.

Apart from these requirements, where possible, monitoring should not defeat transparency (i.e., be non-intrusive) and be low-cost. The rationale behind this is twofold: independence of bitrate and format, and low capital and operational expenses.

A. Monitoring scenarios for detecting bit errors

At the following we describe the most relevant monitoring scenarios that we may encounter at the core nodes and receiving end of a lightpath (edge node) in a QoS enabled, all-optical IM/DD system.

1) L1/L2 monitoring (electrical):

- **Framework:** A carrier owns one or more all-optical networks (from source to destination ports of two IP routers).
- **Challenges:** This scenario resembles bit/block error measurements in the receiving ends of SDH networks (section II-B). For example, the OTN uses the DW to multiplex data streams from various sources into common telephony-based payloads. Multiple data streams from different sources are mapped into the same DW bandwidth at time domain multiplexing (TDM) payloads. The information in the communications stream is multiplexed at the physical layer (TDM payload).
- **Solutions:** If using SDH or GFP framing, bit/block error measures [1] [8]. If using GigE, parity check. Another option is the estimation of BER from the received electrical signal (section II-B).
- **Monitoring:** This scenario requires intrusive monitoring. Some IP routers have embedded GigE/SDH/GFP framing capabilities. Alternatively, devices for bit/block error check and/or SNR testers with embedded BER estimation must be employed. In core nodes, opto-electronic conversions must be added to the equipment.

2) L1 monitoring (optical):

- **Framework:** Same as previous scenario.
- **Challenges:** The main complication in this scenario is that the performance measurements available, which are typically limited to optical power, Optical Signal to Noise Ratio (OSNR) and wavelength registration, do not directly relate to QoS measures used in SLAs. Since the monitoring system only accesses the optical layer, no parity checks or SNR measurements are possible. Moreover, transparency means that it is not possible to access overhead bits in the transmitted data to obtain performance-related measures.
- **Solution:** Estimation of the BER from the OSNR. Since this solution is non-intrusive and performed in the optical domain, it can be applied at any point in the network by tapping a small portion of the transmitted WDM signal. The use of the channel OSNR ($ONSR_c$) as a means to estimate the BER of the signal (BER_c) is based on the assumption that the Q factor can be used as an intermediate parameter. Humblet and Azizoğlu [4] derived widely-used approximate expressions for the Q factor as a function of the OSNR. While the Q factor (eq. 1) can be directly converted to an electrical SNR value [5], the relationship to the OSNR is unfortunately not so simple. The study of Humblet and Azizoğlu [4] for ASK systems has the following result: $P_e = Q(\frac{2\frac{S}{N}}{\sqrt{4\frac{S}{N}+M}+\sqrt{M}})$, where *Q(x)* denotes the CDF of a zero mean, unit variance Gaussian random variable [4], and $2M = 2B_oT + 1$ and S/N is the signal to noise ratio. Assuming M=1, and combining the results of Humblet and Azizoğlu [4] and Becker *et al.* [14], the relation between the Q factor and the OSNR can be approximated as:

$$Q = \sqrt{\frac{B_o}{B_e}}\frac{2OSNR_c}{\sqrt{4OSNR_c+1}+1} \quad (2)$$

where B_e is the electrical bandwidth of the receiver filter. IM/DD systems with low inter-symbol interference and Gaussian noise distribution verify that equations 1 and 2 are equal [4] [5]. Gaussian distribution is used to model the ASE noise introduced by optical amplifiers [4], which in this work is assumed to dominate the receiver shot and thermal noises. Therefore, we obtain the channel BER (BER_c, Figure 3 top) form the channel OSNR:

$$BER_c = \frac{1}{2}erfc(\sqrt{\frac{B_o}{2B_e}}\frac{2OSNR_c}{\sqrt{4OSNR_c+1}+1}) \quad (3)$$

- **Monitoring:** Optical Performance Monitoring (OPM) devices perform non-intrusive monitoring by tapping a WDM fiber. Commercial OPMs monitor several fiber ports, each supporting tens to hundreds of WDM channels (e.g. a single device can monitor 1000 channels). OPM monitors can be integrated in edge and core nodes using optical splitters.

3) L3 monitoring:

- **Framework:** Customer-empowered fiber networks, which are becoming a reality due to the access to dark fiber resulting from the liberalization of leased line provisioning. Little effort on OPM is expected from these networks, which basically provide IP services (packet-level monitoring).
- **Challenges:** The Packet Error Rate (PER), defined as the rate at which errors in transmission/reception result in the rejection of a packet, is a standard measure of network-layer performance. Packet loss is the main SLA parameter monitored by users and service providers. This parameter can be monitored in real time with fairly good accuracy. In an all-optical network, packet errors occur because of errors and impairments in the physical layer, which cause data bits to toggle. An all-optical WDM network is seen by the IP layer as a single hop, which means that network load, congestion avoidance mechanisms or IP header corruption do not cause packet losses, simply because they do not exist. The Packet Loss Rate (PLR) is the average proportion of packets lost during a given measurement period. The PLR is typically expressed as 10 to the negative power. Examples for standard applications are 10^{-5} for MPEG-2 video and 10^{-2} for voice, without Forward Error Correction (FEC). Some studies differentiate between lost (errors in the header) and errored (errors in the payload) packets, depending on the location of errors in the packet [15]. In this work, the PER and the PLR are considered equivalent. Many research efforts have been put, especially in radio communications, into reflecting the relationship between the raw PLR and the link BER when the packet loss is a result of bits in error at the physical link layer. For example, the analytical approach discussed in [16] clearly reflects the relation $BER_c = 1 - \sqrt[s]{1-PER}$, where s is the size (in bits) of a packet. This holds true if no coding is done (Figure 3 bottom), otherwise the relation may not be straightforward. For example, if we assume that IP packets are encoded with (2,3) block coding and that

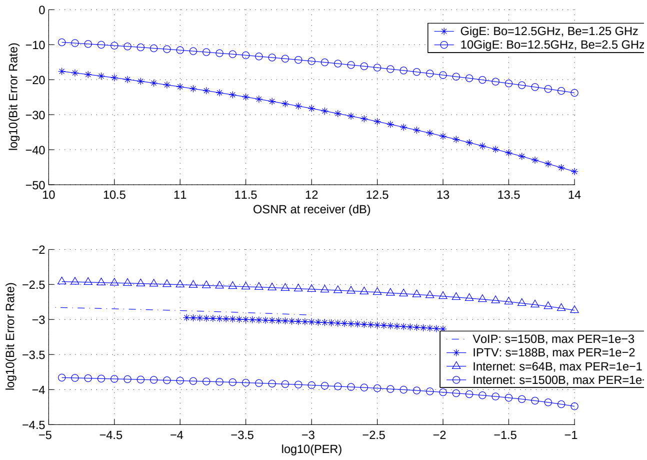

Figure 3. Estimated BER vs. OSNR and PER (with no coding).

1 bit can be corrected in every block, the PER can be approximated as:

$$PER = 1-((1-BER)^b + bBER(1-BER)^{b-1})^{s/b} \quad (4)$$

where b (in bits) is the size of a block.

- **Solution:** Equation 4 illustrates how the coding scheme affects the way in which bit errors on the physical layer propagate up the network stack. That is, both the errors occurring on an optical channel and the protection scheme applied have an impact on the PER for the packets transmitted over that channel, as shown in [17]. In a low power regime, [18] shows that 8B/10B block-coding causes a non-deterministic relationship between PER and BER in optical GigE packets. Therefore, PER monitoring does not seem a substitute to BER monitoring, but rather a complement. A solution in this case would be to design IP SLAs, which are packet-oriented and contain parameters such as network availability, latency (roundtrip) or packet loss (packet delivery), or to combine this scenario with scenarios 1 or 2.
- **Monitoring:** For non-intrusive monitoring, IP routers connected to edge nodes have embedded packet statistics capabilities. Otherwise, packet analyzers can be used. In core nodes, optical splitters (after demultiplexing) and packet analyzers are needed. For intrusive monitoring, IP test traffic generation and monitoring nodes are needed both in edge and core nodes.

Table I summarizes the above-described scenarios and solutions for real-time estimation of BER in all-optical networks. In a network with N core nodes with F in/out fibers per node and C WDM channels per fiber, and M edge nodes with W channels per receiving end, the capital expenses for estimating the BER on-line ($c_{scenario}$) are:

- End-to-end (edge): $c_1 = Mc_{L1/L2}$; $c_2 = M(c_{OPM} + Fc_{splitter})$; $c_3 = Mc_{L3}$
- At each hop (core and edge nodes): $c_1 = 2NFCc_{O/E} + (N+M)c_{L1/L2}$; $c_2 =$

TABLE I.
MONITORING SCENARIOS FOR BER ESTIMATION

Scenario	BER estimation from	Monitoring type
1	Bit/block errors, SNR	Intrusive
2	OSNR	Non-intrusive
3	PER (if no coding)	Non- and intrusive

$(N+M)c_{OPM} + (2N+M)Fc_{splitter}$; $c_3 = NFCc_{splitter} + (N+M)c_{L3}$

where $c_{O/E}$ is the cost of a transponder, $C_{L1/L2}$ is the cost of bit/block error count capability, $c_{splitter}$ is the cost of an optical splitter, c_{OPM} is the cost of an OPM monitor and c_{IP} is the cost of a dedicated device for packet statistics. For simplicity, in scenario 2 we assume that each optical node is equipped with a single multi-fiber OPM monitor. For scenario 3, we assume that L3 monitoring is done non-intrusively with a single packet-capturing device per receiving end and that no coding is done. Note that the O/E cost for the MW channels added/droped at the edge nodes is not included because it is an expense necessary for the operation of the network. Note also that scenario 1 is the only one that requires overhead to compute bit/block errors (e.g., GFP). These scenarios can be combined to monitor the BER in edge and/or core nodes, and combine this monitoring with packet-level metrics. Figure 4 illustrates possible combinations of the above scenarios with minimum opto-electronic conversions. In Figures 4a and 4c, edge nodes comply with scenario 1 and core nodes with scenario 2 and 3, respectively. In Figures 4b and 4d both the edge nodes and some core nodes have electrical capabilities (scenario 1 and scenario 3, respectively) and the remaining core nodes are all-optical (scenario 2).

IV. CASE STUDY: THE ADRENALINE TESTBED

The ADRENALINE testbed is an all-optical ring network developed at the Centre Tecnològic de Telecomunicacions de Catalunya. The ADRENALINE transport network is an IM/DD system equipped with 3 ROADMs, each interconnected with a 35-km fiber-pair link (up to 6 dense-spaced WDM channels, DWDM, of 2.5 Gbps per link) and enabled with an OPM monitor that measures channel power, frequency drift and OSNR of the in/out fibers (Figure 5). Moreover, a broadband tester is employed to generate IP traffic and measure L3 statistics.

A. On-line SLA validation in ADRENALINE

ADRENALINE supports three service types, which are inspired in the requirements of Triple Play services: voice over IP (VoIP), IP television (IPTV) and Internet data. Table II lists the service-intrinsic parameters of ADRENALINE's SLA. The QoS of these services can be verified in real-time by an in-service monitoring system (ADNETMON-T, previously named INIM) through non-intrusive monitoring and suitable processing. For further details, the interested reader is referred to [19]. The

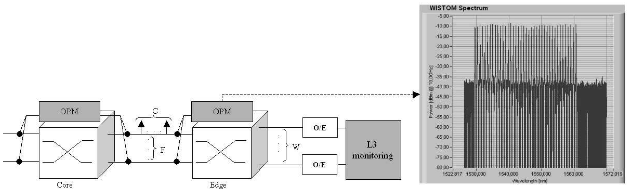

Figure 5. Monitoring capabilities and OPM samples of the ADRENALINE testbed.

monitoring scenario of the ADRENALINE testbed is a combination of scenarios 2 and 3 (Figure 4c). The rationale is to accomplish the monitoring goals listed in section III and to build a solution that supports easy migration to full OPM once the technological limitations are removed:

1) The OSNR is obtained through non-intrusive OPM allows (fiber tapping) and it leads to BER estimation in core nodes (eq. 3) and in the edge nodes to fulfill the values in Table II.
2) Spectral monitoring is bitrate-independent.
3) Non-intrusive OPM allows monitoring of DWDM channels in milliseconds.
4) Non-intrusive OPM allows detecting degradations such as OSNR levels and power losses in milliseconds. Suitable fault location algorithms are needed for proactive response due to the propagation of faults in all-optical networks.
5) Non-intrusive OPM and non-intrusive IP monitoring (packet capture at router interfaces, Table II) add neither overhead nor latency.

Moreover, non-intrusive IP monitoring at the edge nodes results in a minimum amount of opto-electronics and low cost by using embedded packet statistics capabilities of the routers. Figure 5 illustrates OSNR samples obtained in real-time (less than 50 msec) by a commercial OPM [20] during an experimental emulation of 48 dense WDM channels in the ADRENALINE testbed. The capital expenses for performing on-line BER estimation in the testbed are $c_{ADRENALINE} = 3c_{OPM} + 12c_{splitter}$. Note that no overhead is added to the transported data for monitoring purposes, because no bit error checks are done. On the other hand, this model relies on the OSNR as the means to estimate the BER through eq. 3. In some cases, the difference between the real and estimated BER may be too large. For example, Feuer demonstrated in [21] that significant errors in estimated BER from the OSNR could occur if the degree of ASE polarization becomes high. Then, it may be interesting to add an offset to the estimation, which can be obtained from the periodic computation of the received bits (non-real time) or through integrating the effects of other impairments in the BER estimation model.

V. CONCLUSIONS

The BER will continue to be a key parameter of future wavelength-based SLAs. Accurate BER estimation

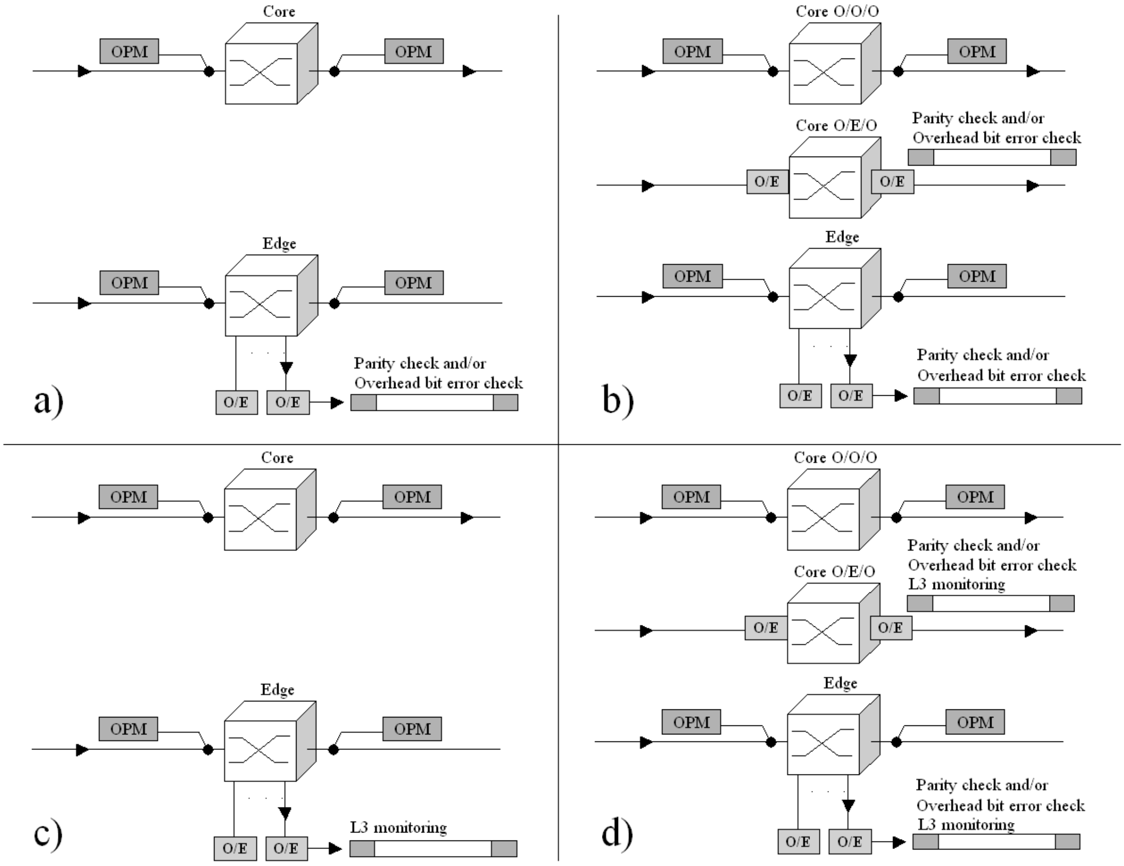

Figure 4. Combination of scenarios for BER estimation in all-optical networks.

TABLE II.
SERVICE-INTRINSIC PARAMETERS OF ADRENALINE'S SLA

Service	Setup delay	Blocking at setup
1	$< 1sec$	10^{-3}
2	$< 10sec$	10^{-2}
3	$< 1.5min$	10^{-1}

Service	Max. PER	Min. BER	Max. packet delay
1	10^{-2}	10^{-8}	$< 50msec$
2	10^{-3}	$[10^{-6}, 10^{-8}]$	$< 500msec$
3	$5 \cdot 10^{-2}$	10^{-6}	$< 5sec$

requires the termination of a channel (wavelength) at an O/E conversion point, and in an all-optical network this is only possible at the edges. Therefore, the optimal monitoring solution for all-optical networks will be one that implements the minimum amount of O/E conversions required to measure or estimate the SLA parameters. We have presented several alternatives to estimate the BER in all-optical networks that provide different levels of intrusion (and hence, of cost), and have provided a real example of non-intrusive BER estimation that uses optical-layer monitoring. We believe this is the way to go; although still emerging, optical-layer monitoring will become more of the norm than the exception to the rule as all-optical networks are deployed, and it is expected to be the basis for measuring paramount parameters of SLAs. Moreover, these solutions are the most cost-effective. Service providers are beginning to use non-intrusive monitoring capabilities in their WDM metro networks to determine optical performance metrics that measure the integrity of optical signals. Among them, the OSNR seems a good candidate to estimate the BER [4] [14], although further research is needed to integrate the effects of homodyne cross-talk and non-linearities into BER estimation methods. This is very challenging due to the complex relations of electrical and optical parameters. To overcome this, network-layer parameters, such as the Packet Error Rate (PER), may also help in guaranteeing service quality as a complement to BER estimation. This has been pointed out in the case study presented in the paper.

ACKNOWLEDGMENT

The author thanks the Journal of Computers for soliciting this paper submission.

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