Minimum-intrusion approaches for in-service BER estimation in transparent WDM networks

P. Closas, C. Fernández-Prades, J. A. Fernández, A. Ramírez

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Carolina Pinart

Centre Tecnològic de Telecomunicacions de Catalunya
`carolina.pinart@cttc.cat`

Abstract. The bit error rate (BER) is a key measure to quantify the reliability of a transmission system. In transparent networks, link bit error checks are not cost-effective. This paper proposes approaches for low-cost, real-time BER estimation with minimum opto-electronic conversions and applies them to a transparent optical networking testbed[1].

1 Introduction

Today's optical transport networks are based on the Synchronized Digital Hierarchy (SDH) [1]. Electrical regeneration may amount to 70-90% of the cost of lighting up a new wavelength in an SDH network [2]. Therefore, the removal of opto-electrical (O/E) conversions in core nodes, which is known as transparency, will result in the efficient transportation of any type of data traffic (predominantly based on the Internet Protocol, IP), regardless of its payload or format. Moreover, equipment for Wavelength Division Multiplexing (WDM), tunable lasers, reconfigurable optical cross-connects and optical add-drop multiplexers, along with emerging approaches of optical intelligence, have matured sufficiently to build ultra-high-capacity networks. Future optical networks are also expected to provide new on-demand connectivity services with different quality levels. In the context of transparency (analog transmission), this results in a major challenge for in-service performance monitoring due to the lack of electrical regeneration in the core elements, which limits the amount of monitoring information available, especially a paramount digital parameter: the Bit Error Rate (BER).

In the first deployment phase of transparent networks, each WDM connection is expected to transport a single service, which is known as a wavelength-based or lambda service. A WDM connection is an amplified intensity-modulation, direct-detection (IM/DD) system [3][4]. Physical-layer (layer 1, L1) quality of service (QoS) will be crucial here in the sense that each service class 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). Defined as the ratio of errored bits to the number of transmitted bits, the BER captures the overall performance of the physical layer, and is a basic SLA parameter.

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However, in practice it takes long to calculate the BER in terms of received bits. Therefore, the BER is usually estimated in real time by performing bit and block checks at each link, that is, in edge and core SDH nodes. In a transparent network, such checks are only possible at the edges, which makes on-line link BER estimation a challenge. Service providers are beginning to use non-intrusive monitoring (NIM) capabilities in their WDM networks to determine physical-layer performance metrics that measure the integrity of optical signals without electrical regeneration. Among them, the Optical Signal to Noise Ratio (OSNR) seems a good candidate to estimate the BER [3] [5]. Network-layer parameters, such as the Packet Error Rate (PER), are also candidates for in-service monitoring.

This paper proposes scenarios with minimum or absence of O/E conversions to estimate the BER in transparent networks using non-intrusive capabilities where possible and provides a practical example in the form of a laboratory testbed. The remainder of the paper is organized as follows. In Section 2 we propose three monitoring scenarios for detecting bit errors at layers 1, 2 and 3 in transparent WDM networks. Section 3 provides a practical example of BER estimation according to the scenarios of Section 2 that do not require O/E at the core nodes, which is implemented in the ADRENALINE testbed, a transparent network that supports QoS-enabled services monitored non-intrusively.

2 Scenarios for BER estimation in transparent IM/DD

When offering a transparent lambda service, traffic is mapped natively onto individual wavelengths. The service is logically and physically terminated directly onto the end user's IP router or layer 2/3 (L2/L3) switch, and is transported across an individual wavelength over the transparent 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 transparent 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. Real-time performance monitoring and management will be essential in this context, which results in the following requirements:

1. Accurate monitoring of the raw bit stream in real time at multi-gigabit rates.
2. Independence of the bit rate.
3. Use with high number, dense-spaced, multiple-bitrate WDM channels.
4. Rapid detection of degradation and proactive response.
5. Limited latency and/or overhead.

Apart from these requirements, 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.

2.1 L1/L2 monitoring (electrical)

- **Framework:** A carrier owns one or more transparent 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 [1]. For example, the Optical Transport Network [6] uses the digital wrapper (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 as time domain multiplexing (TDM) payloads. The information in the communications stream is multiplexed at the physical layer (TDM payload).
- **Solutions:** If using SDH or Generic Frame Procedure (GFP), bit/block error measures [1]. If using Gigabit Ethernet (GigE), parity check. Another option is the estimation of BER from the received electrical signal [4].
- **Monitoring:** This scenario requires intrusive monitoring (O/E conversions). Some IP routers have embedded GigE/SDH/GFP framing capabilities. Alternatively, devices for bit/block error check and/or Signal to Noise Ratio (SNR) testers with embedded BER estimation must be employed.

2.2 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, 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 [3] derived widely-used approximate expressions for the Q factor as a function of the OSNR. While the Q factor can be directly converted to an electrical SNR value [4], the relationship to the OSNR is unfortunately not so simple. The study of Humblet and Azizoğlu 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 [3], and $2M = 2B_oT + 1$ and S/N is the SNR. Assuming M=1, and combining the results of [3] and Becker *et al.* [5], the relation between the Q factor and the OSNR can be approximated as:

$$Q = \sqrt{\frac{B_o}{B_e}} \frac{2OSNR_c}{\sqrt{4OSNR_c + 1} + 1} \tag{1}$$

where B_e is the electrical bandwidth of the receiver filter and B_o is the optical bandwidth. IM/DD systems with low inter-symbol interference and Gaussian noise distribution verify that the Q-factor expression [4] and eq. 1 are equal [3]. Gaussian distribution is used to model the ASE noise introduced by optical amplifiers as dominant over the receiver shot and thermal noises. Therefore, we obtain the channel BER (BER_c) from the channel OSNR [7].

- **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. OPM monitors are integrated in edge and core nodes using optical splitters.

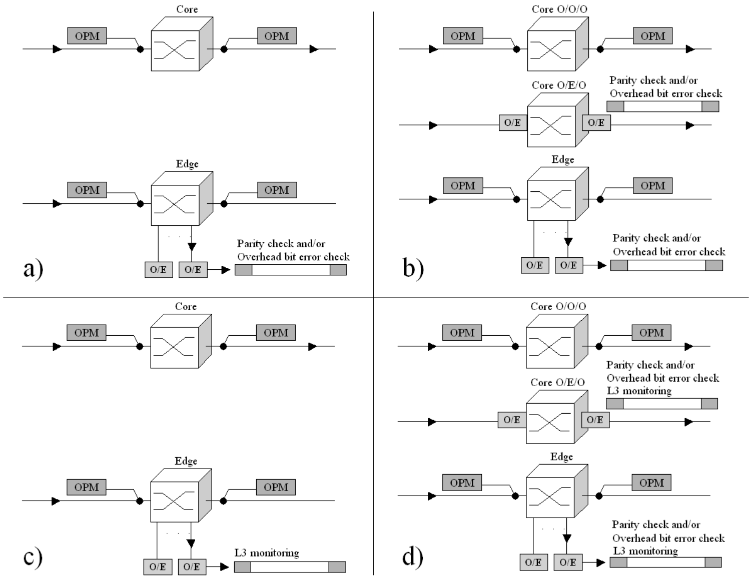

Fig. 1. Combination of scenarios for BER estimation in transparent networks.

2.3 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 a transparent network, packet errors occur because of errors and impairments in the physical layer, which cause data bits to toggle. A transparent 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. Many research efforts have been put into reflecting the relationship between the raw PER and the link BER when the packet loss is a result of bits in error at the physical layer: $BER_c = 1 - \sqrt[s]{1 - PER}$, where s is the size (in bits) of a packet when no coding is done.
- **Solution:** The coding scheme affects the way in which bit errors on the physical layer propagate up the network stack. Both the errors occurring on a WDM connection and the protection scheme have an impact on the PER for the packets transmitted over that channel. In a low power regime, [8] shows that 8B/10B block-coding causes a non-deterministic relationship between PER and BER in optical GigE. Therefore, PER monitoring does not seem a substitute to BER monitoring, but rather a complement.
- **Monitoring:** For NIM, 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.

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 ($c_{number\ of\ scenario}$) 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): $c_1 = 2NFCc_{O/E} + (N+M)c_{L1/L2}$; $c_2 = (N+M)c_{OPM} + (2N+M)Fc_{splitter}$; $c_3 = NFCc_{splitter} + (N+M)c_{L3}$

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). Figure 1 illustrates possible combinations of the above scenarios with minimum O/E.

3 The example of the ADRENALINE testbed

The ADRENALINE testbed is a transparent dense WDM network developed at the Centre Tecnològic de Telecomunicacions de Catalunya. Each node is enabled with an OPM monitor that measures channel power, frequency drift and OSNR of the in/out fibers. A broadband tester measures L3 statistics for IP traffic.

3.1 On-line SLA validation in ADRENALINE

ADRENALINE supports three service types, whose QoS of these services can be verified in real-time by a NIM system [7]. The monitoring scenario of the ADRENALINE testbed is novel because it combines pure non-intrusive scenarios at L1 and L3 (scenarios 2 and 3, Figure 1c). The rationale is to accomplish the monitoring goals listed in Section 2 and to build a solution that supports easy migration to full OPM once the current technological limitations are removed:

1. The OSNR is obtained by NIM and allows link BER estimation.
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 transparent networks.
5. L1 and L3 NIM add neither overhead nor latency.

Moreover, L3 NIM at the edge nodes results in a minimum amount of O/Es and low cost by using embedded packet statistics capabilities of the routers. The cost of on-line BER estimation in the testbed is $c_{ADRENALINE} = 3c_{OPM} + 12c_{splitter}$. 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. In some cases, the difference between the real and estimated BER may be too large. Then, it may be interesting to add an offset or to compensate estimation errors.

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