Issues for Optical Monitoring in All Optical Networks

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Abstract: A range of practical issues regarding the deployment of histogram optical monitors is discussed. A simple detect and sample monitor is considered in detail. Issues such as signal power and noise requirements to produce accurate histograms, data collection times, monitor placement and design are considered.

I. INTRODUCTION

A key motivation for All Optical Networks (AONs) is the desire for AONs to be bit rate, protocol and format transparent. This transparency will deliver a network that it flexible and independent of service and protocol. Electronic systems, such as regenerators and electronic Add Drop Multiplexers, hinder this objective. In an ideal AON, the signal will remain in an optical form from the ingress edge to the egress edge. As a minimum, we seek the network that is transparent within each administrative domain, which may be 100's to 1000's of kilometres.

Such a high degree of transparency raises many issues with respect to AON management and monitoring. Network management and monitoring are essential components of any telecommunications network. However, monitoring an optical signal without converting it to an electronic form remains a challenge.

Several proposals are being actively researched and developed[1]. Commercial devices already exist to monitor optical channel power, wavelength and Optical SNR (OSNR). These parameters, although essential, do not provide a complete picture of the signal's condition. For example, none of these parameters will detect signal degradation due to dispersion, Self Phase Modulation or Cross Phase Modulation. To monitor degradation arising from these phenomena, researchers are looking at the use of signal power histograms and, related to the histogram, signal Q measurements[2,3].

With histogram monitoring, the optical signal is periodically sampled at a monitor point, with a sampling period that may or may not be independent of the signal bit rate. If the signal is in good condition, the resulting monitor histogram displays two distinct humps, corresponding to the "mark" and "space" signal powers, as shown in Figure 1.

As the signal propagates through the network and undergoes distortion, the histogram progressively changes shape as the mark and space levels deform due to the various degradation mechanisms. An example of such a histogram is shown in Figure 2

Although there has been much work on analysing the histogram data[2,3,4], not much consideration has been given to the practical difficulties which may arise when a network operator attempts to deploy histogram monitoring. The operator will need to trade off the cost and complexity of the monitor against the amount and accuracy of the data collected. It can be expected that an AON will carry WDM traffic of differing bit rates and protocols, possibly within the same fibre. Therefore, we would prefer a monitor that can sample multiple channels of varying bit rates and data protocols. Some of the practical issues that are related to these questions are the subject of this paper.

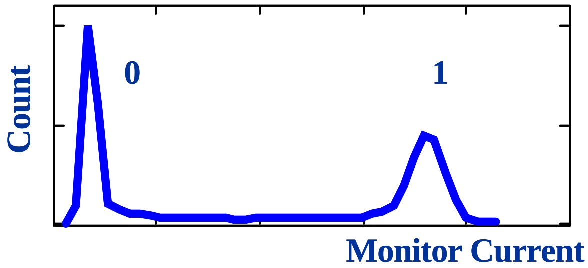

Figure 1. *Histogram for "good condition" signal*

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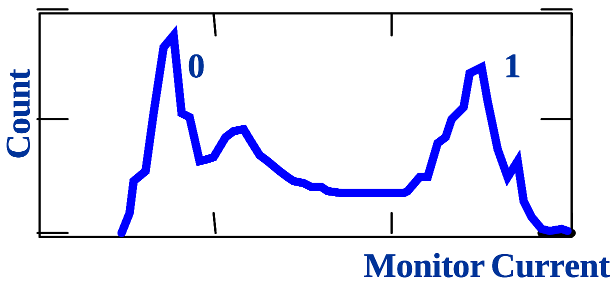

Figure 2. *Example of a histogram for degraded signal*

II. MONITORING DESIGN

The signal monitor is expected to sample the optical data stream at a pre-set rate without degrading the signal. The current approach to this is to tap off a small portion of the optical signal power, direct this portion of the optical signal onto a detector and periodically sample the detector current. This design is depicted in Figure 3. Although this approach does not give a direct measure of the optical signal[5], it can provide a significant amount of information about the condition of the signal[6].

Several techniques have been proposed for sampling the monitor signal[7]. The simplest and cheapest approach to this is to electronically sample the detected signal at a fixed rate. If the sampling rate is set equal to the bit rate and the sample taken at the decision instant (i.e. in the centre of each bit), a "synchronous histogram" is produced. An advantage of synchronous histograms is that they focus on that region of the signal that the receiver will use to determine the received bit sequence.

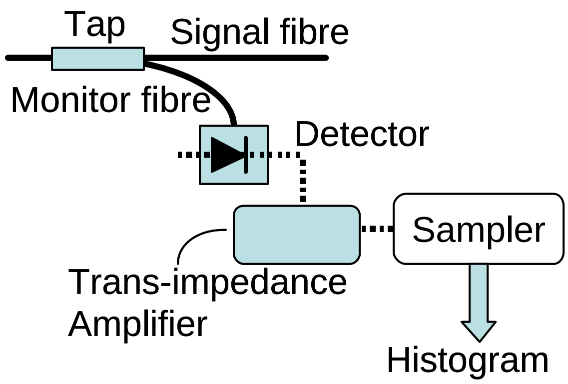

Figure 3. *Basic monitor layout. The solid lines indicate optical signal, dashed line indicates electrical signal. The Sampler includes signal processing to produce the histogram data. Optical amplification can be added.*

Alternatively, the sampling rate may be relatively prime to the bit rate (or based upon a Poisson noise process). In this case, an "asynchronous histogram" is produced. These histograms will include samples across the entire bit period, including the transitions between transmitted marks and spaces. Hence asynchronous histograms are less related to the decision point bit sequence.

Asynchronous sampling does not require clock extraction, and can be done at less than the bit rate. This will result in cheaper electronics and we expect adoption of asynchronous monitoring will be more common. However it will take longer to collect the histogram data.

Given the industry standards on bit rates, provided the sampling rate is relatively prime to 622Mbit/s, 1.25Gbit/s, 2.5Gbit/s, 10Gbit/s and 40Gbit/s, a single sampling rate will provide an asynchronous histogram for all these bit rates.

We can expect the monitor detector circuit to be similar to a typical receiver circuit with a detector followed by a trans-impedance amplifier and then the sampler. (See Figure 3)

Although this layout has the advantage of simplicity, it presents a problem in that the trans-impedance amplifier must have a bandwidth that can accommodate the fastest bit rate to be sampled. This design may present several problems.

The first is fundamental to the monitor's operation. The monitor depicted in Figure 3 is an analog system, even though it is monitoring a digital optical link. Therefore, we need to apply analog analysis to determine the maximum amount of noise that the monitor can be allowed to add to the tapped signal.

The "signal" is the tapped-off optical signal, E_{mon}, which enters the monitor fibre. The noise processes arise from any optical amplification deployed in the monitor fibre, detector noise processes and noise from the trans-impedance amplifier. We represent these noises with a variance σ_{mon}. (We assume these noise processes are adequately well modelled as Gaussian processes.)

It is worth noting that the tapped signal will have already been subject to distortion and noise due to processes in the optical link. The purpose of the monitor is to quantify these processes and to trigger a network management alarm if necessary.

The impact of increasing σ_{mon} is to broaden and merge the peaks of the histogram of the detector current, which is proportional to $|E_{mon}|^2$. This can result in details of E_{mon} being buried in the monitor noise, as shown in Figure 4. This figure shows the resulting histogram for three values of the SNR at the sampler, due to added Gaussian noise. Figure 4 was produced using a numerical simulation of a 60km, 10Gbit/s link with standard single mode fibre (dispersion = 17ps/nm/km, loss = 0.2dB/km, effective area = 80μm^2). The simulation included the tap, optical amplification in the monitor fibre (if required), the detector and added optical and electrical noise.

The example shown in Figure 4 corresponds to a 10Gbit/s signal that has been severely distorted due to fibre dispersion. A characteristic of dispersion dominated histograms is the spike seen in the region of 0.5mA monitor current. Although this spike is clearly visible for the higher SNR values, it becomes buried in noise for the lower SNR values. In fact, for an SNR value of 10dB, one may incorrectly conclude that this signal is suffering from too much added noise (such as Amplified Spontaneous Emission) rather than being dispersion affected.

The histogram for SNR = 20dB closely resembles the histogram at the decision point current of the link (the solid line). From this we can see that a SNR of around 20dB is required for the histogram to reveal the details of the monitored signal.

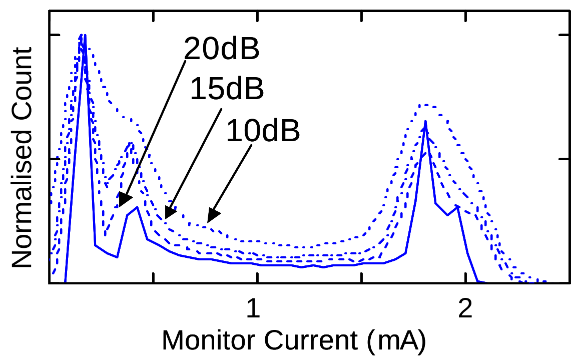

Figure 4 *Histogram resolution for a range of SNR ratios at the sampler. The lower the SNR, the more detail the monitor loses.*

The next issue relates to link design. It is well understood that the optical signal power on a receiver, which is required to attain a given Bit Error Rate (BER), is dependent upon the signal bit rate. The lower the bit rate, the smaller the required received signal power (or OSNR in an optically amplified system). This fact allows lower speed optical links to be designed with lower receiver powers.

If this approach to link design is maintained in an AON (or if the AON carries legacy systems) we could have a monitor trans-impedance amplifier with a large (noise) bandwidth (eg. 40GHz) but a very low power narrow bandwidth signal (eg. 622MHz). In this case, even without optical amplification in the monitor, the noise from the trans-impedance amplifier may then swamp the monitor signal producing a noisy histogram.

A solution to this will be to design all the link channels, irrespective of bit rate, with equal power. This is a well-established approach for single bit rate WDM systems, irrespective of optical monitoring; however, it would result in all channels being designed as though they are 40Gbit/s channels. This results in over-design of the lower speed channels.

This equal channel power approach also may complicate the analysis of the histograms. A typical detector integrates the signal power over each bit period, via low pass filtering. (This is why lower speed signals can operate at lower channel powers.) In contrast, the monitor is more like taking short “snap shots” of the signal power. Therefore, in so far as added noise is concerned, a given histogram shape will correspond to a lower BER for slower channel bit rates.

III. POWER CONSIDERATIONS

The amount of power required on the monitor detector is a compromise between several conflicting requirements. As stated above, an optical SNR at least 20dB is required at the sampler. We also wish to minimise the amount of power tapped from the signal fibre, since this represents a loss in the signal path. We also need to consider the resolution required of the monitor.

The monitor repeatedly samples the amplified PIN output current, and then stores these values to construct the histogram. This requires converting the analog power measurement into digital form for storage (in RAM) and compilation into the histogram. The measurements are therefore subject to digitisation noise, which is reduced by minimising the power intervals of digitisation. A typical modern sampling oscilloscope has a power resolution of about 10μW for such measurement. (Ignoring noise, for PIN responsivity of ~0.5 and trans-impedance amplifier gain ~200, the value of 10μW corresponds to ~1mV resolution in the A/D converter in the sampler.) The number of digitisation levels is typically done as a power of 2. We select 16 levels (ie. 4 bits to encode each level) as a lower limit. That is, we require the monitor power resolution to be at worst $1/16^{th}$ of the tapped-off transmitted “mark” power. This requirement means the power of a “mark” on the monitor PIN must be at least 0.16mW. This, in turn, corresponds to a required average signal power of approximately 0.08mW or -11dBm.

It is worth noting that higher powers will require more quantisation levels. To cover the full possible range of power levels, with a resolution of 10μW, may require up to 128 quantisation levels. This gives 7 bits to encode each level.

Using a 40Gbit/s PIN detector followed by a 40GHz bandwidth transimpedance amplifier (Figure 3), we find the noise at the sampler is dominated by the transimpedance amplifier noise. Assuming typical published values for the PIN and amplifier equivalent input current noise of 15μA, to attain an SNR = 20dB the power on the PIN must be at least -7dBm (> -11dBm based on power resolution estimates given above) which now makes this power the key requirement.

Assuming the monitor is deployed just after an optical amplifier (see discussion below) we can assume the signal power in the signal fibre is around 0dBm. The tap will tap off say, between 1% and 5% of the signal. This gives the signal power in the monitor fibre of -20dBm and -13dBm respectively. Both of these are less than -7dBm, hence some form of optical amplification and ASE filtering will be required.

The most convenient optical amplifiers will be either a Semiconductor Optical Amplifier (SOA)[8] or a compact EDFA[9] The price of an SOA and compact EDFA is approximately $(US)1000. To ensure the SNR at the sampler > 20dB, we need to consider optical amplifier noise. For an SOA, Noise Figure (NF) is about 7dB and for a compact EDFA, NF is about 4dB.

Using these figures and an optical channel bandwidth of 100GHz, we find the noise contributions from the optical amplifier and transimpedance amplifier are of similar magnitude. This means we must increase the optical power on the PIN to attain the required SNR of 20dB. The required optical amplifier gain and power on the PIN for a 1% and 5% tap are shown in Table 1.

Despite the lower NF, the EDFA does not give a significant improvement relative to the SOA due to the low amplifier gains and relatively high trans-impedance amplifier noise.

Gain/Power	1% Tap	5% Tap
SOA	15dB/-5dBm	6.6dB/-6.4dBm
EDFA	14.3dB/-5.7dBm	6.4dB/-6.6dBm

Table 1 *Optical amplifier gain and power on the PIN which give SNR = 20dB at the sampler for combinations of tapped off power and optical amplifier type.*

The issue of the tap fabrication may also be a consideration. We can expect that a batch of “5%” taps will, in fact, have a range of actual tap values. Depending upon the spread of actual tap values arising from a given fabrication technology, a tap ratio of more than 5% may be required to ensure an acceptable SNR at the sampler.

A common tap value used in histogram experimental research is 10%. Although this reduces the demands on the monitor specifications it represents at least 0.5dB insertion loss per monitor point. The 1% and 5% taps give a loss of 0.04dB and 0.22dB respectively. Therefore, in a long haul system, in which there may be many monitor points, the loss due to 10% taps will accumulate much more rapidly.

IV. MONITOR ASSEMBLY

The deployment of a separate monitor for every wavelength will significantly increase the cost of network monitoring. Therefore, we now consider an approach that allows sharing of a single monitor across multiple WDM wavelengths in an AON. It is unlikely that histogram monitors will be used to detect catastrophic failures in an AON. Fibre breaks, power failures and the like will be most economically dealt with by optical layer protection. It is more likely histograms will be used to analyse gradual degradations in system performance. For example, increasing dispersion due to filter frequency drift or increasing cross talk due to increased traffic in the AON. Such degradations, which may increase over hours or even days, will result in a gradual increase in the BER and cannot be detected using other all-optical monitoring methods.

Detecting such gradual changes in link performance does not require continuous monitoring of the optical signal. Rather, repeated monitoring over a time scale much less than that of the degradation will be adequate. This will enable a single monitor, as depicted in Figure 3, to be shared over several WDM channels.

In this set up, a monitor is shared amongst several wavelengths. The sharing is attained using a low cost Nx1 fibre switch, which sequentially directs the tapped power from each channel in the demultiplexed fibres into the monitor in sequence. The Controller coordinates the switching with the sampler to ensure the newly collected data corresponds to the appropriate histogram.

Because this design is sequentially monitoring the channels, we need to determine the data collection time for each channel. Also, we may find that, for a very high channel count WDM system, we may require several such assemblies spread across the WDM channels.

The data collection time is determined by the required accuracy of the histogram and the sampling rate. We can calculate approximate minimum data collection times for the standard data rates. We assume a sample collection rate is 2.135×10^5 samples/sec, based upon the sampling rate of a commercially available sampling CRO. This rate is relatively prime to all the data rates under consideration. We assume a sample window of 5ps. Hence, we have 20 sample intervals per bit period for a 10Gbit/s signal. We require at least 64 samples per 5ps window to provide 95% confidence that the sample mean is within half a standard deviation of the actual mean. (ie. we have enough samples to give an accurate histogram.) With these requirements, Table 2 displays the approximate number of data points that must be collected and approximate sampling time required. Provided the sampling rate is relatively prime to the bit rate, the total number of samples required is independent of the sampling rate.

Note that, with a fixed sample rate, the number of samples taken per bit period is much larger for the lower bit rate systems. Unfortunately, this is the opposite of what we prefer, since the higher bit rate systems are less robust to degradation and so will require more monitoring.

Bit Rate	Samples/Bit Period	Total # Samples	Sampling Time (msec)
622Mb/s	320	21000	103
1Gb/s	200	14000	66
2.5Gb/s	80	5500	27
10Gb/s	20	1400	6.5
40Gb/s	5	350	1.6

Table 2 *The requirements for accurate histogram data. The Samples/Bit Period is based upon a sampling interval of 5ps. Total number of samples is determined by the required accuracy of the histogram, see text. The Sampling Time is the time taken to collect the Total # Samples with a sampling rate of* 2.135×10^5 *samples/sec.*

As can be seen from Table 2, the data collection times are relatively short. In fact, the time scale is more likely to be dominated by the processing the data for the histogram readout. Therefore, we can be confident that repetitive sampling of multiple channels can be done on a time scale well short of any gradual degradation of the link.

It should be noted that the times listed in Table 2 are based upon collection of 64 data points per bin. Should a larger number of data per bit be required (to improve the resolution of the histograms for analysis), the collection times will be greater. Because this device will monitor link degradations with a time scale expected to be over hours or longer, even with a requirement of 64000 data values per 5ps this device can collect this amount of data in seconds.

V. CONCLUSIONS

In this paper, we have discussed some of the practical issues that must be addressed when deploying optical histogram monitors, which are based upon asynchronous sampling of the optical signal. Sampling is the only optical monitoring technique that can provide information regarding degradation of the signal due to phenomena such as fibre dispersion, Self Phase Modulation and Cross Phase Modulation. Therefore, it is highly likely some form of sampling will be required in an AON.

Because these monitors will be deployed throughout the network, it will be crucial to minimise their cost. The monitor design considered in this paper is simpler (and so cheaper) than other proposals [7]. This design can spread the cost of the more expensive components across multiple channels. Only the taps need be deployed on a one-per-channel basis. The penalty paid for this simplicity is the reduced number of sampling intervals for the higher data rates.

Using some basic values for the components for an optical monitor, it was shown that we can expect these devices to be feasible for both 1% and 5% tap from the signal fibre with optical amplification. We need to minimise the tapped power since this represents a loss in the link which must be compensated.

Many of the issues raised in this paper are not closed. A significant amount of research is yet to be undertaken into the development and deployment of all optical monitors. For example, should the histogram data be analysed at the monitor, or should all the histograms be processed centrally? With centralised analysis, the histograms from many monitors may be analysed collectively. This may enable the use of machine intelligence to attain a deeper understanding of the network as a whole.

The development of a methodology for analysing the histograms is also in its infancy with several approaches being proposed [10,11,12,13]. Depending upon the approach adopted, the amount of data required for collection may differ. However, as shown above, this monitor can provide a collection rate should be more than adequate even for the most demanding of analysis techniques.

Despite progress in these areas, unless these monitors can be cost effectively deployed in an AON, they will not be used. Taking this a step further, given the stringent requirements on telecommunications providers for network reliability, if a communications network cannot be monitored and managed, it will not be deployed. Therefore, it may be that optical monitoring will be a pre-requisite, rather than a side issue, for eventual wide spread deployment of fully transparent All Optical Networks.

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