

A high-loss loopback monitoring system enhancement using an increased averaging repeatability at the supervisory receiver

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We present theoretical and experimental investigation of enhancing the performance of a WDM-based high-loss loopback monitoring system using an increased number of averages of the returned supervisory pulses. We prove that the electrical signal-to-noise ratio of the supervisory signal is significantly improved with more averaging repeatability at the supervisory receiver. We also show that such an enhancement will be at the expense of the pulse measurement time if large number of averages is used. Therefore, we explore the optimal averaging situation in which the monitoring performance is reasonably enhanced while a satisfactory measurement time is simultaneously maintained.

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1. Introduction

Long distance optically amplified communication lines require remote and continuous monitoring to instantaneously discover the possible damage locations along the system. Unfortunately, this requirement has not been met by the most common monitoring technique that uses coherent optical time domain reflectometry (COTDR) [1] for a few main reasons. First, the use of optical coherent detection is still relatively costly. Second, the COTDR is typically used with inactive fibers because it needs a high-power probe signal to yield sufficient Rayleigh backscattering, which corrupts any propagating data signal. Third, the Rayleigh backscattered signal needs to bypass the in-line optical amplifiers due to the presence of optical isolators that are used to prevent lasing in the amplifiers [2].

In fact, the above obstacles have been overcome by proposing a high-loss loopback system [3] in which a simple passive loopback fiber circuit is used to return a probe pulse to the transmitter without affecting the data signals. This approach is shown in Fig. 1. The loopback circuit is set up after each amplifier such that it provides a symmetric connection between the existing two opposite fiber lines. Using optical attenuators, the loopback circuit can return a highly attenuated portion of the optical traffic including a supervisory signal. At the transmitting terminal, the weakly returned supervisory pulses are detected where each pulse is received at different time according to its corresponding amplifier's distance. Therefore, the fault location is only deduced from the returned pulse level and delay as no digital information is returned. Typically, the fault in optically amplified systems occurs due to low gain in an optical amplifier.

The proposed system described above was fully investigated and experimentally implemented [4], where successful monitoring was accomplished through returning a highly attenuated probe signal in a satisfactory time period after propagation over long fiber distance. That was achieved by developing a supervisory transceiver set (referred to as *line monitoring equipment, LME*) such that an appropriate LME probe signal is generated, transmitted and then identified after 45 dB attenuation in the loopback circuit. Further investigation of the same system was successfully demonstrated [5] by increasing the launched LME signal power to enhance the monitoring while simultaneously keeping the data signals unaffected. That is useful in practice as in a few critical situations, the LME pulse cannot be identified unless its input power is fairly increased.

In principle, the number of averaged pulses in the LME receiver plays an important role in the performance of the probe signal. This factor was not studied in the experiments mentioned above, where the number of averages was fixed throughout each investigation. In specific, the latter experiment [5] arbitrarily used 10,000 averages to allow high repeatability, while the preceding one [4] used far fewer averages to minimize the measurement time and to let the results base on the input power only. Therefore, it is essential to investigate the potential enhancement of the probe pulse detection due to increasing the number of averages while keeping the probe signal power at minimum. Nevertheless, this would result in compromising the pulse measurement time which was originally proposed to be as short as possible. Thus, it is worth exploring the maximum acceptable repeatability that ensures considerable improvement in the LME signal's eSNR whilst maintains the shortest possible detection and recovery time.

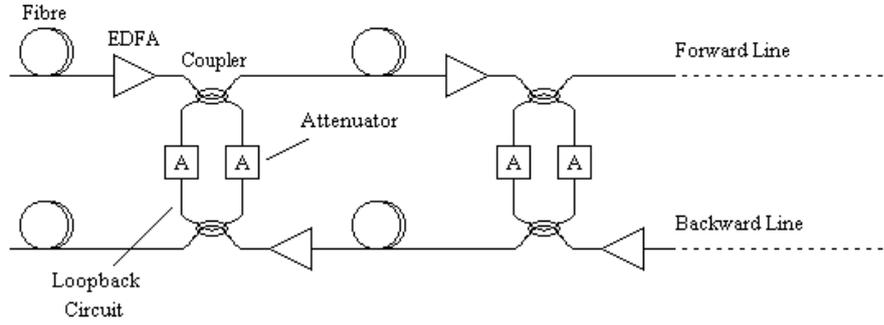


Fig. 1. Schematic diagram of the high-loss loopback system

1.1. Pulse repeatability

Given a minimum required electrical signal-to-noise ratio $eSNR_{req}$ to achieve the desired repeatability, the number of samples required is:

$$n_s = \frac{eSNR_{req}}{eSNR} \quad (1)$$

where $eSNR$ is corresponding to 1 average i.e. no repeatability.

If the sample rate is $2B_e$ (which is the Nyquist rate), then the number of samples per pulse is:

$$n_{sp} = 2B_e T_p \quad (2)$$

where B_e is the electrical bandwidth and T_p is the LME pulse time. Thus, the number of transmitted pulses required is [6]:

$$n_p = \frac{n_s}{n_{sp}} = \frac{1}{2B_e T_p} \frac{eSNR_{req}}{eSNR} \quad (3)$$

In practice, this can be approximated as:

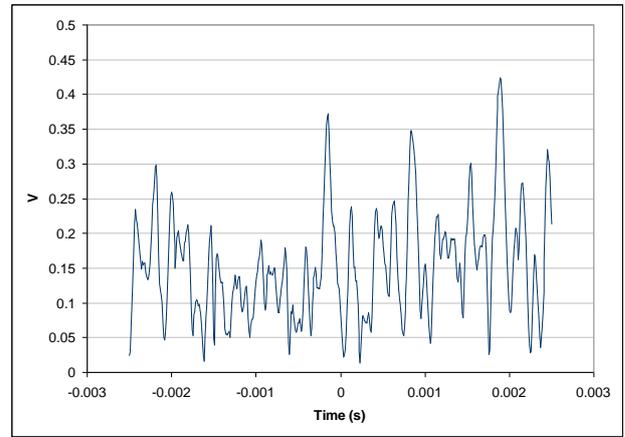
$$eSNR_{req} \approx n_p eSNR \quad (4)$$

It can also be expressed in decibels as:

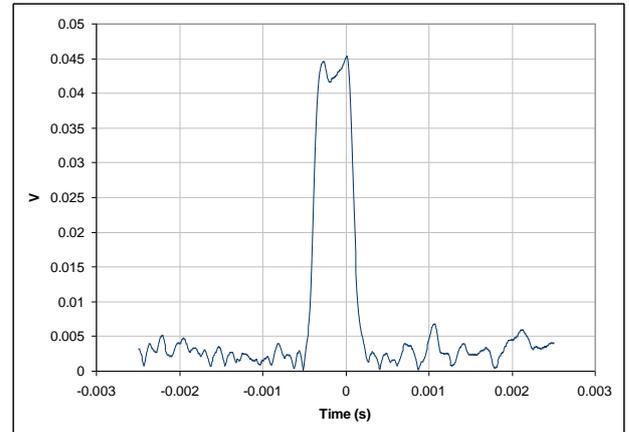
$$10 \log(eSNR_{req}) \approx 10 \log(n_p eSNR) \quad (5)$$

Therefore, the quality of the $eSNR$ measurement of the returned LME pulse is almost directly proportional to the number of pulses (hence averages) taken for the measurement.

The above implies that the probe signal recovery can be enhanced proportionally just by increasing the number of receiver averages in practice. For example, Fig. 2 shows a back-to-back LME pulse with no averaging in (a), and after 4096 averages in (b). It is obvious that the pulse is not discernible until averaging is applied, where it improves linearly according to equation (4). Moreover, with 4096 averages, the noise amplitude is reduced by roughly two orders of magnitude.



(a)



(b)

Fig. 2. Back-to-back LME pulse with: (a) no averaging; (b) 4096 averages

1.2. Pulse measurement time

Given the pulse repetition time T_R , the measurement time T is then given by:

$$T = n_p T_R \quad (6)$$

Using equation (3), the measurement time becomes:

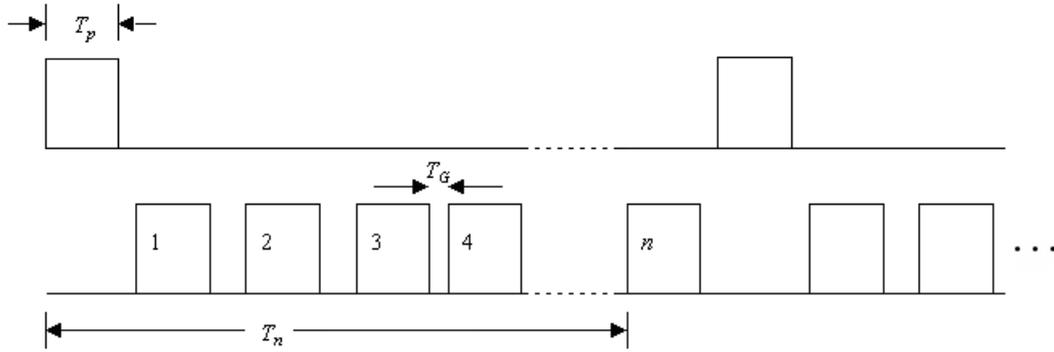


Fig. 3. Launched (top) and returned (bottom) LME pulses

$$T = \frac{T_R}{2B_e T_p} \frac{e\text{SNR}_{req}}{e\text{SNR}}$$

$$\approx T_R \frac{e\text{SNR}_{req}}{e\text{SNR}} \quad (7)$$

where T_R is described as:

$$T_R = T_n + T_p + T_G \quad (8)$$

since T_n is the n th pulse arrival time and T_G is the time between the closest arriving pulses as shown in Fig. 3.

Therefore, the measurement (or identification) time of the returned LME pulse is also directly proportional to the number of averages according to equation (6).

This paper uses the above simple basis to optimize the performance of the LME system demonstrated previously [4]-[5].

2. Experimental setup

Fig. 4 shows the experimental setup for this investigation. For consistency, we use the same configuration used before [5] except that a gain flattening filter (GFF) is added on the recirculating loop to provide an in-line compensation of the spectral gain profile of the cascaded EDFAs [7]. Therefore, the data signal wavelengths (at 1556.4 and 1557.4 nm) are restored to approximately the same intensity; hence similar OSNR characteristics. This shall improve the whole system performance including the LME pulse behavior (at 1558.4 nm).

The insertion loss of the GFF is 2 dB which is obviously compensated by its following EDFA. Moreover, the GFF has variable extinction that is inversely proportional to the flattening range. Since we have only three channels (two data and one LME), the extinction is chosen to be high so that a high amplification is achieved in our operating wavelength region only. This shall minimize the overall noise accumulation throughout the experiment.

The experiment involves monitoring of one propagation path [4]-[5] because a full dual-path system requires setting up two identical recirculating loops. This would increase the cost considerably while no extra benefit is attained. The real system is supposed to be symmetric, and testing one path is enough to predict the behavior of the other path. However, even though there is no counter-propagating LME signal seen in Fig. 4, the real backward traffic is still properly simulated. This is because the counter-propagating probe signal is supposed to be extremely small; hence its effect is totally neglected. This practically allows saving the cost of setting up another LME set.

3. Results and discussions

3.1. Recirculating loop performance

The system is intended to operate at the optimum launched power of the data signals as well as the LME signal. The optimum LME signal power is -8 dBm [4]. For data signals, Fig. 5 shows the maximum distance achieved with $\text{BER} = 10^{-9}$ versus the individual data signal's launched power. It can be seen that the optimum power is achieved at around -1 dBm, where the maximum propagation distance reached is $\sim 5,400$ km. This result is much better than that obtained earlier [5] i.e. without using GFF. Such an improvement can be justified by Fig. 6, which shows a comparison between the LME signal power evolution in the loop with GFF and in that without GFF. In the case of no GFF, the power drops down in distance where it becomes lower by more than 3 dB after 4,500 km. With GFF, the power increases and becomes higher by almost 3 dB at 3,000 km; it then fluctuates and eventually starts to drop very slowly after 4,000 km. The result is that the power is still reasonably high after 4,500 km and has a huge difference to that measured without GFF (> 5 dB). This will absolutely result in an improvement in the eSNR of the returned LME pulse as shown later.

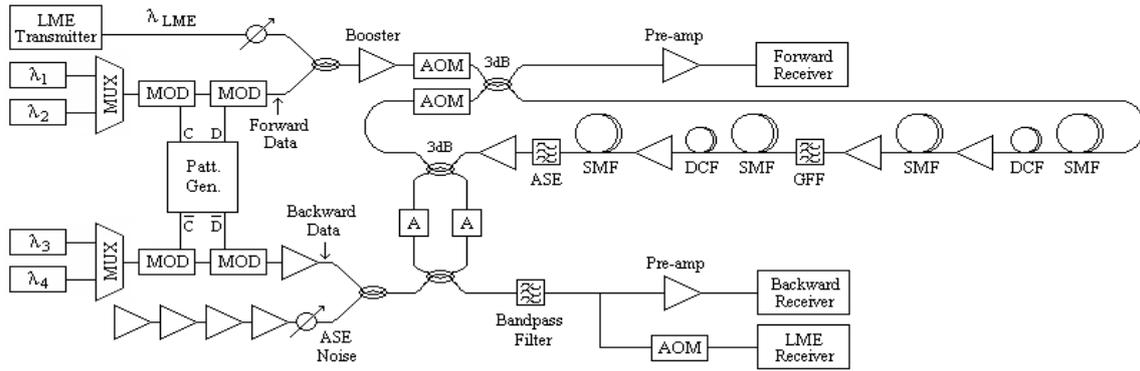


Fig. 4. Experimental setup

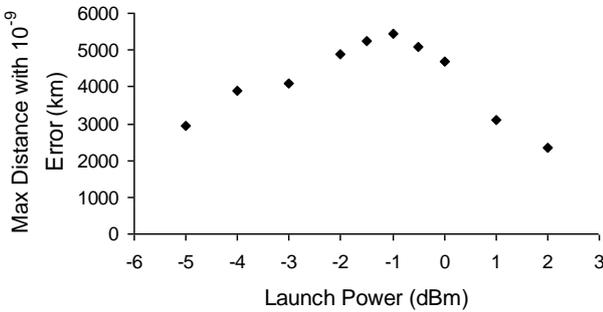


Fig. 5. Maximum transmission distance with 10⁻⁹ errors versus individual data signal's launched power

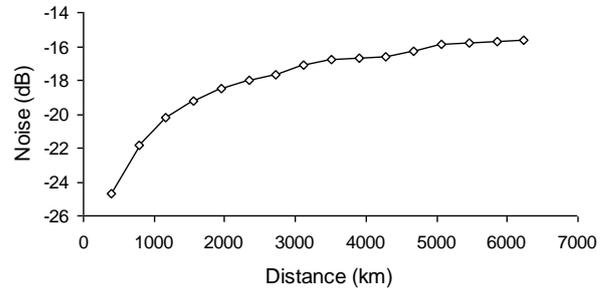


Fig. 7. Noise versus distance for the current setup having GFF

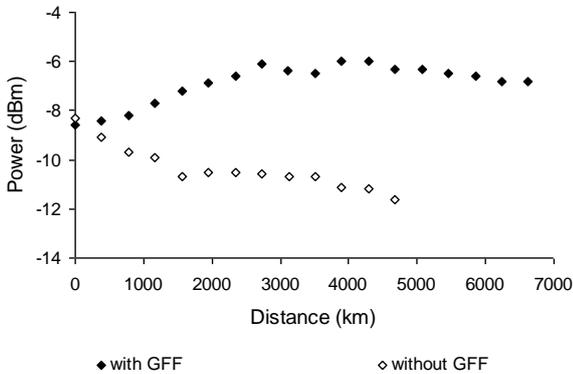


Fig. 6. LME signal power evolution with distance for the loop setup with GFF and without GFF

3.2. Backward noise

As done before [4]-[5], the backward noise is set in a way such that it matches the forward noise at different number of recirculations. The noise measurements for the current setup with GFF are different as shown in Fig. 7, using the optimum power. Note that these measurements are taken within the operating signals region, so even though the noise curve is higher than before (due to a high GFF extinction), the average noise power across the C-band spectrum is still minimized.

3.3. LME signal performance

As a result of running the supervisory experiment using the current setup, the LME receiver has been successful in detecting and recovering the returned LME probe signal after 6,000 km with 45 dB loopback attenuation. Such distance can simulate real segments of the global fiber network as several transatlantic and transpacific submarine links stretch up to 6,000 km.

The eSNR measurements (in dB) for the LME signal as a function of propagation distance are shown in Fig. 8, using 10,000 averages. In general, the LME signal has better performance than before [5] although no repeatability increment is applied yet. This is again due to the GFF.

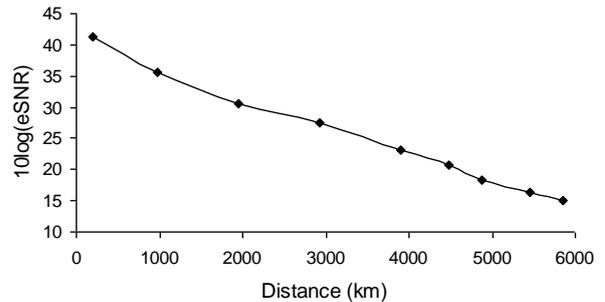


Fig. 8. LME signal's eSNR versus distance using 10,000 averages

3.4. Averaging results

In this section, we examine the quality of the returned LME pulse with different averaging repeatabilities at the LME receiver. Fig. 9 shows the resulting LME signal's eSNR versus number of averages for 3,000 km and 6,000 km. A logarithmic scale is used on the x -axis to match the y -axis and to contain large averaging values. Also, the eSNR values on the y -axis are doubled just to attain slope ~ 1 , thus simplifying our calculations. However, the measurements nearly show linear improvements in the eSNR as a function of number of averages, giving that equations (4) and (5) are practically verified. This basically enables monitoring enhancement without requiring extra power, where better performance is simply achieved by using high receiver repeatability as concluded in section 1.1.

On the other hand, the supervisory pulse may not be identified with small number of averages, thus no monitoring can be performed. This can be realized in the case of 6,000 km in Fig. 9, where no eSNR measurement can be taken for number of averages less than 500. However, using equation (4), the $eSNR_{req}$ for 500 averages is ~ 20 dB assuming eSNR is -6.68 dB for no averaging (1 pulse) as obtained from the y -intercept of the 6,000-km curve. This calculated value is in reasonable agreement with the practical counterpart shown in Fig. 9 for 500 averages.

In contrast, the $eSNR_{req}$ for 10,000 averages is 30 dB for 6,000 km according to Fig. 9. This value is in perfect agreement with the corresponding one shown in Fig. 8 if being divided by 2.

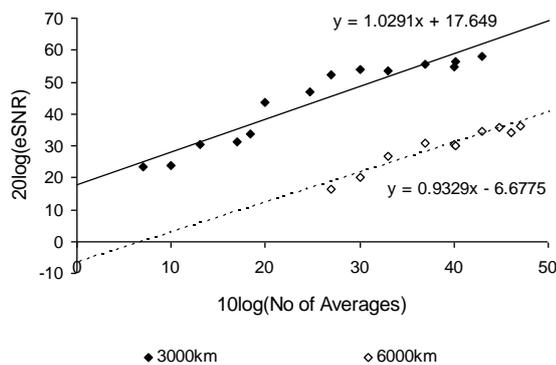


Fig. 9. LME signal's eSNR as a function of number of averages

3.5. Measurement time results

Again, the time required by the receiver to recover the LME supervisory signal is also proportional to the number of averages according to equation (6). Experimentally, Table 1 shows the measurement time required in practice for different number of receiver averages after 6,000 km. Note that this is the total identification time that refers to T in equation (6), while the other time components defined

in section 1.2 and shown in Fig. 3 are already implicitly embedded in the measurement of T .

Since the LME pulse repetition rate ($1/T_R$) is 8 Hz [4], it can be seen that the identification time measured in practice is in good agreement with that described by equation (6). For instance, the time needed for 8,000 averages is 1,000 sec using equation (6), which is fairly close to its measured counterpart in Table 1. However, it is also seen that the receiver needs as long as ~ 40 min to recover an LME signal if 20,000 averages are used. This time will obviously double with 40,000 averages, giving that a balance between the time and performance is required.

In contrast, the minimum time required for good quality measurement over 6,000 km is 1 min that is corresponding to 500 averages in Table 1. This is great as such amount of time is considered very short in the context of monitoring long-haul WDM systems.

Table 1. Probe signal measurement time versus number of averages

No. of averages	Measurement time T (sec)
50	6
100	12
150	18
200	24
300	36
400	48
500	60
700	84
1000	120
1500	180
2000	240
2500	300
3000	360
3500	420
4000	480
5000	600
6000	720
7000	840
8000	960
10000	1200
12000	1440
14000	1680
17000	2040
20000	2400

3.6. Averaging against power

The OSNR for the returned LME signal can be approximately worked out for the above system. The LME has -8 dBm input power, thus it has ~ 1 dBm before the loopback coupler if the loop is balanced [4]. From Fig. 6, the LME signal power improves over distance where it is

increased by roughly 2 dB if measured after 5,400 km, which is the maximum distance for the existing data signals. The resulting 3-dBm LME signal is then attenuated by 45 dB via the loopback circuit and becomes -42 dBm. This signal is swamped by the backward noise of -9.8 dBm (-15.8 at the loop output after 5,400 km, offset by +9 and attenuated by 3 dB through the backward loopback coupler [4]). The received OSNR is therefore ~-32 dB. It was shown earlier [4] that the LME receiver has the ability to detect and recover an LME pulse in the region of -34 dB. This apparently means that the LME input power can be further reduced as the original approach aims to use the lowest possible LME signal power. From equation (4) and Fig. 9, there is a chance to increase the number of averages if the LME signal is not identified with reduced input power values.

In our experiment, the LME signal is lower than the data signals by 7 dB. Having run the experiment with reduced LME signal power, it is found that it can still be recovered if the power is dropped by up to 2 dB. This is practically obtained by using 10,000 averages or more. If the LME signal is dropped by 3 dB and the difference from data signals becomes 10 dB, the LME pulse cannot be identified unless the number of averages is $\geq 20,000$.

3.7. Averaging choice

The averaging choice must be based on the above three LME factors: eSNR, input power and measurement time. In practice, the minimum number of averages can be 500 but there is no limit for the maximum. Nevertheless, if the measurement time exceeds a certain level, the monitoring process experiences a considerable delay and the system continuity is partly broken. This means that the proposed out-of-band [4] LME system would lose its speed feature in comparison with other approaches [8]. We believe that the maximum acceptable measurement time is half an hour, which corresponds to 15,000 averages in our 6,000-km system. However, there is no insistent need to exceed 10,000 averages in most cases as long as the LME signal power is well below the data signals power and no necessity for additional LME power saving [5]. Thus, the ideal repeatability value for such system can be around 10,000 averages at which the complete measurement time is relatively short (20 min) and the system performs reasonably well.

For systems that involve longer than 6,000 km fiber in their single path, the number of averages is preferred to be reduced to maintain a 30-min detection time. For instance, assume we have a 12,000-km fiber link; the measurement time values shown in Table 1 will theoretically be doubled. Thus, the appropriate repeatability can be around 8,000 averages if we want to secure half an hour recovery period. In reality, some transatlantic and transpacific links stretch up to 9,000 km distance. In this case, the T values in Table 1 are theoretically multiplied by a factor of 1.5. Therefore, the ideal number of averages can still be around 10,000 where the measurement time needed to test all the in-line

amplifiers does not exceed 30 min and the LME signal performance is satisfactory.

4. Conclusions

In this paper, we successfully demonstrated a high-loss loopback monitoring system enhancement using an increased averaging repeatability at the supervisory receiver. We theoretically and experimentally proved that the electrical signal-to-noise ratio performance of the returned probe signal is linearly improved with the number of averages. Such an improvement is useful where we can save more optical power of the transmitted probe signal. On the other hand, we investigated the measurement time of the probe pulse against repeatability and showed a linear increment in both experiment and theory. This resulted in a relatively long detection time when large number of averages was used. Therefore, we discussed the optimal averaging choices by which the monitoring performance is reasonably enhanced and a satisfactory measurement time is maintained. As a result, the typical repeatability value of the LME receiver is 10,000 averages for all long-haul optically amplified systems involving up to 9,000 km fiber link. Such averaging level ensures high-quality detection and identification of all cascaded LME pulses in no longer than half an hour, including those pulses returned from the far end of the optical fiber line. In addition, this averaging choice allows keeping the probe signal power at minimum as initially proposed for such supervisory system.

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