Low-cost Optical Reflection Techniques for the Assessment of Intra-office Optical Channel Quality

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driver of the proposed solution, a broader range of applications within metro and access systems is also foreseen.

II. REFLECTOMETRY PRINCIPLES

Most of the current technical solutions used to monitor the physical integrity of the optical networks are based on reflectometry [2]. This technique enables the assessment of the characteristics of a certain medium by the analysis of the back reflections that continuously occur [2]. The backscattering of an optical signal is due to microscopic variation in the fiber material density, resulting in light scattered back in the opposite direction of the pulse propagation, known as Rayleigh backscattering [3]. Moreover, as the optical signal propagates in the fiber, it may run into waveguide discontinuities such as breaks, splice points, connectors or the fiber end, and part of the optical signal is back reflected [4]. This is called Fresnel reflection, which is used by reflectometers to determine the reflective points location [4]. For an open fiber end, the Fresnel power reflection coefficient is approximately 4%, being this case the worst case scenario [2].

III. ACTUAL MONITORING TECHNIQUES

The OTDR (optical time-domain reflectometer) is the best known technique to assess optical fibers [2]. The OTDR is linked to one end of the fiber under test and transmits optical probe signals [4]. The resulting back reflections are received by a photodetector which measures the intensity of the returned reflections along time [4]. This technique faces many challenges such as dead zones or ghosts reflections [5]. Both of these events are imposed by high intensity Fresnel reflections and difficult the analysis of the reflectogram [5]. Additionally, it is not suitable to test short-length optical fibers since the reduction of the probe pulse width to impose resolution, results in a diminished backscattered signal level [6]. In order to reduce operation expenditure, the OTDR functionality is now embedded in most of the commercial transceiver equipment [7].
An OFDR (optical frequency-domain reflectometer) can be categorized by 1-OFDR (incoherent OFDR) or C-OFDR (coherent OFDR) [5]. This technique uses a wavelength-swept laser and the final reflectogram is obtained through Fourier transform analysis [2]. In C-OFDR (the most common OFDR technique) the optical signal frequency is swept linearly in time [5]. This signal is split by an optical coupler to the fiber under test and to a mirror [5]. Then, the test signal returning from the fiber and the reference signal are coupled and the interference between them is observed [2]. This interference signal contains the beat frequencies which are converted to the time-domain by inverse Fourier transform [2]. OFDR faces a unique challenge imposed by the lack of laser sources with high-speed wavelength sweeping [2]. For C-OFDR, the signal polarization mismatch between the interferometer arms can be a problem [2]. Also, the possibility of ghost reflection events cannot be ruled out [5]. Moreover, the OFDR requires great computational effort.

Regarding the described techniques, the OFDR has important advantages over the OTDR technique: larger sensitivity, larger dynamic range and better resolution [8]. However, the OTDR is the most used technique for optical fiber assessment nowadays. It can monitor long fiber spans and the tradeoff between spatial resolution and measurement range is satisfactory [2]. In addition, the OTDR is a much cheaper technique than the OFDR [8].

In 2013, Zhao et al. presented a new method that reduces significantly the costs of fiber assessment [9]. This low-cost and innovative idea uses the traffic signal to monitor optical fibers [9]. The design of the monitoring structure is exposed in figure 1.

Although Zhao et al. have already proposed a monitoring structure with similar principles, operation costs can further be reduced. For instance, the circulator presented in figure 1 is a relatively expensive equipment. The proposed monitoring structure makes us of less resources to locate impairments.

### IV. ONLINE REFLECTOMETRY MIXING

The online reflectometry mixing monitoring structure is based on the Michelson interferometer configuration, as shown in figure 2.

The online reflectometry mixing block diagram.

The data modulated optical signal from the laser source, is injected into an optical coupler, which splits the optical signal to the fiber under test and to a mirror. The reflected signal from the mirror, which serves as reference, is mixed with the back reflections from the optical channel and the resulting signal is received by the photodiode. In order to simulate the presence of several faults, several fiber sections are sequentially linked to the output connector and, at the end of each section, a reflective event is implemented.

The electric field, $E$, that reaches the photodiode is given by

$$E = [F_s \beta e^{i\psi} + \sqrt{M}] E + F_r (1 - \beta) \sqrt{\epsilon(1 - \epsilon)} E_0(t) \cos \left( w_0 t + \frac{\pi}{2} \right),$$  

where

$$F_s = \sum_{k=1}^{N} \sqrt{R_k} \prod_{m=1}^{R} (1 - R_m) (A_{1m} e^{i\phi_m}) \right)^2; R_0 = 0,$$  

A tap of the data traffic from the transmitter that is used as reference, and the back reflected signal resulting from eventual faults on the fiber are received by independent photodiodes [9]. Afterwards, the output signals from the photodiodes are processed in the monitoring module and fiber impairments are diagnosed [9]. Hence, by using the traffic signal as probe, one does not have to disconnect the system in order to examine a fiber plant [9].
In order to be able to distinguish eventual back reflections from the fiber, the output detected signal must be submitted to a digital signal processing step. This step is accomplished by a monitoring module that employs the correlation technique. In order to explain the result from the auto-correlation of the monitoring structure output, the case in which the laser source transmits optical pulses with width \( W \) and period \( T \) is assumed. In this explanation, it is considered that the reflection occurs in a distance longer than the optical signal coherent length. Figure 3 a) presents the plot of the signal evolution over time while b) presents the trace from its respective auto-correlation.

The optical signal in figure 3 a) is described by

\[
H_1(t) = \sum_{k=1}^{\infty} A \text{rect} \left( \frac{t - kT}{W} \right),
\]

where \( A \) is the signal amplitude and \( \text{rect}(t) \) is the rectangular function.

The trace from the auto-correlation of this signal is a well-known result from the literature [10].

As already mentioned, when an impairment exists, the monitoring structure output signal is the combination between a back reflection and the reference signal. When an optical signal propagates in a fiber, it suffers a time delay depending on the fiber length [11]. Thus, a back reflection is delayed in comparison with the reference signal. The back reflection time delay, \( \Delta t \), introduced by an optical fiber is given by [11]

\[
\Delta t = \frac{2nL}{c},
\]

where \( L \) is the location of the reflective event relative to the optical coupler, \( n \) is the fiber refractive index and \( c \) is the speed of light.

Considering the optical signal \( H_1(t) \), its respective back reflection signal is described by

\[
H_2(t) = \sum_{k=1}^{\infty} AR(1 - e) \text{rect} \left( \frac{t - kT - \Delta t}{W} \right),
\]

where \( R \) is the reflection coefficient of the reflective event.

The temporal evolution of the output signal from the monitoring structure is described by the plot in figure 4 a), while b) presents the trace from its respective auto-correlation.

The monitoring structure output signal that is presented in figure 4 a) is described by

\[
H_1(t) = (\varepsilon H_2(t) + H_2(t))\varepsilon.
\]

The highest peaks in the auto-correlation trace of the output signal are due to the correlation between the pulses of the reference signal. By observation of figure 4 b), it is noticeable that there will be an adjacent peak at each side of the highest peaks. The adjacent peaks are due to the correlation between the pulses of the reference signal and the ones of the back reflection signal. As figure 4 b) suggests, the auto-correlation of the output signal, allows the retrieval of information regarding the back reflected signal.

The highest peaks in the auto-correlation trace of the output signal add difficulty to the analysis of the back reflection time delay. Therefore, in order to exclude these peaks from the trace, the designed monitoring module computes the ratio between auto-correlation values of the monitoring structure output signal with the auto-correlation values of the input signal. Since the auto-correlations have different magnitude orders, before the ratio is computed, the values of both auto-correlations must be normalized to the maximum value. Also, the normalized values from both auto-correlations may not match. Therefore, in order to mitigate the undesired peaks and to accentuate the adjacent peaks, the auto-correlation values of the output signal are multiplied by a factor \( \mu \). This factor is the quotient between the mean value of an interval of the normalized auto-correlation values of the output signal, and the mean value of the same interval of the normalized auto-correlation values of the input signal. Figure 5 presents the outcome of the designed technique.
As figure 5 suggests, the back reflection time delay is retrieved by the time of the first adjacent peak. All the remaining peaks are correlation mixing terms and are not considered in the analysis of the trace. Therefore, the plot window dimension must be adjusted for a clear detection of fiber impairments. This introduces a limitation to the measuring range, nevertheless the target intra-office fiber length range is covered. Also, if \( \Delta t > \frac{T}{2} \), then each back reflected pulse will have a significant time difference from its original reference pulse. In fact, in this situation, the back reflected pulse will be closer to the following reference pulse, resulting in an intersection between adjacent peaks in the final output trace. Thereby, the first adjacent peak in the final trace will be an undesirable correlation mixing term that does not represent the real time delay of the back reflection. Hence, the back reflection time delay must not exceed \( \frac{T}{2} \). The red dashed lines mark the adjustment window borders.

Moreover, the time axis of the plot is then converted to distance using equation (4). In order to summarize the proposed monitoring technique, a schematic is presented in figure 6.

V. CONTINUOUS SIGNAL OPERATION

Raman amplification makes use of the SRS (stimulated Raman scattering) occurring in silica fibers resulting in energy transference from the pump to the traffic signal [12]. Considering the proposed monitoring structure, it is analyzed the possibility of monitoring the fiber infrastructure employing the Raman pump back reflection.

The block structure in figure 2 was assembled in a simulation environment and operated with a continuous signal. Although Raman amplified systems need a pump signal with high intensity power, for simplicity purposes, the optical power at the laser source was set to 6 dBm, with negligible linewidth and peaking at 1550 nm. Moreover, the coupling ratio was 80/20 and an additional attenuation of 10 dB, both at the laser output and at the photodiode input, was considered. The attenuation at the laser output was included as a preventive measure to mitigate the effects that the back reflected signal might cause on the laser source. The attenuation at the detector was included to avoid the saturation of the photodiode. The optical fiber length was 1 meter, followed by a reflective event with a reflection coefficient of 4%.

The numerical analysis for this scenario was performed with a Monte Carlo based method. This method is employed to predict the behavior of a system by randomly varying the value of the input variables. The simulation model was repeatedly executed until a sufficient number of combination of input variables was covered, being the output the sum of the results from every simulation cycle. Each cycle produced a histogram, which presented the number of occurrences as a function of the photodiode current values. In order to include the most possible combinations, several system parameters were changed in each cycle: i) the reflection coefficient value, \( R \), was varied from 0 to 4%, ii) the phase imposed by fiber sections, \( \phi \), was varied from 0 to 2\( \pi \) and iii) the signal polarization at the receiver was randomly scrambled. The result from the Monte Carlo simulation is shown in figure 7.
simulation applied to the described scenario is exposed in figure 7.

With resort to equation (1), the photodiode’s output current maximum and minimum values were retrieved. These values are indicated in figure 7 with the vertical arrows, which perfectly match with the limits of the numerical analysis.

In order to represent cases when there is up to 4 reflections in an optical link, 4 fibers sections of 1 kilometer were sequentially connected. At the end of each fiber section, a reflective event with a reflection coefficient of 1% was implemented. Furthermore, the Monte Carlo simulation was applied to each case with the same varying input parameters. Figure 8 presents the Monte Carlo method output for situations with up to 4 reflective events.

As expected, the Monte Carlo simulation output histogram is narrower for cases with less reflective events. With the increasing number of reflective events, the photodiode outputs current values with higher intensity.

In figure 9 the connected black squares represent, for different number of reflective events, the values of the FWHM (full width at half maximum) of the Monte Carlo simulation output divided by the output histogram central current value. The remaining connected symbols represent, for different number of reflective events, the normalized FWHM from the Monte Carlo simulation output when its varying inputs are multiplied by a factor $\theta$. Moreover, the Poincaré spheres represent the state of polarization distribution when factor $\theta$ is 1, 0.1 and 0.01. The individual blue asterisks in figure 9 represent the normalized FWHM of the histograms of the experimental monitoring structure output signal, for different number of reflective events.

Considering the experimental outcome that is marked in figure 9 with blue asterisks, it is demonstrated that through the Monte Carlo simulation, for $\theta$ between 0.01 and 0.05, one can reproduce the experimental results. From figure 9, it is demonstrated the feasibility to use the Raman pump signal to monitor an optical link with several impairments.

![Figure 8 - Photodiode electric output current histograms for different reflective event scenarios obtained with Monte Carlo simulation.](image)

![Figure 9 - Normalized FWHM of the Monte Carlo simulation output as a function of the number of reflective events considering different values for factor $\theta$. The independent blue asterisks represent the normalized FWHM of histograms of experimental results. The Poincaré spheres represent the state of polarization distribution when $\theta$ is 1, 0.1 and 0.01.](image)

VI. MONITORING TECHNIQUE WITH REAL TRAFFIC

The monitoring structure was computationally simulated and the described method was applied for the case when traffic signals are transmitted by the laser source. The SDH traffic frame has overhead information whose purpose is to implement communication protocol features [13]. The first 6 bytes from the overhead section of the STM-1 (synchronous transport module level-1) frame are denominated by frame alignment bytes [13]. These bytes have a constant bit pattern and are used to indicate the beginning of the frame [13]. All the other overhead and payload bytes vary in each frame [13]. Therefore, in order to simulate the broadcast of STM-1 signals, it was compiled a frame where the first 6 bytes have a constant bit pattern while the remaining bytes are pseudo-random binary sequence.

A reflective event with 1.5% of the intensity of the incident optical signal was implemented at 302 meters from the optical coupler. The STM-1 simulated data was transmitted with a bit rate of 155.52 Mb/s [13], peaking at 1550 nm, and was amplitude modulated with NRZ (non-return to zero) format. Moreover, the coupling ratio was 90/10 and an additional attenuation of 10 dB, both at the laser output and at the photodiode input, was considered. Figure 10 presents the online reflectometry mixing reflectogram for this case scenario.
Figure 10 - Online reflectometry mixing reflectogram for a single reflective event at 302 meters from the optical coupler.

As expected, the first detected peak appears at the location of the imposed reflective event. Therefore, a technique for fiber impairment detection, using the traffic signal as probe, is demonstrated.

The technique limitations were analyzed in terms of measuring range, spatial resolution and multi-channel impact. The proposed technique maximum measuring range depends on the traffic signal at the structure input and is obtained with the following expression

$$\text{Range} = \frac{cN_b}{4nR_b}$$

where $N_b$ is the number of bits of the traffic signal frame and $R_b$ is the traffic signal bit rate.

Considering the transmission of SDH signals, the detection maximum range is 6465.5 meters.

Moreover, from the simulation model, it was concluded that, for an optical system working at 100 GS/s, with a bit rate of 10 Gbit/s and 10 samples per bit, one can achieve a precision of centimeters.

Considering that the current transport optical transmission systems make use of the DWDM technology [1], the proposed technique was tested for a scenario with 10 channels and different channel spacing conditions. It was concluded that the impact of the multi-channel technology can be neglected.

VII. EXPERIMENTAL RESULTS

In order to detect real fiber impairments, the monitoring structure exposed in figure 2 was assembled in a laboratory environment. SMF (single mode fiber) fibers with 1 kilometer extension were sequentially connected and reflective events were accomplished by an open end. A STM-4 frame was compiled considering the octet multiplexing specifications [13] and repeatedly transmitted at the laser source. For these tests, the transmitted signal had a bit rate of 622.080 Mbit/s [13], peaking at 1550 nm, and was amplitude modulated with NRZ format. The used coupler had a coupling ratio of 80/20 and the transmitted optical power was set to 2.3 dBm which suffered an attenuation of 6 dB at the laser output. Figure 11 presents the technique output for reflective points at 1 and 2 kilometers.

In these experiments the results presented a precision error of 2.5%. The fiber refractive index was not characterized which imposed error in fault detection precision. The spatial axis of the final reflectogram was defined by equation (4), and a slight variation in the real fiber refractive index introduces a measurement error of several meters. Moreover, the tested fiber was rolled in a box, thus its refractive index might have been altered [14].

There is a high peak at the center of the experimental reflectograms from figure 11 a) and b). In this case, the monitoring technique fails to mitigate the auto-correlation peaks from the final reflectogram. The central peak appears due to the lack of similarity between the auto-correlations of the structure input and output signals. Nevertheless, this peak has no influence on the fault location. The optimization of the factor $\mu$, is an important matter not only for the clearance of undesirable peaks, but also for the improvement of the detected peak magnitude. Although there is some uncertainty on the detected peaks as to the exact position of the fault, for a first approach these results are satisfactory.

VIII. PHYSICAL IMPLEMENTATION

The current nodes of the core optical network use the ROADM (reconfigurable optical add-drop multiplexer) technology. The location of the monitoring structure in the ROADM nodes, considering a WDM (wavelength division multiplexing) system, is presented in figure 12.
In WDM systems, different wavelengths share the same propagation fibers [1]. In figure 12 each colored line represents a single wavelength. The WSS (wavelength selective switch) multiplexes/demultiplexes tributary wavelengths into/from a single ROADM port and the monitoring structure receives all the traffic signal from that port. In order to receive both the reference and the back reflected signals from a single wavelength, an optical filter must be placed at the input of the photodiodes. If a tunable filter is chosen, it will increase the proposed structure cost. The use of a passive filter will reduce costs, however when the filtered wavelength is not in use, the monitoring process is halted.

Following the detection, the ADC (analog-to-digital converter) converts the detected analog signals to digital and the monitoring module processes its inputs by means of a DSP (digital signal processor).

In order to detect real fiber impairments, the explained monitoring algorithm must suffer a slight adaptation. In the adapted process, the DSP selects a sample of the monitoring structure input and output signals. In order to explain the sampling process, figure 13 is presented.

For this explanation, it is assumed that the period $W$ corresponds to the traffic signal start of the frame period, while period $T$ corresponds to the frame time. The DSP is set to capture half of the traffic signal frame time, starting from the alignment bytes. It does not matter which part of the input and output signals is extracted, nevertheless the capture must begin with these overhead bytes. Thus, like figure 13 suggests, if there is a back reflection with a time delay that exceeds half of the traffic signal frame time, it will not be visible in the final reflectogram.

Once the samples are extracted, the algorithm to obtain the final reflectogram is quite similar to the computational model. Due to the previously explained sampling process, the plot window adjustment is not required.

IX. CONCLUSIONS

In this work, a novel method for fiber impairment detection is demonstrated. It is proved that fiber assessment is possible utilizing traffic signals. Considering the SDH technology, it was concluded that one can achieve a measuring range around 6500 meters. Experimental results demonstrate the feasibility of this method and indicated a precision error of 2.5%. Moreover, it is discussed the technique operation and implementation in ROADM equipment.

REFERENCES

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