FIELD MEASUREMENT OF POLARIZATION FLUCTUATION DYNAMICS AND RELATED IMPACT FOR 40 GBIT/S SUBMARINE SYSTEMS

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Abstract: This paper presents results of polarization measurement performed on an in service submarine system of about 1600 km between Penmarc'h (France) and Sesimbra (Portugal). Fluctuations of the state of polarization have been observed with an average speed of about 6 degrees per minute, with some events reaching 20 degrees per millisecond corresponding to tides impact. The dynamicity of polarization behaviour is discussed versus its potential impact on 40 Gbit/s systems design.

1. INTRODUCTION

The performances of any optical transmission system are always fluctuating over time resulting in a Bit Error Rate (BER) variation [1]. The dominant sources of fluctuations are polarization-related effects.

For 10 Gbit/s terrestrial systems, the main source of performances fluctuations is Polarization Mode Dispersion (PMD). In such systems additional margins are provisioned in the power budget to guarantee an outage probability usually lower than 10^{-5}. When the PMD implies dramatic margins, mitigation devices are required to relax the design.

For submarine systems, the PMD (from both fibre and repeaters) is usually low enough to neglect its impact on 10 Gbit/s systems. As a consequence the terrestrial method using the PMD statistics is not applicable. Another approach is thus commonly used; the well known "5 sigma rule". It is based on the assumption that the Q factor distribution over time is Gaussian shaped. The provision is obtained by multiplying the standard deviation of this distribution (sigma) by 5. This leads to an outage probability of around 3x10^{-7}. The estimation of the sigma value is however very complex because it is due to the interaction of different effects. Even if concatenation models have been proposed and experimentally verified [1], sigma is usually estimated in an empirical manner relying on the laboratory suppliers experience and field trials.

However, PMD appears to be an important challenge for the deployment of 40 Gbit/s long haul submarine systems. Recent research efforts have concentrating on improving the transmission resilience against PMD and ensure performance stability. The development of such mitigation techniques implies first to characterize the dynamic behaviour of the polarization in submarine systems. For this purpose, we have performed long time polarization measurement on a in service submarine system with a high speed optical polarimeter.

2. SYSTEM UNDER TEST

The experiment was performed on Segment 9 of SMW-3 cable between Penmarc'h (France) and Sesimbra (Portugal). The total system length is around 1600 km fibre with conventional non slope matched dispersion map (Figure 1). Figure 2 presents the depth as a...
function of the system length. More than 50% of the cable stands by more than 4000m depth and sections below 500m depth are buried. The cable was deployed in 1998 and was originally designed for 8x2.5 Gbit/s. It has been upgraded and is now equipped with a mix of 2.5 Gbit/s and 10 Gbit/s channels.

The measurement set consists in a high speed polarimeter for measuring the State Of Polarization (SOP) of one specific channel in a non-intrusive manner. The complete WDM signal is first extracted from the monitoring port of the first amplifier of the reception chain. Then it is filtered with a 0.4nm bandpass tunable optical filter to extract one of the 10 Gbit/s channels. Two measurements were performed at 1559 nm and 1557.36 nm. The Stokes parameters have been collected with a sampling rate of 1 kHz.

3. SLOW POLARIZATION FLUCTATION

The first objective was to investigate the average velocity of the polarization fluctuation. We analysed the Stokes parameters by averaging the data over one minute during 90 hours (Figure 3). The variation of SOP follows a relatively continuous evolution. In this paper, we define the speed of the polarization fluctuation as the angle between the two SOP (represented on the Poincare sphere) distant from a unit of time.

Figure 4 represents the distribution of SOP speeds averaged over each minute. The mean speed is around 6 degrees per minute. This relatively small value is in line with the measurements previously reported [2] [3].

4. HIGH SPEED EVENTS

The distribution of the average speed on
Figure 4: Histogram of average speed of polarization fluctuation per minute.

<table>
<thead>
<tr>
<th>Time duration</th>
<th>1ms</th>
<th>10ms</th>
<th>100ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Δ angle</td>
<td>1.4°</td>
<td>1.6°</td>
<td>4.2°</td>
</tr>
<tr>
<td>Sigma</td>
<td>0.18°</td>
<td>0.54°</td>
<td>1.23°</td>
</tr>
<tr>
<td>Δ angle + 5 sigma</td>
<td>2.3°</td>
<td>4.3°</td>
<td>10.3°</td>
</tr>
</tbody>
</table>

Detected events

| Events count | 29  | 503 | 363 |
| Δ angle max. | 19.9°| 37.6°| 82.5°|

Table 1: Conditions and characteristics of rapid events detected during 2 months and calculated from figure 5.

Figure 4 exhibits a long tail suggesting that some events have modified the SOP faster than the average polarization fluctuation. To investigate these rapid events we have calculated the fluctuation speed of the SOP on the Poincare sphere over 1, 10 and 100 ms for approximately two months.

The distribution of fluctuation speed was calculated from the collected data, Figure 5. We arbitrary define a rapid event as a fluctuation speed greater than the mean variation speed + 5 times its standard deviation over 1, 10 or 100 ms. Table 1 summarizes the conditions calculated to define these rapid events.

29 rapid events faster than 2.3 degrees over 1 ms have been detected during the 2 months measurement. The maximum speeds were 19.9°, 37.6° and 82.5° respectively over 1, 10 and 100 ms. The Stokes parameter of the fastest event is represented on Figure 6. The observed fluctuation is representative of a cable or fiber vibration due to an external collision (rolling stone on the sea bed, human activity in station,…). As can be seen on this figure, the SOP came back to its initial state after the event. More than 90% of the rapid events detected were of this nature. The occurrence of rapid events over 1 ms seems random but their number is not large enough to perform a statistical analysis (Table 1). Though considering the distribution of events faster than 4.2° over 10 ms, one can draw striking correlation with tides effect.

The time distribution of rapid events was analyzed using a Fourier transform to identify their frequency components, Figure 7a. The spectrum strikingly corresponds to the Fourier analysis of the water height (due to the tide's effect) in Penmarc'h bay over the same period, Figure 7b. This confirms the impact of the tide on the rapid events occurrence. No days/night influence was detected contrarily to observations on terrestrial cables [4].

Figure 5: Histograms of angular SOP fluctuation speed over 1, 10 and 100 ms.
A significant characteristic frequency is also observed at around $8 \times 10^{-7}$ Hz (in the extreme left of Figure 7a). This corresponds to a periodicity of roughly 14 days. To investigate the origin of this frequency we computed, in Figure 8, the distribution of rapid events number in a per days basis. This distribution is compared with the tide's coefficient in Penmarc'h. Results show a very good correlation with the tide's strength. The same behaviour is observed for both 1559 nm and 1557.36 nm wavelengths for rapid events faster than 4.2° over 10 ms and 9° over 100 ms. Such impacts of the tide could be considered as surprising because its effect is usually located close to the coast where the cable is usually buried. The Route Position List (RPL) indicates a repair of about 4 km cable length at less than 100m depth close to Penmarc'h several years ago.

Figure 7: FFT power spectrum of (a) events number faster than 4.2° over 10ms per hours and (b) the evolution of the water height (tide) during the same period.

Figure 8: Comparison between histogram of events number per days faster than 4.2° over 10 ms and the tide's coefficient at the level of Penmarc'h over the same period.

Cable has been replaced without burial operations that could explain the large impact of the tide on the polarization fluctuation.

5. IMPACT ON 40 GBIT/S SYSTEM DESIGN

The fibre average PMD value for most of the submarine cables is between 0.1 ps/$\sqrt{\text{km}}$ and 0.03 ps/$\sqrt{\text{km}}$ (more recent ones). Repeater's contribution is usually specified between 0.2 ps and 0.5 ps each. This signifies that for a typical transatlantic system (6500km) with 80km span length, the total accumulated PMD could vary between 9.2 ps and 3 ps. Both limits are within tolerances for 10 Gbit/s systems (it is still lower than 10% of the bit duration). However for 40 Gbit/s systems using conventional modulation technologies (OOK or DPSK), PMD becomes problematic. The repeaters contribution is non negligible for these systems and their specifications regarding PMD should be improved for future submarine systems (Figure 9). Recent technical developments have improved the system resilience against PMD as well as the performance stability by using optical PMD compensators, DQPSK modulation technique or polarization multiplexing to reduce the symbol rate. Another central enabling
technology concerns the coherent detection that allows efficient Digital Signal Processing (DSP). The use of such adaptive compensation techniques applied in the optical/electrical domain highlights the issue of the polarization dynamicity and its impact on systems design. When considering the "5 sigma rule" to account for performances fluctuations, the system design ensures an outage probability of $3 \times 10^{-7}$. This outage probability should take into account two interdependent factors: (i) the number and the duration of rapid events that will be faster than the tracking capability of the compensator or algorithm of compensation (if any) and (ii) the time to restore the compensation processes after such events. The dynamic behaviour of systems should have been assessed and verified based on the probable highest speed of polarisation variation. In this study this value has reached 20°/ms and this should represent a minimum target for system suppliers. Of course this result has to be consolidated with other measurements on other cables.

6. CONCLUSION

This paper presents the results of a measurement campaign to investigate the polarization fluctuations on a submarine system. Despite the common picture of stable polarization for submarine systems, rapid variations were identified. The maximum SOP variation speed observed reached 20 degrees per ms. When PMD mitigation is required, in particular for imminent long haul 40 Gbit/s systems, the solution proposed by the suppliers must be able to operate faster than this maximal SOP variations and therefore its dynamic working specification should have been validated. Alternatively these events will have to be accounted for in the outage computation in the power budget.

An occurrences frequencies analysis has also clearly demonstrated that rapid variations on this system are mainly correlated with the tide's effects.

7. ACKNOWLEDGMENT

The authors would like to thank P. Talamas and the staff of Penmarc'h landing station for its support during the field test.

8. REFERENCES