STATE OF POLARIZATION SENSING – CORRELATING ACROSS CABLE SECTIONS

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Abstract: State of Polarisation (SoP) sensing is a scalable and low-cost approach to fibre sensing, especially suited for revealing physical movements of the fibre along a fibre path. Any movement of patch-cords, terrestrial landing cables and the subsea cable can be monitored. SoP sensing comes without spatial resolution, but by correlating activity across cable segments, activity in node rooms can be differentiated from movements of the subsea fibre. Correlating with AIS information, vessels performing trawling and anchor drags impacting the cable, may be discovered. Furthermore, active work periods that may cause network flaps as well as quiet periods during e.g. vacation periods are identified.

1. INTRODUCTION

Subsea fibre optic cables are vital components of global communication networks, yet they are susceptible to various external threats that can compromise their integrity. Notably, activities such as trawl fishing and anchor dragging are significant contributors to cable damage. Fishing gear, including trawlers and dredges, can physically impact cables, leading to faults. Similarly, anchors dropped or dragged across the seabed pose substantial risks, with such incidents accounting for 30-40% of offshore cable faults [1].

The extent of damage from these activities varies based on factors like the cable's burial depth and seabed conditions. While proper burial can offer protection, cables may still be displaced, partially damaged with some fibre pairs broken, or, in severe cases, completely severed. Such damages can disrupt communication services and will incur significant repair costs involving repair vessel mobilisation.

To mitigate these risks, the implementation of fibre optic sensing technologies, has become increasingly important. Fibre sensing enables real-time monitoring of subsea cables by detecting vibrations and physical disturbances along the cable's length [2]. This continuous monitoring allows for the early detection of potentially harmful activities, facilitating prompt responses to prevent or minimize damage.

State of Polarization (SoP) monitoring provides a solution for detecting abnormal movements in subsea fibre cables as well as patch cords within node rooms [3]. Unlike Distributed Acoustic Sensing (DAS), which is highly sensitive and can detect e.g. approaching trawlers, ocean surface waves and small microseism events [4], SoP monitoring is less sensitive, and the dynamic range is in the detection of small and large-scale movements along the fibre path. For DAS sensing, saturation effects may typically occur in case of strong signals from earthquakes or cable movements, due to phase wrap-around and limitations in dynamic range [5]. For SoP, any saturation effects are avoided, ensuring that any fibre movements are reliably identified and that a permanent change in the position of the cable or a patch cord is detected through a permanent shift in polarization state [6].
In this paper we demonstrate that by implementing SoP sensing across multiple cable segments, extending from the same landing station, correlation of SoP signals between segments is enabled. By analyzing

these correlations, the system identifies the location of fibre movements, whether they occur within the subsea cable or in terrestrial node rooms. In contrast to using end-to-end monitoring across a complete fibre transmission path, a multi-segment monitoring approach enhances fault detection by distinguishing localized movements from network wide disturbances, enabling an enhanced capability of fibre path integrity and availability monitoring.
For illustration we provide examples on how multiple cable sections are monitored using SoP, showing examples of correlated signals that reveal maintenance activities and its location. We also provide examples on active and quiet periods of work by monitoring across multiple cables.
Additionally, the application of SoP monitoring for tracking environmental conditions in subsea cable environments is illustrated through correlation of wind-speed ground truths and detection of SoP activity.
The approach demonstrates how SoP monitoring provides a scalable method for improving the integrity and protection of critical telecom infrastructure in offshore environments.

2. SOP MONITORING METHODS

When comparing Distributed Acoustic Sensing (DAS) and State of Polarization (SoP) monitoring techniques, a key distinction lies in their operational principles: DAS relies on Rayleigh backscattered light, whereas SoP monitoring utilizes forward-propagating signals. This is illustrated in Figure 1.

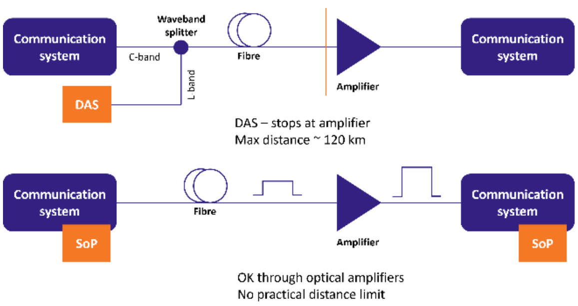

Figure 1, DAS sensing at upper figure and SoP sensing at lower figure.

DAS's dependence on backscattered light enables precise event localization along the fibre path. SoP monitoring on the other hand does not offer spatial resolution due to the monitored signal being integrated over the entire fibre path. However, SoP monitoring offers simpler implementation allowing optical amplifiers in the transmission path, no saturation effects, reduced costs, and lower data volumes, enhancing scalability for extensive coverage, such as monitoring all cable sections in a large subsea network.
SoP can be monitored using data from coherent transponder receivers used in long-distance transmission systems, or through dedicated instruments designed for this purpose. A significant advantage of dedicated instruments is their ability to monitor specific sections of a fibre path. In contrast, transponder-based monitoring typically encompasses the entire path, often involving multiple sections between transponders. The State of Polarization (SoP) of light is commonly described using Stokes parameters, which provide a representation of polarization in terms of measurable intensity components. The four Stokes parameters: S0, S1, S2, and S3 define the total intensity (S0), linear polarization along horizontal/vertical (S1) and diagonal/antidiagonal (S2) axes, and circular polarization (S3). These parameters are typically represented as a vector in a three-dimensional space known as the Poincaré sphere. Simplified polarization monitoring can be implemented using a Polarization Beam Splitter (PBS)-based instrument. Comparative studies between full Stokes-parameter measurements and PBS-based measurements have demonstrated that low-cost PBS measurements exhibit only slightly reduced sensitivity to SoP variations compared to full polarization-state characterization [2,3]. For the SoP measurements presented in this paper, we therefore apply a PBS based dedicated SoP monitoring system [7].

3. IDENTIFYING PHYSICAL MOVEMENTS IN THE FIBRE PATH

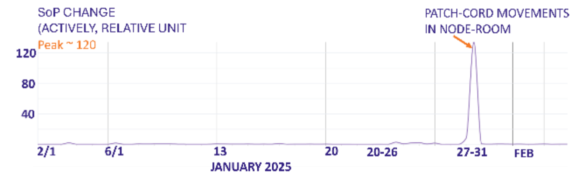

Figure 2, One month of SoP activity. Work in node-rooms involving movements of patch-cables imposes large SoP variations (shown as the peak), compared to environmental impacts. Unit on the Y-axis is a relative value representing changes in SoP. It is found from normalizing a high-pass filtered SoP signal.

Figure 2 presents a one-month record of State of Polarization (SoP) activity along a 150 km subsea fiber cable originating from the south-west coast of Norway, Egersund. The pronounced peak corresponds to a period of planned maintenance within the landing station's node room. This observation underscores the capability of SoP monitoring to detect and distinguish between routine operational activities and environmental influences over extended periods. By capturing such variations, SoP monitoring effectively identifies whether a fiber path experiences minimal disturbances ("quiet") or is subject to frequent mechanical impacts ("noisy"), thereby providing measures of the physical integrity and operational conditions of the fibre path being monitored.

When a patch cord or cable along a fibre path is permanently displaced, the State of Polarization (SoP) typically change. Rapid SoP fluctuations occurring within seconds, followed by a lasting shift, typically indicate such a displacement. This could result from movement of a patch cord in a node room or impact on a subsea cable by equipment like a trencher or fishing trawl. Figure 3 illustrates SoP activity during node-room maintenance, resulting in a permanent displacement of a patch-cord.

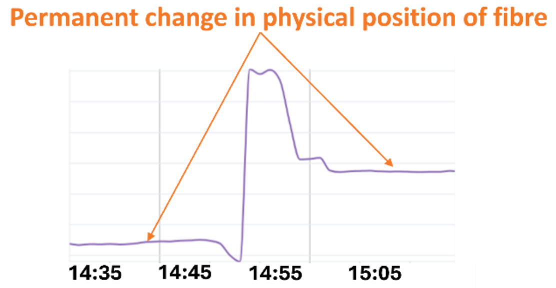

Figure 3, Permanent shift in the SoP after fluctuations indicates a new position of the cable or patch-cord. The Y-axis represents the Stokes S1 value.

4. LOCATING ACTIVITY BY CORRELATING SOP MONITORING ACROSS MULTIPLE CABLE SEGMENTS

Monitoring the State of Polarization (SoP) across multiple fibre cable segments originating from the same node room enable insights into both localized and system-wide activities within optical networks. In typical configurations, node rooms serve as central hubs from which multiple fibre cable sections emanate, each facilitating distinct communication pathways. By implementing SoP monitoring on these individual segments—ideally with monitoring equipment co-located within the same rack and sharing common patch cord pathways—network operators can distinguish between disturbances localized to the node room, and environmental or cable impacts.

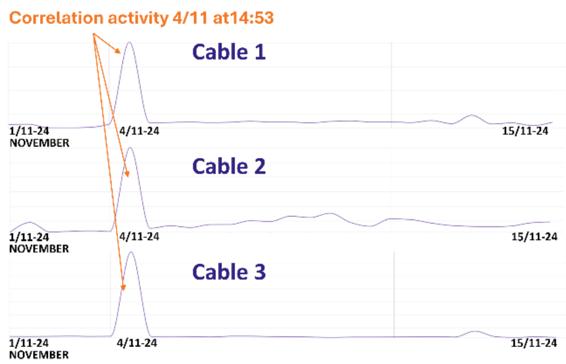

Figure 4, Correlated activity over 15 days on three different cable sections. During work in *the node landing station, simultaneous activity can be seen on all three cable sections. Unit on the Y-axis is a relative value representing changes in SoP.*

In the illustration in figure 4, SoP monitoring equipment is positioned within the same rack, and patch cords share portions of their pathways. Simultaneous disturbances affecting multiple cable segments can therefore be identified. For example, maintenance activities within the node room, such as equipment adjustments or patch-cord relocations, are likely to induce correlated SoP variations across several of the monitored fibre segments. The example in figure 4 shows fluctuations caused by planned works in a node room where all the three monitored cable segments are originating. Detecting such synchronized changes therefore enables operators to attribute the disturbances to internal factors within the node room, facilitating targeted responses if there are no registered planned activities for works in the node-room.
When State of Polarization (SoP) fluctuations are detected exclusively on a single fibre segment, without corresponding changes in other segments, this isolation suggests that the disturbance is localized to that specific segment. Such events could result from external physical impacts, environmental conditions, or unauthorized access affecting only that particular cable.

To identify the cause of such disturbances, network operators can analyse Automatic Identification System (AIS) data to monitor vessel activity near the affected cable segment. AIS technology provides real-time, detailed information about vessel locations and movements, enabling operators to detect potential threats to subsea cables. By correlating SoP fluctuations with AIS data, operators can determine if a vessel is operating above or near the cable at the time of the disturbance, thereby identifying potential causes such as fishing trawlers or anchor dragging.

5. PROACTIVE MAINTENANCE AND AVAILABILITY THROUGH ACTIVITY TRACKING

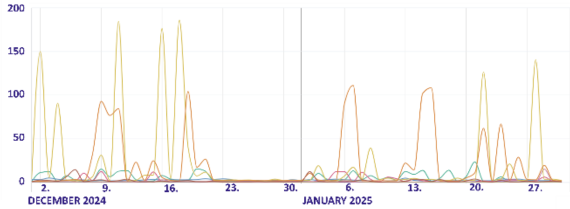

Figure 5 illustrates SoP activity correlation across eight different cables, highlighting a notably quiet period during the Christmas break, correlated across all the cables.

Monitoring the State of Polarization (SoP) in optical fibres offers a proactive approach to maintaining network health and ensuring high availability. By analysing SoP variations across multiple fibre cables, operators can identify patterns of activity and potential disturbances that may impact network performance.
Research has established a relationship between SoP variations and network anomalies [8]. It is demonstrated that significant SoP fluctuations correlate with network flaps, caused by bit errors and packet loss, resulting in short duration service disruptions.
Causes of network flaps include physical disturbances to the fibre infrastructure, causing bending loss and high frequency SoP variations. In high bitrate coherent systems, high frequency SoP variations may induce bit-errors due to polarization being part of the modulation format. A loss induced by bending the fibre reduces the signal to noise ratio which again typically results in bit errors and potential service disruption.
By continuously monitoring SoP variations, operators can detect early signs of such issues, enabling timely interventions before they escalate into major outages.
This monitoring facilitates the creation of proactive availability maps, categorizing cables based on their activity levels. Cables exhibiting minimal SoP fluctuations are deemed "quiet," indicating a lower risk of

network flaps and higher reliability. Conversely, cables with frequent SoP variations are considered "noisy," suggesting a higher risk of potential issues.

The concept of utilizing monitoring of polarization fluctuations for proactive network protection was proposed in 2002 [9]. This method allows for rapid switching to backup paths upon detecting anomalies, thereby enhancing network resilience and potentially avoiding network flaps.

Hence, integrating State of Polarization (SoP) monitoring into network management strategies enables operators to shift from reactive to proactive maintenance, enhancing network availability and performance. By identifying and addressing potential issues before they affect service, and take appropriate action, this approach ensures higher network reliability.

SoP variations can indicate movements or vibrations in subsea fibre cables. If such variations are detected and correlated with Automatic Identification System (AIS) data, tracing nearby vessels that might cause a cable impact, the correlation helps identify vulnerable areas along the cable route. Once identified, these areas can be protected through measures such as rock-dumping to shield the cable or by marking maps to inform mariners to avoid anchoring or fishing in these zones. Hence, implementing these protective measures reduces the risk of cable damage from maritime activities.

6. ENVIRONMENTAL PARAMETER MONITORING USING SOP

Monitoring the State of Polarization (SoP) in optical fibres offers insights into various environmental parameters. SoP variations are influenced by factors such as temperature fluctuations, tidal movements, and gravity waves [11]. For instance, gravity waves, generated by wind interactions with the ocean surface, can induce perturbations in submarine cables, leading to detectable SoP changes.

Figure 6 presents ground truth data of averaged maximum wind speeds alongside measured averaged maximum SoP variations on a cable segment extending from Egersund towards the U.K. The data reveals that temperature variations during the days are observable in the SoP measurements. Additionally, the upper envelope of the SoP variation curve demonstrates correlation with the recorded wind speeds, indicating a relationship between wind-induced oceanic activity and SoP fluctuations. The plot represents all SoP fluctuations up to 20 kHz.

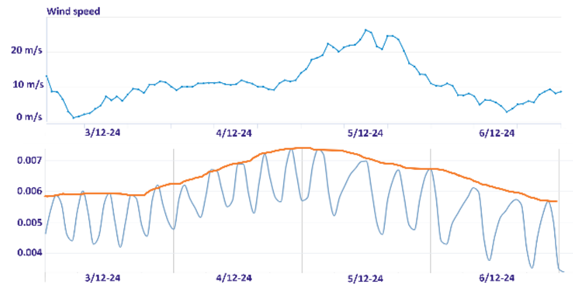

Figure 6, Upper figure: Ground truth data wind maximum average (1h), Eigerøya - Egersund [10]. Lower figure: Averaged SoP peak values observed on a cable segment originating from Egersund. Y-axis on the SoP plot represents relative values of averaged peak SoP variations.

By applying filters with specific cutoff frequencies, distinct environmental influences on SoP can be isolated and correlations are improved. Gravity waves typically exhibit frequencies between approximately 0.01 Hz and 0.5 Hz, allowing their effects to be extracted using appropriate band-pass filters. In contrast, temperature-induced SoP changes, associated with slow cycles, manifest at lower frequencies and can be identified using low-pass filters. These environmental variations are all generally subtle and occur at significantly lower frequencies compared to disturbances from activities such as maintenance work in node rooms, which often cause SoP variations in the range of tens of hertz and higher.

7. CONCLUSION AND SUMMARY

In conclusion, the integration of State of Polarization (SoP) monitoring into subsea fibre optic cable management offers a multifaceted approach to enhancing the reliability and security of global communication networks. By detecting physical disturbances, SoP monitoring serves as a proactive tool for maintaining the integrity of these critical infrastructures.

SoP monitoring effectively identifies physical movements within the fibre path, such as those resulting from maintenance activities in node rooms or external impacts like trawl fishing and anchor dragging. By analysing SoP variations across multiple cable segments, operators can distinguish between node room works and environmental or cable impacts, facilitating targeted responses to potential threats. This capability is crucial, as fishing gear and anchors are significant contributors to cable damage, leading to service disruptions and substantial repair costs.

The proactive nature of SoP monitoring enables operators to transition from reactive to preventive maintenance strategies. By identifying and addressing potential issues before they affect service, like identification of vulnerable areas along the cable route. Once identified, these areas can be protected through measures such as rock-dumping or by marking maps to inform mariners to avoid anchoring or fishing in these zones, thereby reducing the risk of cable damage from maritime activities.

Furthermore, SoP monitoring extends beyond physical threat detection to environmental parameter assessment. Variations in SoP are influenced by factors such as temperature fluctuations, tidal movements, and gravity waves, which are themselves affected by wind speed. By applying filters with specific cutoff frequencies, distinct environmental influences on SoP can be isolated, allowing for environmental monitoring.

In summary, SoP monitoring provides a scalable and cost-effective method for improving the integrity and protection of critical telecom infrastructure in offshore environments. By offering real-time insights into both physical disturbances and environmental conditions, it enhances the resilience of global communication networks against a variety of threats.

8. AKNOWLEDGEMENT

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