First Impact Movement Characterization of Shallow Buried Live Subsea-Cable

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Abstract: Revealing availability threats and security attacks using State of Polarisation monitoring shows impact characteristics from a cable trencher passing over, moving a subsea cable carrying live traffic while dBQ value dips 0.6 dB. © 2024 The Author(s)

1. Introduction

Subsea fibre-cables are the main carrier of the world's data-traffic. Any disruption or degradation of traffic, permanent or temporary, has severe consequences. Service interruption or temporary service quality degradation may have many causes. The capability to detect and identify physical impacts on subsea cables can serve as a basis for determining the necessity of rerouting traffic due to factors such as cable damage or potential security attacks. It can also help assess whether a physical cable inspection is required.

Distributed Acoustic Sensing (DAS) may be used to identify activities such as trawler operations or anchoring in close proximity to a subsea fibre optic cable [1]. However, the DAS interrogation range is currently limited to approximately 170 km [2]. Furthermore, direct cable impacts such as cable movement may result in saturation of the DAS instrument triggered by multiple fast phase rotations. Therefore, differentiating strong vibrations caused by an object passing over a buried subsea cable from a physical movement of the cable has not yet been demonstrated. Nor has information concerning a resulting permanent shift in cable position following an impact. Moreover, because DAS requires high-precision components, including lasers with high phase-stability, the instrument is costly.

State of Polarisation (SoP) monitoring has different characteristics compared to DAS. It comes without spatial information and has lower sensitivity. On the other hand, it is an order of magnitude lower cost fibre-sensing method enabling thousands of km detection ranges with full integration into transmission systems [3]. Unlike DAS it can easily be implemented without saturating for large fibre strains. The amplitude of SoP changes is always within the Stokes parameter range, facilitating signal characterisation during any impact. Furthermore, if a permanent shift in SoP is detected after an impact, it indicates a permanent shift in cable characteristics or position. Hence, SoP sensing complements DAS sensing, enabling high-density deployments through low-cost and reliable detection of fibre movements. SoP information can be extracted from coherent receivers [3], commercially available instruments, or simplified design using a Polarisation Beam Splitter (PBS) to monitor the differential optical output power. The latter is a low-cost, simplified implementation demonstrated sufficient for detection in field environments [4].

SoP monitoring of buried on-shore cables has demonstrated the capability to detect temperature changes, trains passing along the fibre route [4], and to monitor and classify road traffic [5]. Similarly, it has been applied for detecting earthquakes and water waves using subsea cables [6]. Finally, through laboratory experiments, SoP monitoring has been proposed as a method for detecting potential availability threats [7] and enabling proactive protection switching [8]. To the best of our knowledge, detection of availability threats and their position, caused by movements of a sub-sea cable, has so far not been demonstrated.

In this paper, we present the first SoP characteristics proving a mechanical impact on a subsea cable being uncovered and moved by a cable trenching device. Automatic Identification System (AIS) enables information about vessels operating at sea, position and vessel information of the surface vessel operating the trencher is therefore retrievable, enabling location of the movement. The event is registered on a 300 km span-length subsea cable loop on the west-coast of Norway during a cable-crossing operation. The observed SoP change characteristics exhibit large amplitudes occurring exclusively during the crossing operation with no variations observed before or after the crossing. A permanent shift in SoP is observed after the impact, indicating significant movement of the cable due to the impact. Consequently, the SoP observations provide unequivocal evidence of direct impact and movement of the cable.

2. Field-Trial Experiment and Setup

In the field-trial, a separate fibre-pair in the cable is applied for SoP sensing purposes. At the end of the cable-span, the cable is looped back, resulting in a total fibre length of 300 km. The SoP is monitored using a low-cost PBS-based monitoring system [9]. Both static and low-frequency SoP as well as variations up to 20 kHz are measured. The instrument measures SoP variations up to 20 kHz with a lower -3 dB cutoff at 10 Hz and was configured for very high sensitivity, resulting in an observable S1 Stokes parameter space variation within +/- 0.09. Static and very low-frequency SoP variations are on the other hand estimated for the full S1 Stokes parameter, by measuring the balance of the EDFA ASE noise level between the two PBS outputs. Figure 1 a) shows the experimental setup.

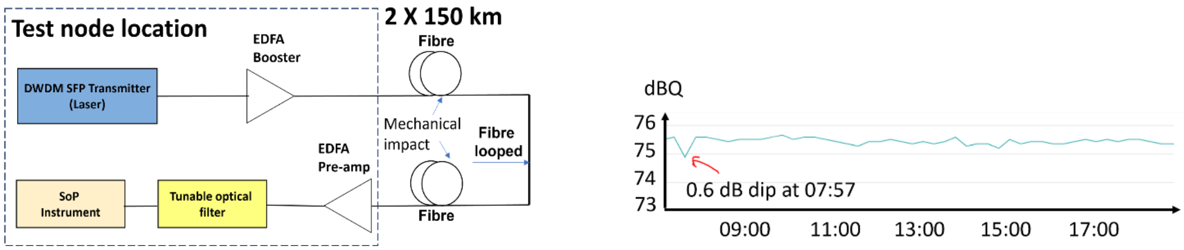


Fig. 1. a) Left: Experimental setup of the SoP monitoring of the 150 km subsea fibre cable. b) Right: dBQ value on the Y-axis and time on the X-axis. One of the services on the cable is being monitored.

To compensate for the attenuation in the cable, an Erbium Doped Fibre Amplifier (EDFA) is applied to boost the power to + 16 dBm from a low-cost transmitter setup using a DWDM Gigabit Ethernet (GE) SFP hosted in a media-converter unit. At the receiver side, the signal is pre-amplified in an EDFA and ASE noise is filtered before the signal wavelength enters the SoP instrument at -11 dBm.
The mechanical impact on the cable was generated by a “Capjet” trenching device using high-pressure water streams combined with a hinged plough designed to move backwards and up if in heavy contact with any object when moving forward.

3. Experimental Results

Figure 1 b) shows a small drop of 0.6 dB in dBQ (quality value) of one of the services on the cable. This drop is observed simultaneously as the SoP variations are observed on the cable. No bit errors or packet drops were registered due to the drop in Q-value. Hence, this type of event involving an insignificant drop in Q-value will typically not trigger any actions in a telecom operator network operation center.
The SoP variations during the period the trencher is passing over the monitored cable are shown in Figure 2. The trencher's physical contact with the cable was confirmed by the personnel operating the vessel. The plough, consisting of a hinged sword of the trencher, was bent backwards, caused by the impact with the cable. This was visible when the trencher was taken out of the water and inspected on the vessel. The 300 km long span, without in-line amplification, limited the achievable Signal to Noise ratio (SNR) for small SoP amplitude environmental vibrations. However, direct physical contact with the cable generates strong SoP variations, easily observable in the current system. Figure 2 shows the SoP variations during the direct impact, including five seconds before and after the impact.

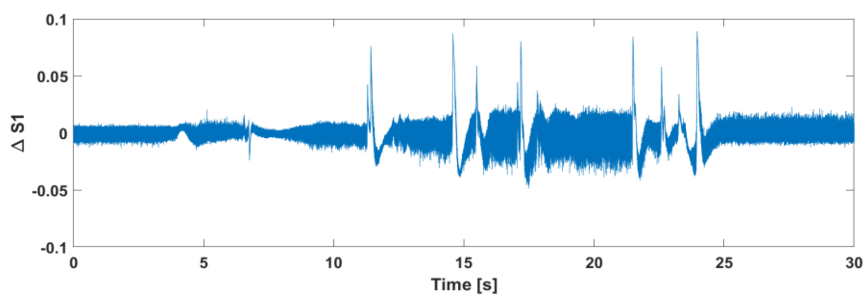
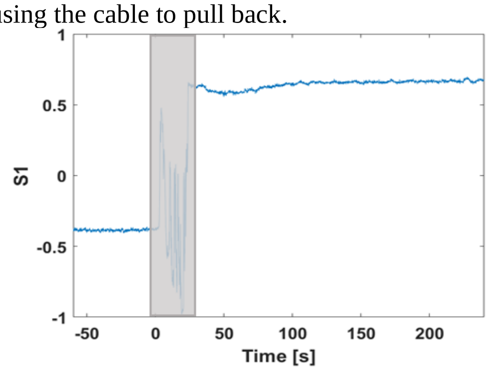


Fig. 2. SoP variations while the trencher passes over the monitored cable at 07:57. The RMS values of the background noise are used for estimating static changes of SoP.

The SoP variations last over a period of 22 s while the trencher is in contact with the cable. The cable was initially not buried, yet it remained concealed on the seafloor due to a light sediment covering. A series of nine short and strong transients can be observed during the trencher crossing period. The transients are very powerful, making the SoP change rise beyond the dynamic range of the instrument, S1=+/-0.09, bringing the instrument into saturation for a short time-period. The trencher passes over the cable first with a high-speed water stream, then two wheels in front, before a sword-shaped with 8 high-pressure nozzles is in direct contact with the cable followed by two wheels at the back of the trencher passing over the cable. We find the peaks in the SoP observations to be caused by the different objects and water/streams of the trencher when in contact with the cable.
Furthermore, in Figure 3 a), it can be observed that SoP is permanently changed after the crossing. The SoP instrument has a lower cutoff frequency of 10 Hz, allowing high sensitivity to SoP changes beyond the cutoff frequency but also

measuring the EDFA noise spectrum, filling up to 50 % of the instrument's dynamic range. The static SoP is estimated over the full S1 Stokes parameter range by using the amplitude-modulated EDFA noise signal, calculating the RMS value of the noise spectrum envelope over a period of 300 seconds, 60 seconds before and 240 seconds after the event. S1 changes from -0.4 to 0.7, showing that the position, or the rotation of the cable, has been significantly and permanently changed by contact with the trencher.

For studying the frequency content of the event more in detail, Fig. 3 b) shows a spectrogram of the trencher crossing event. Frequencies up to 20 kHz are observed, but the main power in the signal is up to 300 Hz, which is the maximum frequency in the spectrogram. Sharp vertical lines propagating beyond 100 Hz are observed, corresponding to the observed transients in Fig. 2. For the strongest peaks, the instrument saturates, and blue fields can be observed. From the pattern, the strength, number of, duration and frequency content of transients form a pattern caused by the trencher pulling the cable, followed by a sudden release causing a transient. We find the trencher's pull and movement of the steel armoured cable have similarities to pulling a steel spring. It is identified by the falling flank in the pattern corresponding to a sudden release of a strain caused by the trencher first pulling the cable before suddenly releasing it, causing the cable to pull back.



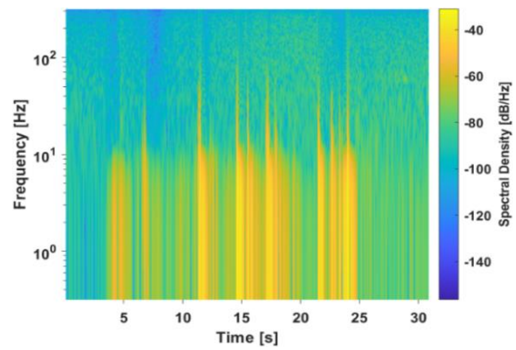


Fig. 3. a) Left: S1 value is estimated from the RMS value of the background noise from before and after the trencher impact shown in the grey area. b) Right: Spectrogram showing the frequency content of the signal during the trencher-cable contact period. Time along the X-axis and frequency on the Y-axis. Colour indicates amplitude.

4. Conclusions

Internet and critical infrastructure rely on subsea fibre-cables for its operation. Subsea activity like trawling and anchoring, as well as potential sabotage, brings a need for continuously monitoring the cables for impacts that may partly or fully damage the cable. The telecom-market is cost-sensitive, making low-cost methods easily integrated with transmission systems an attractive choice. In this paper, we have for the first time demonstrated how a mechanical impact and a movement of a subsea cable can be detected. Using a low-cost SoP monitoring method characterizes the impact-pattern from the trenching device proving that a movement of the cable has happened. AIS information shows the name, position and time of the surface-vessel operating above the trencher, when crossing the cable. The cable carries live traffic, showing an insignificant dip in service quality during the event, while the SoP variations reveal an impact and movement on the cable. While DAS monitoring brings ability tracing e.g. trawlers approaching a cable, we conclude that SoP monitoring complements, enabling detection of direct physical impacts on subsea fibre-cables, proving movements. Separating direct physical impacts and cable movements from strong nearby vibrations from subsea activity is valuable as it can be used for triggering actions from telecom operators and cable owners to prevent potential cable damage and security events.

5. Acknowledgements

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6. References

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