A Scalable Data Collection System for Continuous State of Polarisation Monitoring

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ABSTRACT

Our dependency on the telecommunication infrastructure is continuously increasing, as different infrastructures – such as energy and telecommunication – now have mutual dependencies. This calls for increased monitoring of the fibre network, which is a highly critical part of the infrastructure. State of Polarisation (SoP) of light propagating through fibre transmission systems is impacted by any vibrations and mechanical impacts on the fibre. By continuously monitoring the SoP, any unexpected movements of a fibre along a fibre-path may be traced. Movements may be caused by e.g. work in node-rooms impacting patch-cords, trawlers or other types of sub-sea equipment touching or hooking into sub-sea fibre cables, digging close to a fibre-cable, or geophysical phenomena like earthquakes. In this paper, we describe a low-cost, scalable system for SoP monitoring and give examples of patterns monitored in different types of fibre infrastructures. The monitoring system consists of single-unit rack-mount instruments connected to taps from live optical transmission signals. Each instrument has local storage for 1-2 years of data, and is periodically automatically uploading data to a server for backup and data-access purposes. Examples of observed patterns are impact from a thunderstorm on a Fibre-To-The-Home (FTTH) cable, 50 Hz on a fibre-cable spun around a high-voltage power air-cable, as well as animal impact on a patch-cord.

Keywords: State of Polarisation, Monitoring, Critical Infrastructure

1. Introduction

The fibre infrastructure is by far the most vital part of our data and telecom infrastructure, carrying more than 99 % of the transcontinental traffic. The physical fibre infrastructure is subject to both accidents and sabotage that may cause disruptions in communication. Examples include trawler fishing, anchoring, digging, work in node rooms as well as eavesdropping. For revealing different type of anomalies in the physical infrastructure, monitoring of vibrations and movements in the fibre cable has been proposed [1], [2]. The monitoring technique has also been proven applicable for e.g. earthquake and tsunami-monitoring [3], [4], extending the application space of the fibre optical network from communication only, also to include seismic sensing and tsunami warning. Furthermore, large earthquakes and volcano eruptions may cause damage to fibre-cables, and may cause the cable to break. An example of this is the volcano eruption at Tonga-Hunga [5] that broke both sub-sea fibre-cables connecting the island, leaving it isolated without a proper Internet-connection. Another example is the cut of both of the two fibre-cables to the Shetland Islands, likely caused by trawler fishing or anchoring, leaving the society in isolation without proper communication [6]. Hence, this motivates the need for monitoring of fibre-cables for proactive detection of movements that potentially may cause harm to the fibre-cable. There are three important techniques that have been demonstrated for this purpose. The Distributed Acoustic Sensing (DAS) system is demonstrated on sub-sea cables with integration of Automatic Identification System (AIS) information, plotting the positions of ships along the cable using both, DAS- and AIS-based positioning data, revealing if any fishing vessels are crossing the cable without first lifting the trawl [7]. DAS systems are however expensive and have a reach limitation of approximately 150 km. Interferometric sensing is another alternative, but needs a costly laser with high phase-stability, and is mainly demonstrated in loop-experiments [8]. State of Polarisation (SoP) sensing can be implemented as a low-cost sensing technique using a simplified Polarisation Beam Splitter (PBS) based instrument, allowing detection of fibre-movements and vibrations [9]. Using SoP monitoring, detection of fibre patch-cord movements has been demonstrated [1], [10], as well as the 50 Hz electromagnetic field induced in fibre spun on high-voltage cables [10]. Other examples of detection includes e.g. earthquake detection [3]. However, when detecting SoP, any variation along the end-to-end optical fibre-path is shown as an integrated signal at the detection end. Hence, the longer the cable, the more likely that simultaneous events are detected. This complicates the identification of events, since the detected signal in these cases may be a result of the combined impact from two or more events. In this paper, we focus on SoP measurements in access and metro length of optical fibre-cables. The lengths of the fibre-cable for these cases are 6 km or shorter, lowering the probability of many simultaneous events to occur along the cable. On the other hand, the cables are aerial cables, causing influence from weather conditions like e.g. wind. Furthermore, we demonstrate in lab experiments how small movements of a patch-cord caused by an animal, a cat, may be visible as SoP variations at the receiver end. As mouses and rats are known to gnaw on the insulation of fibre-cables, identification of such events may be helpful for early detection and prevention of fibre breakage.

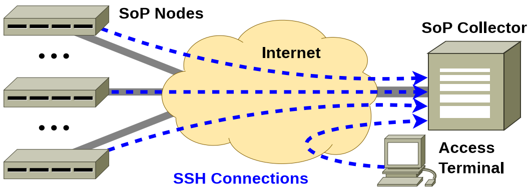


Figure 1. SoP data collection system.

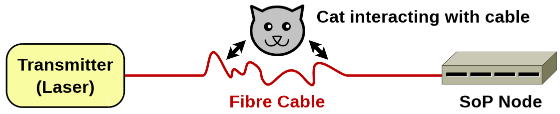
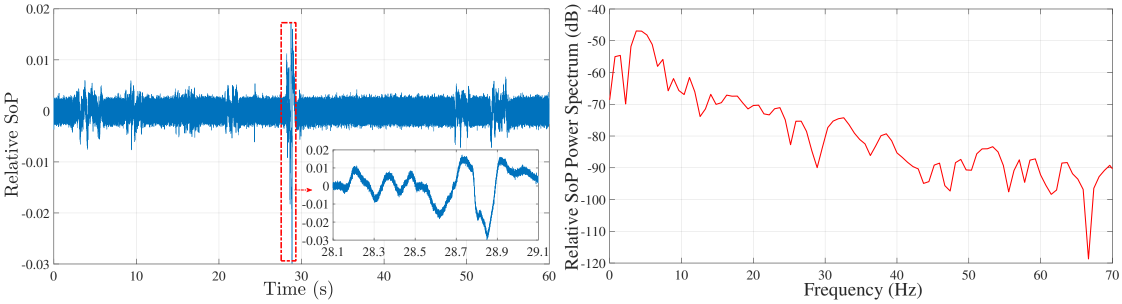


Figure 2. Cat interacting with a fibre cable.



(a) (b)

Figure 3. (a) Detection of SoP caused by patch-cord movements triggered by a cat. (b) The FFT plot corresponding to the SoP variation caused by patch-cord movements during [28.1,29.1] s.

2. SoP Measurement Infrastructure

For exploring SoP sensing on different cable types, and for different network sizes, we have implemented a scalable monitoring system. This system consists of 1-rack-unit monitoring nodes for SoP characterisation. A block diagram of the SoP collection system is illustrated in Fig. 1. The SoP monitoring hardware is a PBS-based low-cost design. The optical input signal is split using a PBS into two optical signals, according to the SoP of the input signal. Each of the two optical signals is fed to respective photodetectors, converting to electrical signals that are converted using a dual AD-converter connected to a processing unit.

The SoP Node's processing unit then stores the recorded data as audio files. It supports the Free Lossless Audio Codec (FLAC) for lossless compression, to reduce storage requirements. The files are written to a harddrive, allowing recording of 1-2 years of internal data storage. Furthermore, the data is regularly synchronised to a central server, denoted as SoP Collector, providing ample storage space for collecting data from the nodes as well as external secured access to the recorded data. Secure Shell (SSH) connections are used to secure all network communications. The base software of both, SoP Node and SoP Collector, is based on open source components running on Linux distributions with long-term support. Furthermore, SoP Nodes and SoP Collector are configured to automatically install all security-relevant updates, ensuring to keep all systems – which are deployed in the context of critical infrastructure – secure.

3. Experimental Setup and Results

For illustrating the capability of detection and separation of different types of events potentially impacting availability, we give examples from three different experiments. The SoP node detects frequencies relevant for detection of physical movements caused by direct impacts on cables or fibre-cords, up to 20 kHz, while amplifier AC coupling prevents detection of sub-Hz variations. First, we illustrate in a lab-experiment, activity in a node-room, emulating impacts from an animal (cat) on a fibre patch-cord. We then give an example from a field-trial using a metro-network fibre, illustrating how strong electromagnetic fields can be detected. In a second field-trial, we show how heavy weather conditions can be detected on a fibre to the home air-cable access.

Any type of movement of a patch-cord in a node-room will indicate activity typically induced by a human or an animal. Typically, sharp bending, disconnection or breaks may occur as a result of the activity. In our lab-experiment, our target was to induce movements of different magnitudes and duration time. The experimental setup is illustrated in Fig. 2. We put some cat-food close to a fibre patch-cord and let a cat search for the food and play with the cord. As a result, the cat induced small movements as well as a quick strike of the cord. In Fig. 3(a), the impacts during 60 s are plotted in time-domain. The quick strike generates a strong and quick movement and is shown in the zoomed part of the Fig. 3(a). A Fast Fourier Transform (FFT) plot is shown in Fig. 3(b). The frequency analysis of the movement shows a signal with a powerful frequency peak around 5 Hz, decaying up to approximately 40 Hz. Hence, this type of activity, involving patch-cords, shows that most of the power in the SoP variations can be found in the low-frequency region below 20 Hz.

In a metro-network field-trial, we monitor a 6 km cable in the network of the operator GlobalConnect in Norway, where a part of the cable is spun on top of a High Voltage (HV) cable and a second part of the cable is buried. In the node room, a 20 km length of Dispersion Compensating Fibre (DCF) is located before

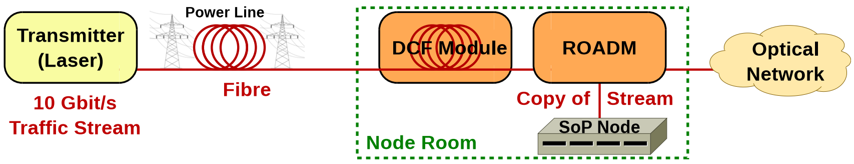
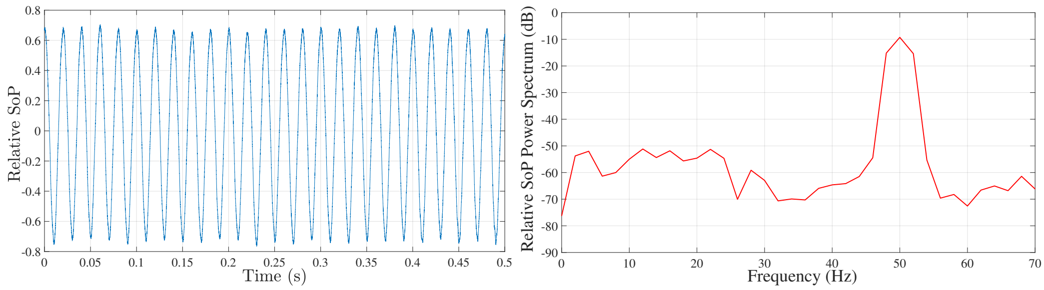


Figure 4. Setup with metro network fibre path containing 6 km of fibre and a 20 km DCF module.



(a) Time domain

(b) Frequency domain

Figure 5. 50 Hz SoP variation caused by electromagnetic fields induced in the fibre cable

the SoP monitoring unit. A live data communication signal is copied in a Reconfigurable Optical Add-Drop Multiplexer (ROADM), being applied for SoP monitoring purposes, while simultaneously also being transmitted to its destination through the optical network. The setup is illustrated in Fig. 4. As a result of parts of the cable being spun around a HV-cable, a strong electromagnetic field from the 50 Hz current is impacting the SoP of the signal in the cable. This is illustrated in time-domain in Fig. 5(a) and in frequency domain in Fig. 5(b). A continuous, pure 50 Hz signal as illustrated in the figure does not indicate security or availability risks. However, variations in the signal amplitude or other frequency components may indicate e.g. sparks or unexpected current-variations occurring along the cable, potentially causing failures in power or telecom-systems.

In our second field-trial, we monitor an access network FTTH air-cable by splitting off 50 % of the live data-communication signal at the subscriber-end of the cable, as illustrated in Fig. 6. During a period of six months, different types of events have been observed. In this paper, we show an example during a thunderstorm event on August 15, 2022, in Oslo, causing heavy rain and wind impacting the air-cable. Strong windy weather may cause air-cables to break because of e.g. trees falling on the cable, poles breaking, or any of the cable-attachments failing. Thunderstorms and lightnings may therefore cause interruption of telecom-services due to breakage, power or equipment failures. In Fig. 7(a), a 60 s plot of the signal in the time-domain is shown. A stable signal is found for the first 10 s before the thunderstorm heavily increases in strength. After 10 s, the SoP variation increases, due to the heavy wind and rain hitting the cable. A closer look into a shorter time-window during the period of maximum SoP variations, marked within the red box in Fig. 7(a), shows periodic signals with approx. 0.1 s duration, as illustrated in Fig. 7(b). Looking into SoP variations on an even shorter time-scale, Fig. 7(c) (the red box in Fig. 7(b)), shows short-duration SoP variations within a 40 ms window. The frequency domain analysis over a 1 s window in Fig. 7(d) shows that frequency peak components are found up to 19 kHz, while Fig. 7(e) reveals strong low-frequency components likely to be caused by the wind-induced swaying or vibration of the cable. Hence, the thunderstorm is found to cause SoP variations ranging from a few Hz up to the maximum measured frequency of 20 kHz.

4. Conclusions

Strong physical movements of fibre-cables or fibre-cords may indicate availability and security risks. By monitoring State of Polarisation (SoP) in live data-signals, vibrations and physical impacts on fibre cables and fibre-cords can be traced. In this paper we have described a scalable system for monitoring SoP changes, collecting data from live data-connections in different types of optical networks. The results of three experiments, one in lab, a field-trial in a metro-network and a field-trial in a FTTH network, illustrate that different types of events on varying types of cables typically cause different frequency components in the SoP variations. For a

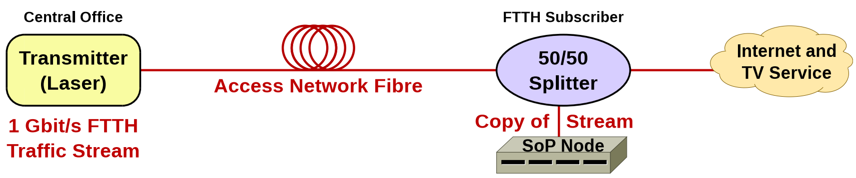


Figure 6. How the measurement node is connected at the subscriber end of an access network FTTH cable. A passive coupler is used for tapping of 50 % of the signal coming into the house. The signal is a live Gigabit Ethernet data-traffic signal applied for a private home user TV and Internet service.

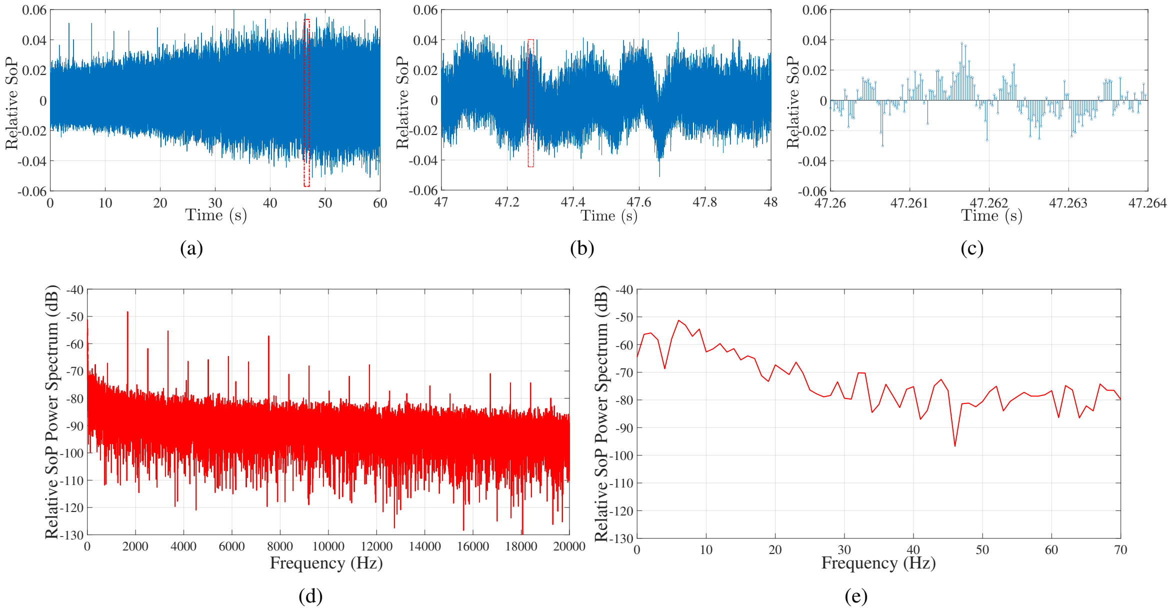


Figure 7. (a) SoP variations observed in the fibre cable during a thunder-storm. (b) Zoomed-in view, marked out with a red box in (a). (c) Zoomed-in view indicated with red box in (b). (d) FFT plot of SoP variation up to 20 kHz during 1 s [47,48] s. (e) FFT plot up to 70 Hz during 1s [47,48] s.

patch-cord in a node room impacted by humans, or an animal in our experiment, the main power of the SoP variations may typically be below 40 Hz. For our metro field-trial, a strong 50 Hz electromagnetic field from a high-voltage cable impacts the SoP, indicating that any other frequency components or variation in the amplitude of the 50 Hz, will indicate an anomaly. In the FTTH network, using fibre cables in the air, SoP variations with frequency components over the monitored frequency range up to 20 kHz is found during a thunderstorm causing heavy wind and rain. The three experiments illustrate that different events in varying types of networks and cables cause distinct frequency components in the SoP variations. Further work will focus on mapping events to SoP variation frequency patterns, with the goal of creating a warning system for the identification of availability and security threats to the fibre infrastructure.

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