A Scalable Infrastructure for Continuous State of Polarisation Monitoring for Revealing Security and Vulnerability Impacts in Optical Networks

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***Abstract*—Optical networks are spanning the world. They are the main medium for carrying all types of data-traffic. From a vulnerability and security perspective, it is therefore the most important part of the network to protect against any physical impacts that may cause disruptions or security incidents. In this paper, we demonstrate and describe a scalable, low-cost monitoring system based on detecting the state of polarisation in the fibre cables. We give examples on how any direct movement of fibre-cables or fibre-cords as well as indirect vibrations on the cable can be detected, and how basic characteristics in the patterns can be used for recognition of these events.**

***Index Terms*—State of Polarisation, Hardware, Software, Monitoring, Infrastructure**

I. Introduction

Today, reliable communication is absolutely crucial for any modern economy and society. Even short outages of services like data communication or telephony may cause major inconveniences and problems. Most of this communication is transported over long-distance fibre lines, often running through remote areas as well as through seas and oceans. Hence, the fibre cables are critical infrastructure vulnerable to accidental damages (e.g. an excavator cutting a cable, trawler fishing or a ship's anchor destroying an undersea cable) or intentional damages (e.g. vandalism and sabotage). Hence, monitoring the cable for any physical impacts on the cable or patch-cords in a node-room, or any ongoing physical activity close to the cable, like e.g. digging activity, will be useful for revealing potential damages to the cables and causes of damages, as well as short outages.

Adding any type of equipment to the telecom-infrastructure calls for cost-efficiency, because of the cost-sensitivity of telecom-services. The cost-sensitivity is typically lowest for the transport network, which connects and serves thousands of people, and highest in the access network, serving typically only a single household. Hence, when adding monitoring, both cost of the equipment as well as the installation, should be minimised, especially in the access and metro type of network segments.

Using the fibre as sensor for sensing any vibrations impacting the cable, like direct physical movements, or vibrations in the ground around the cable, is demonstrated using different types of sensing techniques. Examples of detected events using Distributed Acoustic Sensing (DAS) include e.g. fishing activity using trawlers and sounds from whales [1], [2] and traffic monitoring [3]. Furthermore, eavesdropping on sounds in a room with a fibre-to-the-home installation [4], as well as earthquake monitoring in terrestrial and submarine links [5], [6] have been demonstrated using phase interferometric detection. By utilising phase detection from telecom coherent transponders [7], [8], monitoring external disturbances such as utility pole knocking and site intrusion in deployed field fibres have been demonstrated.

Using State of Polarisation (SoP) monitoring, vibrations and movements of fibre-cables and fibre-cords can be detected using inexpensive equipment [9]. In addition to direct movements of the fibre, environmental parameters and geophysical effects monitoring have been demonstrated for sub-sea fibre cables, where detection of earthquakes has been demonstrated [10], [11]. Furthermore, strong electromagnetic fields may be detected, like e.g. detection of lightning strokes using fibre optical cables on aerial high-voltage cables [12], [13]. Trains causing vibrations along the fibre route as well as temperature changes around the fibre are shown to be detected in [14]. Also, movement of vehicles on a road can be detected using SoP monitoring on a metropolitan optical cable [15].

The ability to detect events in a metropolitan network using two different methods, SoP-based sensing and a commercial DAS system, were demonstrated in [9]. In the 30 km field-trial, the SoP monitoring provided a simpler method for monitoring, complementing the DAS by demonstrating how SoP monitoring can be used for distinguishing between different types of perturbations. Different events, like pulsing the bend of the fibre, bending and holding the fibre, and bending and shaking the patch cord, demonstrated specific SoP patterns.

Comparing with other sensing techniques like DAS and phase sensing, SoP may easier be integrated into a communication system. In high-performance optical transmission systems supporting wavelength bitrates of 100 Gbit/s and above, polarisation is applied as part of the modulation format, and coherent receivers enable the detection of SoP. Hence, SoP information may be extracted directly from the coherent receiver. The extracted data has a resolution in time-domain that is sufficient for earthquake detection involving frequencies below approximately 10 Hz [10]. However, detection of SoP variations of approximately 100 Hz and higher has not been reported using this method. For measuring SoP variations of 10 Hz and higher, a dedicated polarimeter instrument can easily be connected on the receiver side of an optical system. By tapping off part of the optical signal (a copy) using a passive optical splitter at the receiver side of a data-transmission system, the SoP in a fibre-cable can be monitored simultaneously as data is transmitted in the same signal [16]. Furthermore, long-distance optical communication involves optical amplification along the path, allowing fibre-spans of around 60-120 km between each amplifier. Contrary to techniques based on back-scattered light, like e.g. DAS, SoP allows sensing through the complete optical path that may span 10,000 km or more [10].

When not using the coherent optical data receiver for SoP detection, a separate SoP monitoring equipment can be implemented and simplified using a Polarisation Beam Splitter (PBS) and two photodetectors in a compact implementation [17]. For monitoring e.g. a telecom-operator's fibre infrastructure, the number of required monitoring devices may be high, since typically the providers have a high number of fibre-cables. Furthermore, fibre-cables in the transport network typically involve transmission distances of hundreds or thousands of km, posing the need for optical amplification. Hence, the sensing system must be scalable both in path distance and number of cables being monitored. In addition to a low-cost and compact hardware, a scalable SoP data collection system is therefore needed. Typically, commercially available equipment for SoP monitoring is designed for accurate measurements of SoP in lab or field [18]. It is not tailored to the needs of telecom-operators, which includes low-cost, easy-to-install, 19 inch rack-mountable equipment, as well as a structured way of data-collection and storage from a high number of monitoring probes.

In this paper, we explain how SoP monitoring can be applied for detecting activity that involves direct movement of the fibres as well as activity close to the fibre-cable. The target is to reveal activity that may indicate an availability risk, like works in node-rooms involving movements of patch-cables and digging activity close to the cable, and also reveal security-related eavesdropping attempts involving any bending or physical impact on the fibre-cable. We show how our scalable SoP collection system enables efficient and secure collection of large amounts of data. The solution involves a low-cost SoP monitoring device, where hardware is based on low-cost off-the-shelf components. Furthermore, the data collection and maintenance infrastructure is based on open source software. Examples of SoP patterns are given from both, lab- and field-trials, illustrating different types of events and how events can be separated by analysing frequency and magnitude of the SoP variation.

The rest of this paper is structured as follows: In Section II, we explain the basic design of the monitoring units and how they are applied for collecting data. This is followed by an introduction of the software in Section III. After that, we show examples of results in Section IV. We conclude our paper in Section V.

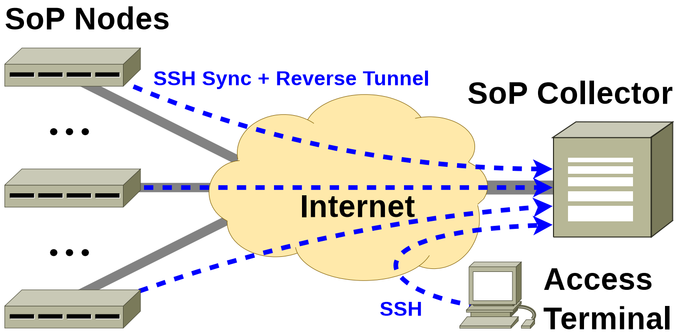


Figure 1. The Data Collection System

Figure 2. An assembled SoP Node

II. System Design

The data collection system design is depicted in Figure 1. A number of SoP nodes can be used for monitoring, and data is both stored locally and securely uploaded to a server. The user may also remotely access the different SoP nodes in a secure way. We explain the details of our software in Section III of this paper.

The assembled SoP Node is illustrated in Figure 2. It is contained in a 19 inch metal rack case. All connectors, with exception of the 230 V Alternating Current (AC) power connector, are located on the front panel of the unit. This includes the optical input, external USB keyboard and mouse, as well as an HDMI display port that can be connected for configuration, development and debugging. The SoP Node is controlled by a computing unit running Linux. It is booting from an integrated Secure Digital (SD) card. The device also includes an additional hard-disk drive (HDD) to offer large, inexpensive local storage space.

Figure 3 illustrates an overview of the SoP Node's hardware components. Maximum optical input power is -10 dBm, while the dynamic range allows SoP variations to be registered down to -55 dBm. Frequencies of up to 20 kHz can be

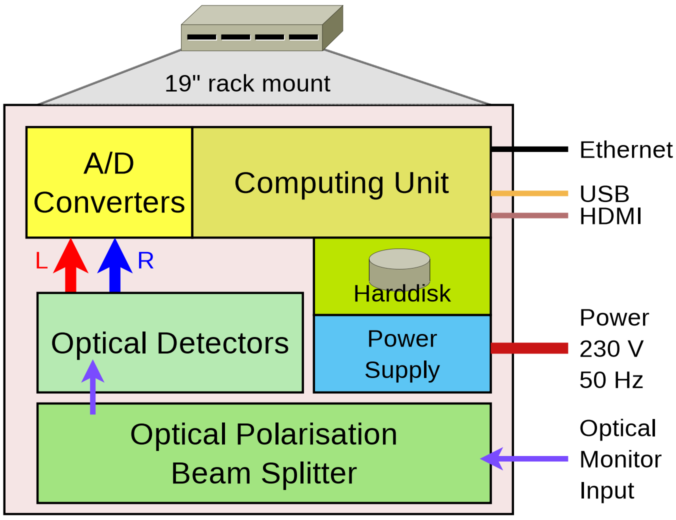


Figure 3. SoP Node Hardware System Design

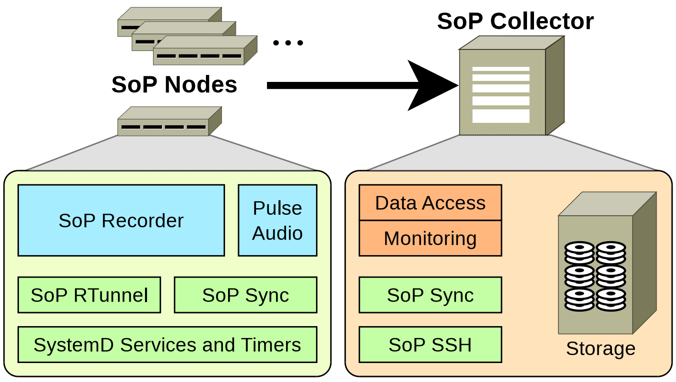


Figure 4. The Software Overview

registered, while there is a first-order high-pass filter with cutoff at 10 Hz blocking DC components. The optical input is connected to a PBS, splitting the optical power of the input signal according to the SoP of the input signal. Hence, if the SoP varies, the optical power balance between the two PBS arms will vary. The two PBS outputs are each connected to photodetectors, where the output signal is converted to electrical signals. The electrical signals are sampled using two analog-to-digital (A/D) converters. The computing unit collects the sampled data, stores the data locally, and uploads the data regularly through the Internet to a remote server.

III. Software

The software parts of our system are illustrated in Figure 4. First, we describe the SoP Node software in Subsection III-A. Then, in Subsection III-B, we describe the SoP Collector server. This is followed by the introduction of the software management in Subsection III-C.

Sampling Rate	Bits/Sample	Format	MiB/min	GiB/day
44100	8	WAV	5.05	7.10
44100	16	WAV	10.10	14.19
44100	24	WAV	15.14	21.29
44100	24	FLAC	≈5	≈7

Table I
SoP Recorder Storage Space Requirements

A. SoP Node

The computing unit in the node can run e.g. Debian Linux or Ubuntu Linux. We currently test with these two distributions. However, the software is generic and could run on, or easily be adapted to, other Linux variants as well. The operating system is installed on the SD card fitted into the computing unit.

1) SoP Recorder: The SoP Recorder is the core part of the SoP Node. It uses PulseAudio[1] to record the SoP data, in form of raw, digitised audio data with configurable sampling rate (e.g. 44100 Hz) and bits per sample (e.g. 24) on the two channels. In a configurable interval (e.g. 1 min), the recorded data is written to a file. For each interval, a separate file is generated in a time-based directory hierarchy[2] (year/month/day). That is, if the node is turned off or rebooted, just the current interval gets lost. All files are stored on a file system on the embedded HDD, instead of using the internal SD card. This prevents wearing out the SD card quickly, while providing ample of inexpensive space. The space required depends on the output format:

- WAV (Waveform) stores uncompressed data in the RIFF WAVE (Resource Interchange File Format Waveform Audio File[3]) format, which is widely supported by audio applications.
- FLAC (Free Lossless Audio Codec[4]) provides lossless audio compression using the libFLAC[5] library, in order to reduce the required disk space. FLAC is also standardised and well-supported by various applications.

Table I provides typical storage requirements, depending on output format and recording parameters.

The SoP Recorder software is written in C++, for best performance. While it is currently only used for recording, a part of ongoing work is to also add pre-analysis features to quickly identify interesting events in the data, and to issue alerts on such events.

2) SoP Reverse Tunnel (RTunnel): SoP Nodes are typically located in remote locations like data rooms, i.e. on-site servicing may not be easy (somebody has to drive to the location, get access, etc.). It is therefore crucial to have remote access possibility via SSH. Clearly, allowing SSH from the "outside" Internet causes security issues, need for appropriate firewall configuration, and a public IP address. Therefore,

[1]PulseAudio: https://www.freedesktop.org/wiki/Software/PulseAudio.
[2]File system performance degrades if there are too many files in a directory.
[3]RIFF WAVE documentation: https://www.mmsp.ece.mcgill.ca/Documents/AudioFormats/WAVE/WAVE.html.
[4]FLAC documentation: https://xiph.org/flac/documentation.html.
[5]libFLAC: https://github.com/xiph/flac.

instead of allowing SSH from the Internet, the SoP Reverse Tunnel (RTunnel) service – based on SystemD[6] – establishes an SSH reverse tunnel connection from the SoP Node to the SoP Collector. From a certain port on the SoP Collector, this reverse tunnel forwards TCP data to/from the SSH port on the SoP Node. That is, on the SoP Collector, it is possible to establish an SSH connection to the SoP Node via the reverse tunnel. The reverse tunnel connection is automatically established. If it breaks, e.g. due to network outage, IP address change, etc. it will be reestablished after a short waiting period (ca. 5 min).

For the SoP Reverse Tunnel service, each SoP Node gets a separate account, with public/private SSH key pair for authentication, on the SoP Collector. So, the access of each node to the SoP Collector can be revoked separately.

3) SoP Sync: While the HDD allows plenty of space, and recording of data for months, the basic idea is to have an infrastructure of SoP monitoring nodes. Therefore, the SoP Sync synchronisation service simply regularly pushes the recorded data to the SoP Collector server (to be explained in Subsection III-B). SoP Sync is a another SystemD service script, being invoked by a corresponding SystemD timer in a varying, randomised interval[7]. The service performs RSync[8] via Secure Shell (SSH) [19]. For this SSH connection, the same per-node account as for the SoP Reverse Tunnel is used (see Subsubsection III-A2).

4) Monitoring: SoP Sync and SoP Reverse Tunnel also allow basic monitoring, by recording the time of the last synchronisation, last reverse tunnel observation, and basic system information like boot time and SoP software version on an SoP Node. This can be used to simply keep an overview over the nodes, and to detect problems like node outages.

B. SoP Collector

The SoP Collector is the central server for collecting the data from all nodes (via SoP Sync, see Subsubsection III-A3) and maintaining the SSH reverse tunnels (via SoP Reverse Tunnel, see Subsubsection III-A2). It therefore requires ample of disk space (e.g. a RAID array) as well as a sufficiently performing network connection and a public IP address.

The data files are stored in a 4-level directory hierarchy (node/year/month/day). For each SoP Node, there is a separate user account with the node's public SSH key for authentication. Password-based authentication is disabled, i.e. only the corresponding node can connect via its account and synchronise its data as well as establish the SSH reverse tunnel.

C. Software Management

Both, SoP Node and SoP Collector, use the Advanced Package Tool[9] (APT) for managing the software installation. This includes managing the SoP software packages, which are simply provided in a private APT repository. That is, the SoP software is provided as Debian/Ubuntu packages, with well-defined dependencies. These dependencies are resolved and ensured by APT. APT also verifies the signatures of all packages being installed, to ensure they are signed by trusted keys.

Besides standard Debian/Ubuntu software and SoP packages, System-Tools[10] is installed to display basic status information upon SSH login, like interfaces and IP address(es), SSH key fingerprints, disk and memory usage, as well as some operating system information.

Furthermore, both, SoP Node and SoP Collector, make use of the automatic update mechanism provided by Debian/Ubuntu. That is, software updates are installed automatically, in order to ensure having the latest security updates deployed.

IV. Proof of Concept Evaluation

In the following, we give examples of experimental results achieved by using our SoP Nodes. SoP Nodes are now installed for long-term monitoring, collecting SoP data from different types of infrastructures, including access, metro, and transport cables. Results from these trials will be published later, along with becoming available. In this paper, we show some first results from a field-trial where parts of the fibre path consist of a fibre-cable spun on top of a high-voltage cable. Both, a continuous induced 50 Hz and movements of the patch cord connecting the recorder during installation, are shown as examples of patterns that can be observed. Furthermore, in a lab-trial, we demonstrate how sounds can be picked up by a fibre. A piece of guitar-music played through a loudspeaker close to fibre-spools induces SoP variations that are recorded by the SoP node. The guitar music is easily recognisable, suggesting that eavesdropping on voices close to fibre installations may be feasible by decoding SoP variations in the fibre.

When monitoring SoP with the target of discovering anomalies in the vibrations and movements of cables and patch-cords, the magnitude of the SoP variations will vary according to type of cable, and how it is deployed (e.g. in the air or buried in the ground). Hence, it is not a direct relation between the SoP variation and the mechanical impact on the cable. Our measurements are a relative representation of the Stokes S_1 parameter, where values are varying between -1 and +1, representing the maximum polarisation variation that can be measured before the instrument goes into saturation. A high sensitivity of the instrument is therefore achieved using AC coupling of the A/D converter, utilising its full dynamic range. During the measurements, saturation of the instrument has however not been observed. The relative SoP of the optical signal R is represented by the difference in the measured relative values (V_1, V_2) [17]:

$$R = V_1 - V_2.$$

[6]SystemD: https://systemd.io.

[7]To prevent all nodes trying to synchronise their data at the same time.

[8]RSync: https://rsync.samba.org.

[9]APT: https://wiki.debian.org/Apt.

[10]System-Tools: https://www.nntb.no/~dreibh/system-tools.

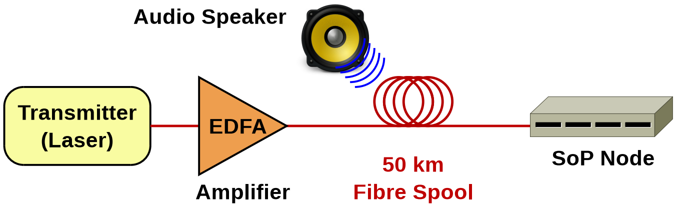


Figure 5. Laboratory setup illustrating the eavesdropping on an audio signal by observing SoP variations induced by a loudspeaker in fibre-spools.

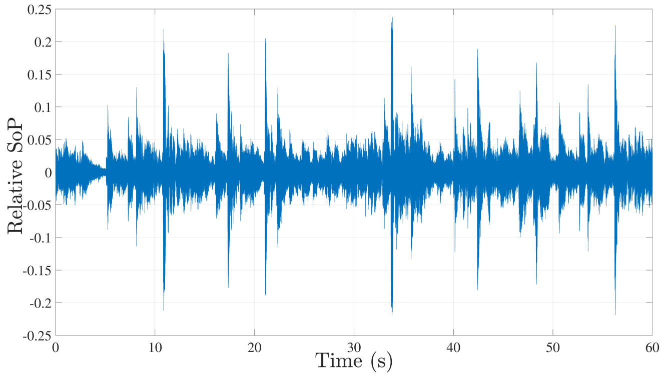


Figure 6. Time domain of relative SoP for 60 s of guitar music

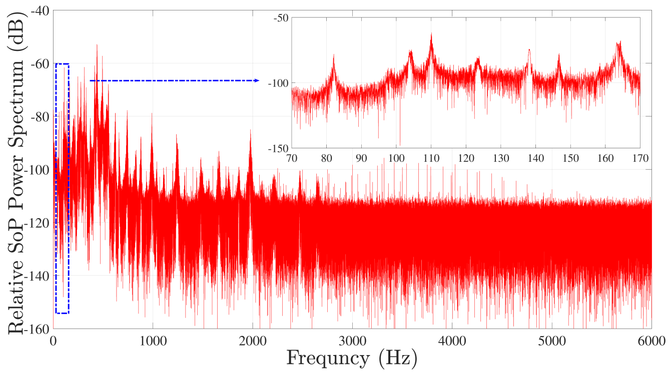


Figure 7. Frequency domain of SoP for 60 s of guitar music. Frequency components for all the different guitar tones played wthin the 60 s is shown.

V_1 and V_2 represent the signal amplitude of the photodetectors output, detecting the optical power in the two arms of the PBS. The values of V_1 and V_2 are varying between -1 and +1. The PBS splits the incoming optical signal into two signals with orthogonal polarisations, each detected by a photodetector with a TransImpedance Amplifier (TIA) that converts the optical power into voltages. If there is no vibration in the optical cable, the optical power in the two arms of the PBS will be constant. However, if there is a vibration in the fibre causing a change in the SoP, the optical power to the two arms of the PBS will be split according to the input SoP and its variation.

A. Audio Signal decoded from SoP Variations in Fibre Spool

In our first experiment, we demonstrate decoding of an audio signal played from a loudspeaker nearby fibre spools. The experimental setup is illustrated in Figure 5: The optical output from a continuous wave laser is amplified using an Erbium Doped Fibre Amplifier (EDFA), boosting the optical signal before entering two fibre-spools of 25 km (i.e. a total of 50 km) G.652 fibre, then terminating in the SoP monitoring node at a power level of -10 dBm.

Since the loudspeaker is located close to the fibre-spools, significant lengths of the fibre in the spools can be expected to be impacted by vibrations caused by the audio-signal from the loudspeaker. This amplifies the SoP variations caused by the vibrations from the audio-signal. While observing SoP variations caused by audio sounds induced into e.g. a patch cord may be difficult, because very loud sounds may be needed, the sound from a Jabra 510 Bluetooth audio-conference type of loudspeaker is sufficient when being induced in a long fibre-path as for the fibre-spools. For modern infrastructures, coherent receivers with electronic dispersion compensation are applied for dispersion compensation. However, for the old infrastructures, Dispersion Compensating Fibre (DCF) spools are inserted as part of the transmission path along the fibre-path for compensating the chromatic dispersion of the transmission fibre. DCF fibre-spools may therefore be found in node-rooms of older long-distance transmission infrastructures, although shorter lengths than 50 km are being used for this purpose. Hence, for these types of older installations, the DCF fibre-spools may induce SoP variations caused by vibrations in the rack and loud sounds in the node room.

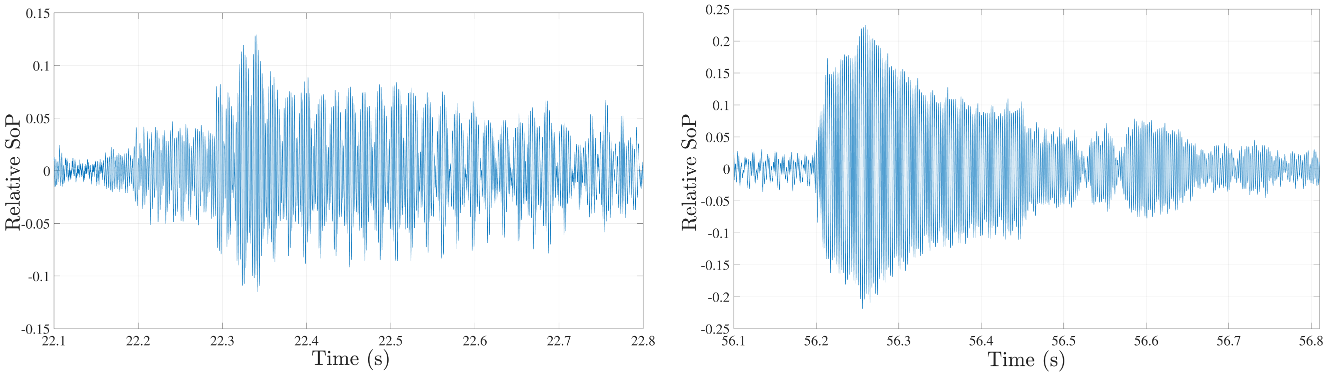
Figure 6 illustrates a piece of guitar music being played through the loudspeaker and recorded as SoP variations. The Fast Fourier Transform (FFT) plot in Figure 7 shows how the varying sounds from the guitar generate different frequency patterns, forming distinguishable frequency signatures for the sounds. This illustrates how events along a fibre-optic cable may generate distinct frequency patterns that can be identified as unique signatures for each event.

In addition to this, Figure 8 depicts two distinct frequency patterns (Subfigure IV-A and Subfigure 8(b)) that correspond to two distinct tones being played on the guitar. The tones can be observed in the time plot, while the distinct frequency signatures can be seen in the FFT plots in Figure 9.

B. Field-Trial on Fibre-Cable spun around Power Line

Field-trial measurements are being conducted in GlobalConnect's[11] fibre infrastructure, using a metro fibre-path of G.652 fibre having a length of approximately 6 km. The cable path is split into two different sections. A first buried section of approx. 4.5 km, and a second section of approx. 1.5 km, where the cable is spun around a high-voltage air AC powerline. The order of the sections, and hence, the induced SoP variations does however not impact the measurement results, since the monitored signal is an integration of the signal and the mechanical impacts along the total cable section. However, in general, aerial fiber-cables shows larger SoP fluctuations than buried cables, due to impact from e.g. wind, rain and

[11]GlobalConnect: https://www.globalconnect.no.



(a) Within [22.1, 22.8] s

(b) Within [56.1, 56.8] s

Figure 8. Time domain plot of the relative SoP for two different guitar tones

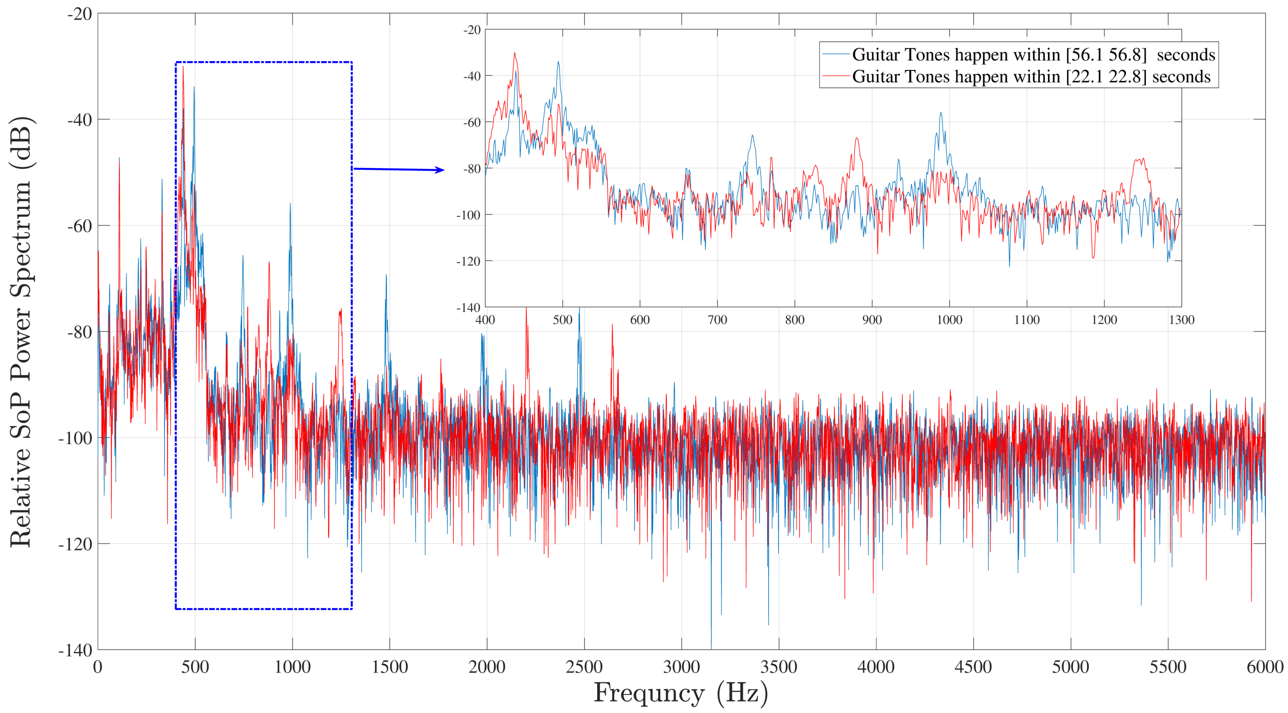


Figure 9. Frequency domain of the relative SoP for Guitar tones occurring within [22.1, 22.8] s and [56.1, 56.8] s.

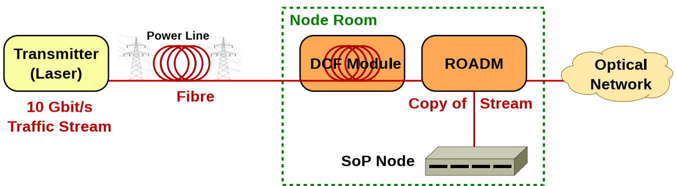


Figure 10. Field trial with a fibre cable spun around a power line.

large temperature variations. The monitoring is conducted on a 10 Gbit/s optical wavelength, copied from a Reconfigurable Optical Add/Drop Multiplexer (ROADM) along the fibre-path which also includes 20 km of DCF. The setup is illustrated in Figure 10.

The first observation of interest is performed during installation of the node. The patch-cord to the node is then being moved for a few seconds. This can clearly be seen in the time-plot pattern in Figure 11. At the beginning of the plot, large variations in SoP of relatively low frequency can be observed as highlighted in the left dashed box in Figure 11 and the zoomed time domain signal from 1 s to 10 s presented in Figure 12. The FFT plot of the frequency pattern of the movements in Figure 13 shows large low-frequency signal components, but also a significant 50 Hz component caused

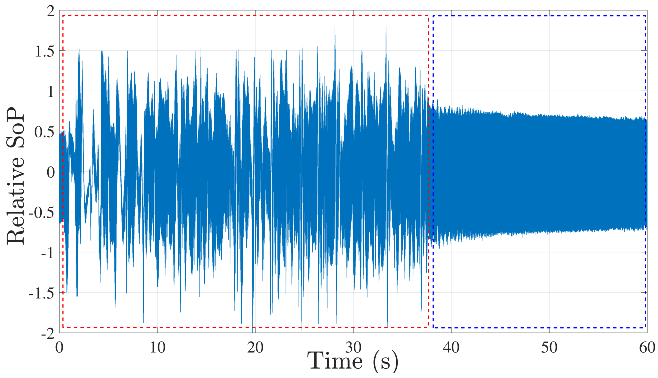


Figure 11. 50 Hz variation due to electromagnetic field with a patch cord movement illustrated in the red dashed box and a stable 50 Hz variation in the dashed blue box.

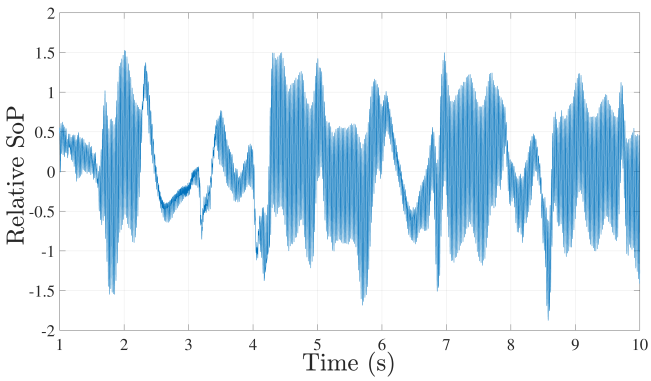


Figure 12. Time domain of SoP variation due to patch cord movement and 50 Hz electromagnetic field.

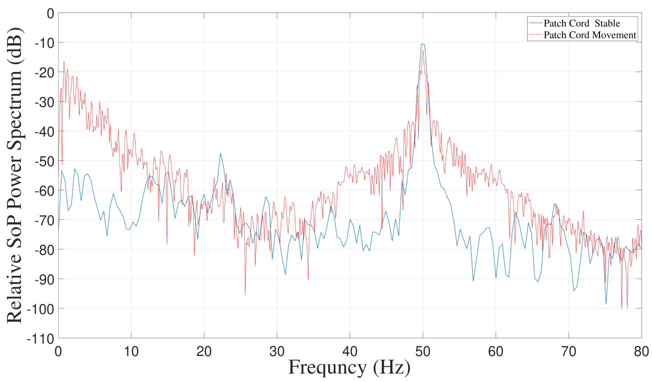


Figure 13. Frequency domain of relative SoP variation due to patch cord movement and 50 Hz electromagnetic field.

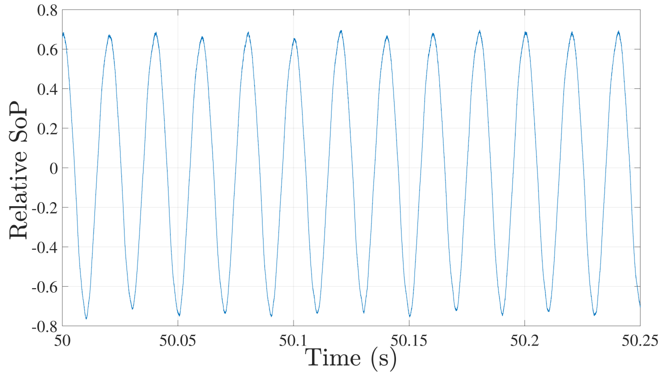


Figure 14. Time domain of the relative SoP when no patch cord movements are present. A significant 50 Hz SoP variation can be seen caused by the electromagnetic field of the HV-cable.

by the high-voltage-cable electromagnetic field.

When the movement of the cable stops, a stable 50 Hz pattern from the magnetic field of the high-voltage-cable can be seen in the blue dash box of the time-plot pattern in Figure 11 and the zoomed 250 ms illustration in Figure 14. This illustrates how work in a node-room involving movements of patch-cords in the cable path may be identified by using SoP monitoring, even when there are other types of events causing relatively strong SoP variations (like the illustrated 50 Hz). The movements show a significantly different pattern that can be recognised by its lower frequencies and strong variation. During periods where there are no strong movements of the patch-cord, the SoP does not vary with a comparable strength, due to e.g. weather conditions impacting the aerial cable-section.

V. Conclusions

The optical network infrastructure is a highly critical part of the communication infrastructure. In this paper, we have shown how monitoring the State of Polarisation (SoP) of optical wavelengths carrying live data signals can be used for identifying different types of events that may lead to outage, like work in node rooms causing physical vibrations, or movements of any fibre along the optical path. By analysing the frequency pattern of SoP variations, signatures of different movements may be found. Even when continuous strong SoP variations are present due to interference from a high-voltage cable electromagnetic fields, movement of a fibre patch-cord shows a significantly different signal pattern. This type of monitoring may be important for revealing any potential security threats involving sabotage of fibre-optical cables or attempts of eavesdropping through physically connecting and tapping the signal along the optical paths.

For the first time, we have described a scalable monitoring infrastructure for collecting SoP data consisting of easy-to-install, low-cost hardware nodes for monitoring combined with a software-based infrastructure for central storage. Our software infrastructure is based on open source software, making the system highly adaptable to changing underlying hardware, like varying types of computing units, including changes of CPU architectures and hardware capabilities. Furthermore, we base our software on open standards, easing data-processing. Secure management of software installations is enabled through signed packages and repository, and keeping the installation automatically up-to-date.

As part of our ongoing and future work, SoP monitoring nodes are currently being installed for monitoring different types of fibre infrastructure, including access, metro, and transport, involving aerial, buried, and subsea fibre-cables. Based on the experiences from the collected data, further work will address methods for identifying event signatures in varying types of cables and networks.

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