Optical Fiber Sensing Network Control Plane Enabled by a Novel Sub µs Response Time Fiber Sensing Control Device

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Abstract: We propose and implement a novel fiber sensing control device and sensing control plane that controls backscatter and polarization-based fiber sensing. We experimentally demonstrate in a fiber network that this device achieves sub-µs response time. ©2024 Nokia

1. Optical Fiber Sensing in Communication Networks

Network sensing is recognized as a key element for future networks and as a fundamental pillar for 6G [1-2]. Backscatter light sensing (BLS) systems such as optical time domain reflectometry (OTDR) and distributed acoustic sensing (DAS), provide information about the fiber network infrastructure and mechanical events occurring in their vicinity [2-5]. Tracking the state of polarization (SoP) of optical communication signals also allows the detection of events in and around the fiber [6-8]. Fiber sensing has multiple networking applications that can increase network efficiency, reduce design margins, and localize fiber breaks, as well as environmental sensing applications such as distributed temperature and acoustic sensing; wildfire, earthquake, and intrusion detection [2-8]. However, such a powerful tool can become a security concern if used by ill-intentioned actors. Infrastructure details can be obtained using OTDR and conversations in the proximity of fiber can be detected using DAS [3]. Therefore, providing control over where, when, and how fiber sensing occurs is critical for future optical networks. In this work we propose and implement for the first time a fiber sensing control device (FSCD) and the associated sensing control plane that provides network owners and end users control over fiber sensing activities. The FSCD can be placed in strategic locations in the fiber infrastructure creating demarcation points and sensing regions where sensing activities are independently controlled through the sensing control plane as shown in Fig. 1. The fiber sensing control plane is a new system that can be implemented independently or in collaboration with the existing control and management of the communication network that oversees fiber sensing activities across the network.

2. Optical Fiber Sensing Control Device and Real-time Sensing Control Plane

The FSCD device we propose in this work can control both SoP sensing (SoPS) and backscatter-based sensing. Fig. 1(a) shows a schematic representation of a reconfigurable FSCD. The first element from the left side of the figure is an optical coupler that combines the forward and backpropagating optical signals. The forward propagation direction is shown by the purple dashed arrow on the top of the figure. Forward-propagating light passes the coupler through the top arm and reaches the optical circulator that directs the light to the optical output port. A polarization scrambler is placed before the output port, affecting both propagation directions. To limit SoPS, the polarization scrambler is activated, varying the state of polarization to obscure certain polarization transient events (depending on the frequency of scrambling) that could be detected through SoP tracking at the receiver. The red arrow at the bottom of Fig. 1(a) represents the backscattered light path. Light entering from the output port (backscatter) is directed by the optical circulator to a secondary path which is controlled by an optical gate. An optical isolator is used after the optical gate to prevent light in the forward direction from reaching the gate. The real-time sensing agent provides the fast electronic signals to control SoPS and BLS, translating and executing sensing policies defined by the sensing control plane. Fig. 1(b) shows a FSCD implementation using a variable optical attenuator.

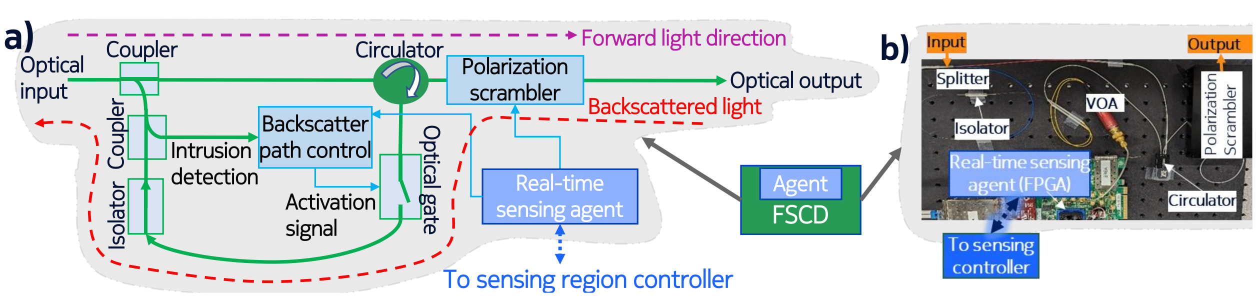

Fig. 1: Backscatter and state-of-polarization fiber sensing control device (FSCD), a) functional scheme, b) Example of implementation using a variable optical attenuator (VOA).

As the network itself becomes a sensor and more sensors are distributed across the network, it becomes a more complex system to manage. We implement hard slicing between communication and sensing control planes to adapt to the needs of each application and to operate the two systems separately. Sensing regions and network segments/domains do not need to overlap as they can be driven by different constraints and needs. The real-time nature of the sensing control system is critical because any delay in the reaction time can be exploited by an attacker to extract information from the optical network. Three sensing control layers are defined: the real-time sensing agent integrated in the FSCD, makes local decisions in less than 50 ns. The sensing region controller manages FSCDs located in a single sensing region (SR). The multi-region sensing manager enables fiber sensing coordination over multiple sensing regions. Each of these control layers has different control scope and reaction time. The two upper sensing layers are subject to additional propagation delay if not collocated with the FSCD. The FSCD is an instrument of the real-time sensing control plane and is the focus of this work. Other sensing elements can be introduced, for example, to route sensing signals through an optical network, and these devices could also be controlled by the sensing control plane.

3. Device Experimental Evaluation

We have implemented a real-time sensing control plane similar to the one presented for real-time edge-cloud network control [9], with a real-time FSCD local controller (agent), a sensing network segment controller and the multi-region sensing manager. The FSCD implementation, as shown in Fig. 1(b), includes a real-time agent implemented in an FPGA and the optical components include a 3-dB coupler, an optical circulator, an optical isolator, and the backscatter path optical gate. Each FSCD implemented in our experimental setup uses different optical gate technologies. The FSCD real-time control agent controls SoPS and BLS independently. It has four possible states. In the first one, all sensing is enabled, in the second and third, only SoPS or BLS is enabled, respectively. In the fourth state, no sensing is enabled.

a) Backscatter Sensing Control: we tested the BLS control using a commercially available OTDR operating at 1550 nm and an optical fiber of ~13 km as shown in Fig. 2(a). When BLS is enabled, we detect the length of the fiber, the existence of a connector at 1.1 km and the end of the segment as shown in Fig. 2(a). This figure also shows the effects of the attenuation set at the variable optical attenuator (VOA) used as the BLS gate, decreasing the return optical power down to the noise floor level. The high responsivity of the FSCD agent combined with a fast electro-optical switch used as a BLS gate allows the “obscuring” of specific sections of the fiber infrastructure by disabling the backscatter path during a configurable time interval after each detected OTDR pulse. Both the obscuring duration and its delay after each OTDR pulse are configured at the agent (FPGA). Fig. 2(b) shows two examples of section obscuring. In the first case, the connector at 1.1 km is obscured, while in the second, the fiber section between km 5 and km 6 is obscured. The section obscuring feature can be used to protect sensitive fiber sections while allowing pulsed DAS or OTDR systems to function in the rest of the fiber. The BLS control response time depends on the optical gate technology used to control the backscatter branch of the FSCD, see Fig. 1(a). To determine the BLS control response time, we set a policy in the local agent that detects OTDR pulses entering the FSCD with a fast photodetector, see backscatter path control unit in Fig. 1(a). The FSCD agent is configured with a power level threshold such that when an unauthorized OTDR pulse is detected by the threshold crossing of the photodiode output, it sends a control signal to open the optical gate to block backscattered light. The total response time of the FSCDs we implemented for this study -from the moment the pulse is detected until backpropagating light is blocked- ranges from less than 340 ns (electro-optical switch) to about 3 ms (MEMs-based VOA). Note that there is one FSCD at each end of the fiber to control BLS from both sides.

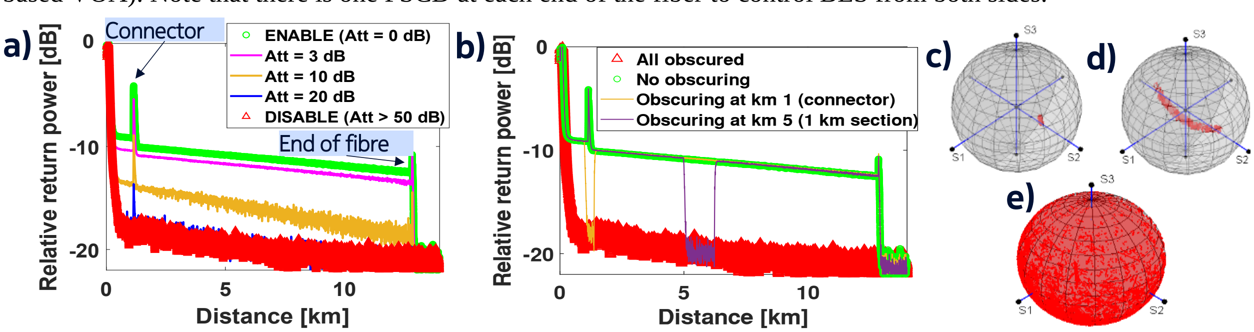

Fig. 2: Experimental results. OTDR trace affected by the fiber sensing control device, a) BLS control by VOA gate for different attenuation, b) Section “obscuring”. SoP variation in Poincaré sphere when FSCD SoP sensing is: c) Enabled-no event, d) Enabled- robotic arm event, e) Disabled (event not distinguishable).

b) State-of-polarization sensing control: we use a polarization scrambler to obscure SoP events in a frequency range of interest. High polarization rotation rates above a certain range induce bit error rate penalty at the dual-polarization coherent receiver. We choose the scrambling rate to minimize transmission penalty while obscuring the frequency range of interest for the targeted SoP events. We use commercially available coherent 400 Gb/s, 67 Gbaud transceivers to extract the the SoP state. The SoPS control has an activation delay below 400 µs, limited by the response time of the Adaptif A3000 SoP controller. Fig. 2c, 2d and 2e show the effects of FSCD SoPS in the Poincaré sphere control with 5 ms SoP sampling period at the coherent receiver.

4. Sensing Network Experimental Evaluation

We emulate a two-sensing region architecture with six FSCDs, as shown in Fig. 3(a). SR 1 represents a premise traversed by 12.8 km of fiber and SR 2 is a transport link composed of a 40 km 7-core uncoupled fiber span from Sumitomo [10]. The first fiber sensing path traverses SR1 and SR2 and represents a path owned by a network operator with sensing enabled (all FSCD in this path are deactivated), see Fig. 3(a). The second sensing path represents a leased transport fiber that only uses one core of the multi-core transport section (SR2). The user of the second sensing path is not authorized to perform sensing, thus, the FSCDs in this path are activated. Note that EDFA amplifiers can include OTDR/DAS ports to bypass the optical isolators that are typically part of the amplifier subsystem [11]. The sensing control policies were set by the sensing manager running in a general-purpose CPU with direct connection to the SR controllers that enforce the policies through the FSCD agents. Sensing region controllers and FSCD agents are implemented in FPGAs for fast reaction. Real-time control plane links between all control layers use 10G Ethernet. We measured the real-time sensing control plane reaction time at different control layers using the fastest BLS control gate (fast electro-optical switch) in the scenario of unauthorized OTDR pulse detection. The measured response time are 340 ns at the FSCD agent level, 1.9 µs at sensing region controller level, and 2 ms at the multi-region sensing manager level. Note that there is less 2 m fiber distance between control layers in this setup. Longer distances would increase the delay in the two upper control layers (region controller and sensing manager). Fig. 3(b,c) show the measured SoP traces for the two sensing paths. We mechanically disturb the multi-core fiber and test the effectiveness of the SoPS control. In sensing path 1 (SoPS enabled), we can clearly distinguish when the fiber is disturbed from the static state, see Fig. 3(b). A simple SoP slope threshold can be used to detect the disturbance. In sensing path 2, (SoPS disabled), the polarization scrambling obscures the SoP signature of the event, see Fig. 3(c). The polarization scrambling frequencies of the FSCD have negligible impact on the communication signal wavelengths bit error rates.

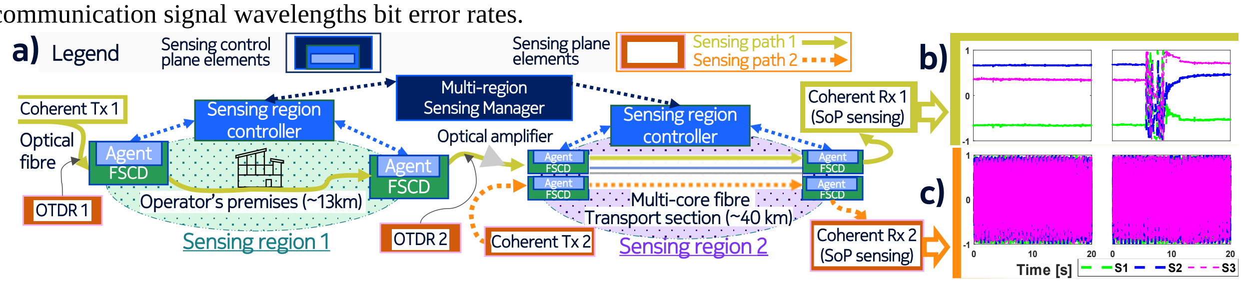

Fig. 3: a) Sensing network control experimental scheme with FSCDs demarcating two controlled sensing regions. Experimental SoP traces with and without mechanical event for: b) Sensing path 1, c) Sensing path 2

Conclusions

We experimentally demonstrated the control of both backscatter- and polarization-based fiber sensing, across different fiber sensing regions using the proposed fiber sensing control device and fiber sensing control plane, providing a responsivity below 1 µs for local control. This concept can deliver high value for optical networks as the network-as-a-sensor concept is further established, enabling control over fiber sensing activities.

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