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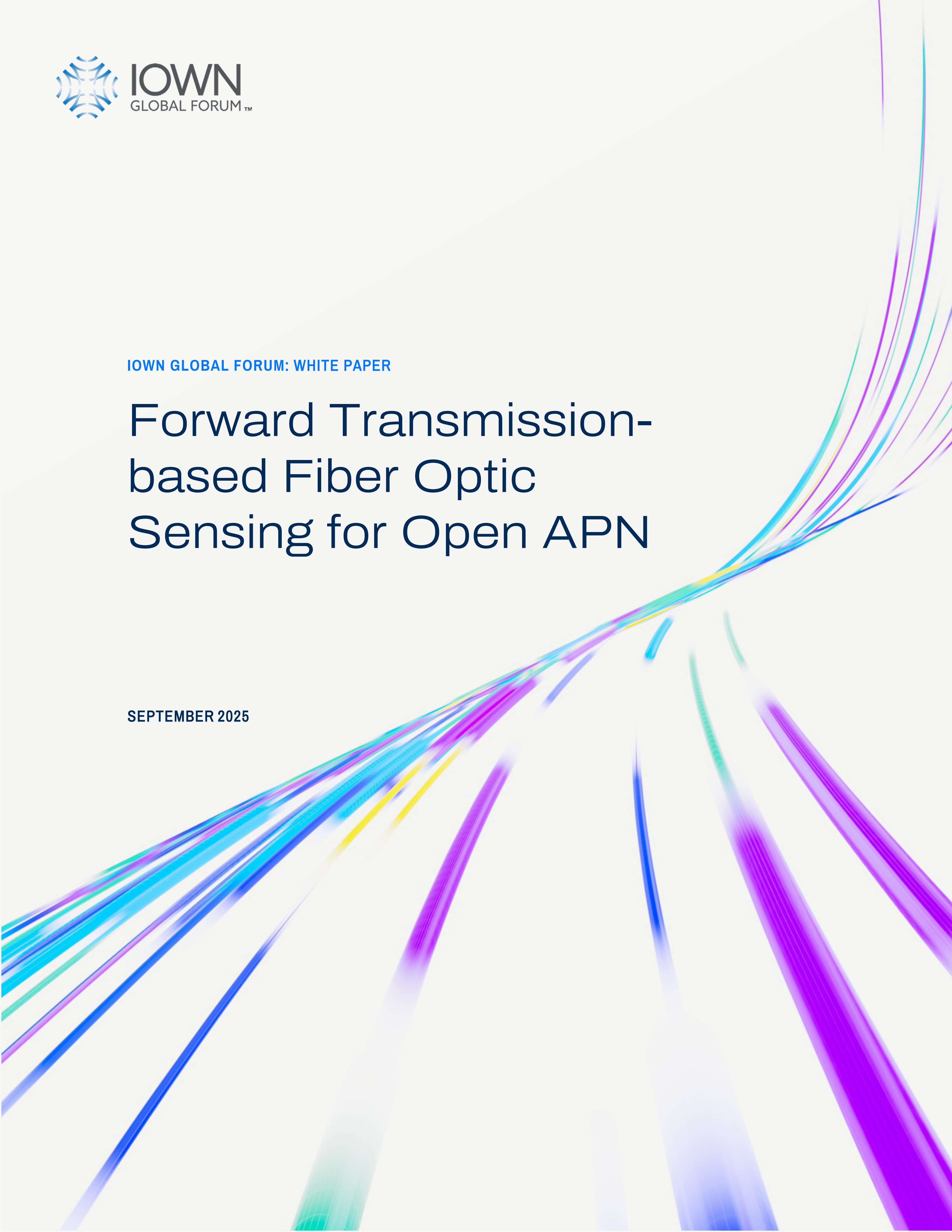

IOWN GLOBAL FORUM: WHITE PAPER

Forward Transmission-based Fiber Optic Sensing for Open APN

SEPTEMBER 2025

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1. Introduction

1.1. Fiber sensing and its market

Fiber optic sensing is the technology of performing real-time and continuous measurement of change environmental conditions along the entire fiber optic cable. Fiber sensing systems monitor and rapidly report, with meter-scale spatial resolution, environmental characteristics such as temperature, strain, vibration (including acoustic), and more over long distances in a fiber-optic network.

Compared to conventional discrete mechanical or electrical sensors, fiber optic sensing technologies offer many benefits such as: long sensing distance, large amount of sensing points with intrinsic synchronization, high sensitivity, low latency, compact and lightweight, not requiring line-of-sight, immunity to electromagnetic interference, not requiring electric power supply in the field, built-in data communication, environmental robustness. These advantages make them suitable for many applications in diverse market segments, ranging from perimeter security and border protection, oil and gas exploration and production, environment and natural disaster monitoring, traffic and roadway monitoring, power and energy system monitoring, civil infrastructure health monitoring, etc. Therefore, the deployment and utilization of fiber optic sensing solutions has been growing in recent years.

Since telecommunication network consists of large amount of optical fiber already deployed in the field, these fibers can be utilized for sensing applications, which will reduce the installation expense – a significant factor for fiber optic adoption. By utilizing the fiber sensing technologies and solutions, the telecom owner can make their network operation more efficient and make their service more reliable, such as providing early detection and warning for link outrage, speeding up the network diagnosis and repair process, monitoring the infrastructure health and status, etc. Furthermore, fiber sensing can provide the network owner the opportunity to generate extra revenue from their existing infrastructure by offering new services and acquiring new customers.

1.2. Current fiber sensing in IOWN GF

Since IOWN Global Forum aims to bring innovation and new features to the current telecommunication networks, fiber sensing is included as a key feature for IOWN GF’s Open APN. The goal is to achieve a smooth integration of fiber sensing function with the communication function in the Open APN.

Two reference documents have been published by IOWN GF on the topic of fiber sensing for Open APN [1, 2]. In these documents, three types of architectures have been defined, based on different levels of interactions between the sensing signals and the communication signals. Due to the unique optical signal characteristics and requirements from fiber sensing system (as well as other non-conventional services such as QKD), fiber path service has been defined in APN Functional Architecture, compared to the wavelength path service for standard WDM communication signals [3]. A single-span point-to-point wavelength path service is also being defined [4].

Various use cases that utilize fiber sensing over Open APN network have been proposed, including wide-area traffic monitoring, remote monitoring for construction site, and data center monitoring. Some proof-of-concept (PoC) field trials have been conducted, demonstrating the benefit of fiber sensing over Open APN network [5].

1.3. Forward transmission-based fiber sensing

So far, most of the fiber sensing solutions studied in IOWN GF is based on optical backscattering technologies, such as Rayleigh backscattering-based distributed acoustic sensor (DAS), Brillouin backscattering-based Brillouin optical time domain reflectometer (BOTDR), and Raman backscattering-based distributed temperature sensor (DTS). The architectures listed in the two reference documents [1, 2] are also targeting backscattering-based distributed fiber optic sensing (DFOS) systems.

However, in recent years, forward transmission-based fiber sensing technology has emerged and started to gain attractions. This is mainly due to the advancement in high-speed digital signal processing (DSP) technology in the latest optical transmission systems, making it possible to extract physical fiber parameters using transceivers mainly designed for networking purposes. As the data rate in optical transmission systems increases to meet the growing demand in global communication, advanced modulation formats are adopted, the symbol rate is increasing, and multi-dimensional multiplexing techniques are used. These techniques require better tolerance and robustness against system impairments such as low signal level, optical dispersion, and fiber nonlinearity. Conventional optical schemes are no longer sufficient to mitigate these impairments and to recover the data. Therefore high-speed electronic DSP technologies have been developed and applied in the current optical transmission systems. These systems can calculate the optical characteristics of the received signal in real-time at the rate between kHz ~MHz, and use them to recover the original transmitted data. These optical characteristics include the amplitude, phase, state of polarization (SoP), dispersion, etc., and can be derived from the DSP in real-time.

For the communication purpose, the variation of these optical characteristics is usually considered as system noises, which should be removed in order to recover the original signal. These system noises come from the internal hardware property, as well as external environmental disturbance. Therefore, some of the optical characteristics changes in the transmission signal can be used to extract the physical movement along the transmission link and to monitor the events occurred in the environment. This type of sensing technique is called the forward transmission-based sensing, because it utilizes the signal from the data transmission system, which is in the forward direction (in contrast to the backscattering signal from sensing system).

Even though not being the main sensing technology at this moment, forward transmission-based sensing technology was discussed since the beginning of IOWN GF's fiber sensing study. This technology is suitable for IOWN GF's Open APN since it can utilize APN's optical transmission equipment for sensing purpose and use the WDM networking hardware for network-wide monitoring. On the other hand, IOWN GF is a suitable organization to study this topic since IOWN GF consists of major international technology companies from both the communication and sensing fields, as well as end users from different industries.

IOWN GF develops this document for the first time to provide a review of the fundamental and latest technologies related to forward transmission-based sensing, to discuss its benefits and limitations, especially with respect to the backscattering-based sensing technologies, and to propose some practical use cases. It is shown that this technology can work well with IOWN's Open APN, and can provide valuable functions and novel capabilities to the network with little additional modification effort. Therefore, it has great potentials for commercialization. However, several work items need to be addressed to ensure that it will provide technical and economical benefits to the end users. These work items will be raised in this document.

2. Technology for Forward Transmission-based Sensing

2.1. Operation principle

As discussed above, the forward transmission-based sensing technology uses the real-time variation of optical characteristics of the transmission signal provided by the optical receiver's DSP hardware to deduce the physical change along the transmission link. Currently, two optical parameters have been proposed, investigated, demonstrated, and verified experimentally for such purpose. These two parameters are the optical polarization and the optical phase.

2.1.1. SoP-based forward sensing

SoP-based forward sensing technique analyzes the temporal variation of the polarization state to deduce the perturbation in the transmission route.

The state of polarization (SoP) in coherent optics refers to the orientation of the electric field of an optical signal. It describes the direction in which the electric field oscillates as the light wave travels through the medium. For fiber sensing systems, the medium is an optical fiber. During the propagation, light waves can oscillate in different directions, and the orientation of the electric field can change as the light interacts with different components in a coherent optical system. If there is a perturbation in the propagation path, the SoP of the light at the receiver will fluctuate. These changes in the SoP can result in signal degradation or even complete signal loss if the system is not designed to compensate for them. Therefore the modern digital coherent receiver in the transmission system offer the function to monitor and compensate for the SoP fluctuation. An SoP monitoring functionality incorporated into a coherent receiver is used to collect SoP fluctuations in real-time. Specifically, the Stokes parameters ($\boldsymbol{S1}$, $\boldsymbol{S2}$, and $\boldsymbol{S3}$) are recorded periodically. More descriptions of the physical principles of SOP-based monitoring can be found in Appendix 1.

Such a function in the digital coherent receiver can be used to provide sensing function for the perturbations in the transmission link. Figure 1 shows a schematic of such a sensing system.

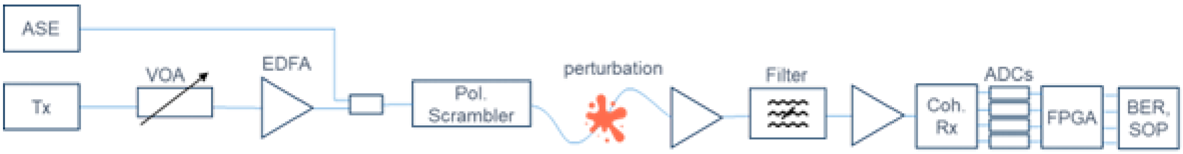

Figure 1 Schematic of SoP-based forward transmission sensing system

In this system, each SoP recording is a multivariate time series of variable length that incorporates the variation of Stokes parameters as a function of time. The SoP recordings are then sent to a remote-control system controller for analysis.

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The approach consists of three steps: i) splitting the continuous SoP time series; ii) transforming time series into a single image made up with 3 stacked (1 per Stokes parameter) time-frequency spectrograms, iii) an ML model leveraging vision transformer to output the event type, start time $\boldsymbol{x1}$, end time $\boldsymbol{x2}$, and frequency range ($\boldsymbol{y1}$, $\boldsymbol{y2}$) coordinates in the spectrogram. The first step splits the time series of each Stokes parameter $\boldsymbol{Si}$ into non-overlapping sequences of fixed length $\boldsymbol{l}$ where $\boldsymbol{l} < \boldsymbol{T}$. The second step transforms each generated time series sequence into an image of time-frequency spectrogram by using the short time Fourier transform (STFT). In the third step, ML algorithms can be trained to recognize specific patterns of SoP transients related to different activities, allowing users to identify the events.

2.1.2. Phase-based forward sensing

Environmental vibration also causes phase change in transmission light in the optical fiber, therefore optical phase variation can also be used to monitor the vibration even along the transmission fiber [6-8]. When there is no external vibration, the phase of the light at the receiver will vary slowly due to the carrier phase noise and other phase noises resulting from environmental fluctuations (wind flow, acoustic, thermal variations, etc.). When an external vibration occurs at a certain position of the fiber route that exerts strain on the fiber, the path length and refractive index experienced by the optical signal will change accordingly, which in turn will induce a phase change in the transmission light.

Compared with SoP, the use of optical phase can be 1 to 2 orders of magnitude more sensitive, as optical phase change is directly proportional to longitudinal strain induced by vibration. By contrast, SoP fluctuation is a nonlinear function of longitudinal strain and depends on fiber birefringence.

The phase detection technique requires ultra-low phase noise laser for interferometry. Therefore, to make the transponder compatible with vibration detection function, the existing external cavity lasers in the regular telecom transponders should be replaced with better lasers with more stringent phase noise specification. This is a disadvantage of phase-based interferometry approach, because phase-stable laser is more expensive than a typical laser used for communication function. The sensing scheme can be implemented on a dedicated sensing channel or added as a vibration-monitoring function in a coherent data transmission channel. As the sensing signal is normally continuous or data-modulated, the impact nonlinearity on neighboring telecom channels are relatively low.

2.1.3. Forward sensing with reflection back circuits

For the SoP sensing technique above, each transceiver will detect the overall SoP state fluctuation for the whole fiber link. In certain network designs, such as an integrated bi-directional submarine fiber optical cable, it is possible to retrieve individual polarization parameters for each defined fiber section. In the submarine cable designs, reflection back circuits (RBCs) are embedded in the in-line repeaters to facilitate repeater monitoring, as illustrated in Figure 2. The RBCs or high-loss loop back paths are commonly set up in long distance submarine transmission links for supervisory purposes such as monitoring the pump health and span loss.

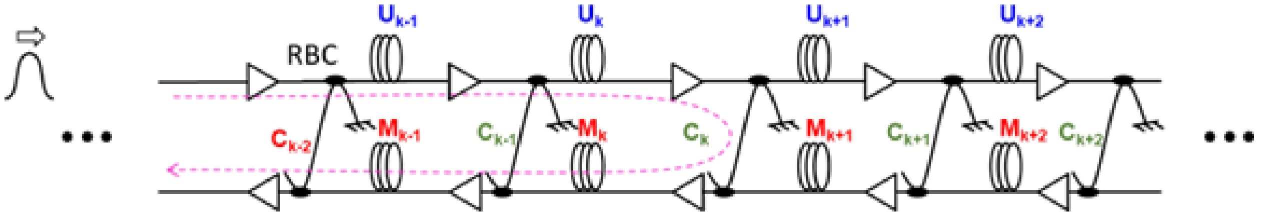

Figure 2 Forward sensing system with RBCs

Utilizing RBC and a dedicated sensing signal, a polarization rotation-based method can be used to identify the relative location of mechanical disturbance on the cable. In this approach, multiple independent SoPs are sent in the sensing signal [9]. From the returning SoPs, the polarization rotation matrix (PRM) for the traversed path is measured. Because of the RBCs, each fiber span can be separately detected. The independent SoPs can be sent separately in time domain or frequency domain or both, as long as they are sufficiently independent and within a time frame where the PRMs can be assumed to be almost constant.

It has been demonstrated that by measuring PRM of the return paths, instead of monitoring only the SoP, location of the polarization disturbance can be determined using this RBC-based scheme even for large polarization rotations [10].

2.2. Event localization in forward transmission-based sensing system

Based on the basic principle of forward sensing (both SoP-based and phase-based), the detection is by analyzing the optical signal transmitted through the entire fiber length. Unlike backscattering-based sensing where the backscattering signal generated at each location processes a different round-trip path length that leads to a different round-trip time-of-flight, which is then utilized to determine the event location through temporal discrimination, all received signals in the forward transmission-based sensing travel through the same optical path inside the fiber (except for those with reflectors throughout the sensing path). Therefore it is not possible to determine the event location based on the optical path distance and temporal discrimination.

For some applications, it is sufficient to know whether an event occurs without knowing the exact location. However, in most of the fiber sensing applications, the localization of the events is a required feature, and is one of the key features offered by DFOS technology. Therefore, it is important to develop techniques to localize the event.

A proposed method is to use two fibers in bidirectional transmission configuration [6-8]. Continuous-wave laser signals are transmitted from each end of a fiber cable. A single external vibration will affect both fibers. Because these two fibers are very close to each other, the phase shift caused by the external vibration will be the same, therefore the phases detected by the coherent receivers at both ends can be correlated to determine the position closest to the event location. Lab experiment demonstrated the ability to identify the location of an environmental perturbation to within 1 km over 101 km of spooled fiber [6]. This method has been demonstrated for earthquake localization function. By utilizing a frequency-shifted optical delay line, the scheme can be simplified to a looped back

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configuration [6, 7] to mitigate the effect of the inherent auto-correction interference. Typically, the spatial accuracy of the localization scheme depends on the excitation bandwidths from the vibration events, which can be less than 100 m when the bandwidth exceeds 100-kHz [7]. Similar accuracy can also be achieved when the correlation method is implemented on two sets of optical networking transponders for optical phase recovery instead of dedicated sensing channel [8].

For RBC-based system, the reflector at each span enables the measurement of the optical characteristics at each span, therefore it can be considered as a coarse distributed sensing system with span resolution. By monitoring the phase and polarization information in each span, the span where the event occurs can be identified [10].

Event localization in forward transmission-based sensing can also be performed using non-optical method. The way is to utilize machine learning (ML) techniques to analyze the signatures of the received signal. For example, through ML-based analysis of accurately timestamped SoP vibrations in both temporal and spectral domains, the vibration events can be classified and localized, even in the presence of overlapping SoP events. Even though this ML-based technology is still being developed and improved, the recent rapid advancement of ML and artificial intelligence technology indicates great potential of this approach.

2.3. Networking and routing

Since the forward transmission-based sensing uses regular or modified communication signals for sensing, it can be integrated well with WDM optical networks.

Most terrestrial metro and long-haul optical networks are not just a point-to-point link, but contain multiple nodes and links connected in different topologies. In certain network-monitoring applications, identifying which link the anomaly occurs is sufficient, or provides the first essential step. Therefore, by network-wide global planning of the sensing routes, anomaly events can be detected and localized in large-scale optical networks using forward transmission-based sensing [11].

In this scheme, multiple forward sensing routes are selected to cover the entire network, and each link in the network is guaranteed to be passed by a different combination of sensing routes. These routes are then monitored concurrently and analyzed centrally. When an anomaly event occurs at a specific link, the receivers in the corresponding routes will detect the optical characteristic change. Since the sensing route combination is unique for each link, the global analysis of the optical characteristic change will indicate the exact link that causes the event. Heuristic algorithm has also been developed to optimize the route selection.

3. Benefits and Limitations

3.1. Benefits of forward sensing

Due to its operation principles, forward transmission- based sensing scheme processes several key advantages compared to the conventional backscattering-based sensing.

Long sensing distance: The optical signal-of-interest in conventional backscattering-based sensing system is the backscattering of the transmitted light, which is tens of dB weaker than the transmitted signal itself. Among the three backscattering types, Rayleigh backscattering is relatively stronger. However, it is still several orders of magnitude weaker than the input signal. The backscattering signal is even lower in the newer low loss optical fibers used for telecommunication purpose. It is also not possible to significantly increase the transmission signal's optical power since it will cause nonlinear effects which are undesirable. Using coding schemes can effectively increase the signal power, but the improvement is limited. Therefore, the sensing distance for backscattering-based DFOS system is typically 100 km or lower without repeaters. Standard optical amplifiers in the WDM transmission network cannot be used due to the blocking of backscattering signals by the internal isolator. Repeater bypass methods using additional optical coupler and switch or circulator have been proposed for APN network [5]. Even with specially designed repeaters, the maximum sensing distance demonstrated so far is about 1000 km [12].

For forward transmission-based sensing system, the sensing signal is the regular WDM transmission signal for communication, therefore the optical power level is as high as standard WDM communication signals, and the existing WDM repeaters can be used. Therefore the operation distance is the same as the WDM communication system, which can be ten thousand kilometers or longer. This is significantly longer than the backscattering-based system. This enables the sensing applications over long-haul, ultra long-haul, and transoceanic networks.

No additional hardware required: Since some forward transmission-based sensing systems, such as those based on SoP monitoring, use WDM communication signal as the sensing signal, no additional hardware is required by definition. Existing optoelectronic hardware for data communication, such as the digital coherent DWDM transponder, is used as the sensing transmitter and receiver. The current DSP processor in the digital coherent system provides the sensing data for analysis, such as SoP and phase. This greatly reduces the hardware cost, since it does not require a dedicated interrogator as in backscattering-based sensing systems. In fact, the optoelectronic hardware can serve the communication purpose and sensing purpose at the same time, which means that no additional hardware cost is required while the additional sensing function is achieved.

Of course, some of the advance event localization or sensitivity enhancing schemes discussed above cannot be directly achieved with the existing communication hardware. Therefore additional hardware or modified hardware will be required.

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WDM network compatibility: The forward transmission-based sensing systems do not have the repeater isolator issue similar to the backscattering-based DFOS systems, because the signal only needs to travel in the forward direction (for the loopback-based system and dual fiber system, the signals in the second fiber is also transmitted in its forward direction). Therefore, the sensing system can work with, and as part of, the WDM communication network (the so-called "in-band sensing"). The existing hardware in the communication network, such as multiplexers, demultiplexer, ROADM, and wavelength cross-connect, can be directly used without modification. The sensing channels have the same optical power and spectral characteristics as the other WDM channels, therefore the channel planning and management does not need to be modified.

Dual-function operation: For SoP-based sensing, the sensing channel can be a data transmission channel, therefore the same channel can perform both functions simultaneously. In other words, sensing can be a bonus function without affecting the existing communication system. This makes spectral resource utilization more efficient, and makes the network control simpler.

3.2. Limitations of forward sensing

Even though forward transmission-based sensing technologies offer many advantages, there are still various limitations so far, in particular, the sensitivity and localization capability.

Sensitivity: Even though the optical power level of the received optical signal in the forward transmission-based fiber sensing system is much stronger than the backscattering signals, the different sensing principle leads to different vibration sensitivity response.

Mechanical vibration on an optical fiber induces longitudinal strain on individual fibers within the fiber, manifesting in change in optical path length Δz which can be detected as a phase shift $\phi_{vib} = 0.78(2\pi/\lambda)\Delta z$, where λ is the wavelength of the optical signal. The factor of 0.78 accounts for the strain-optic effect, where 22% of the phase change is due to strain-induced refractive index change in the fiber. There exist a frequency range in $\phi_{vib}(t)$ that are above the level of the non-vibration components. The vibration event can only be detected when a vibration event occurs whose amplitude exceeds the sensitivity threshold. For phase-based forward sensing, the threshold is high, leading to a sensitivity level of around 10~100 mrad/√Hz (compared to 0.1~1 mrad/√Hz for Rayleigh backscattering-based sensing). For SoP-based forward sensing, the sensitivity is related to fiber birefringence, which has an indirect relationship with strain. Therefore, the sensitivity is even lower.

Event localization capability and accuracy: As discussed above, the basic forward transmission-based sensing technologies do not provide event localization capability, due to the same optical transmission path length. Additional optical processing techniques, such as optical loopback, dual transponder pair, or per-span RBCs, need to be used, instead of just the existing WDM data transmission hardware. These techniques require modification of transmission link configuration, costly low noise laser, or additional high-precision clock synchronization circuit. Furthermore, even with these techniques, the spatial resolution of event localization remains poor (in the order of hundreds or thousands of meters). This is significantly lower than the meter-level spatial accuracy from backscattering-based DFOS systems. The reason is that due to the different round trip path length for the optical backscattering signals from different locations, the vibration signal at each location is processed independently, while the signal from all locations are received and processed together under the forward transmission-based sensing scheme.

The ML-based event localization method is yet to be mature, and the anticipated localization capability in long distance, multi-event environment is yet to be proven in real-world condition.

3.3. Comparison between forward sensing and backscattering-based sensing

Table 1 summarizes the comparison between forward transmission-based sensing and the conventional backscattering-based sensing methods. Several forward transmission-based sensing techniques are included.

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Table 1 Comparison between forward transmission-based sensing and backscattering-based sensing

Fiber Sensing Technology	Backscattering-based Distributed Acoustic Sensor (DAS)	Forward sensing with SoP Monitoring	Forward phase interferometry	Forward sensing with reflection-back circuits
Sensitivity	Very High: 0.1~1 mrad/√Hz	Very low (relies on fiber birefringence with indirect relationship with strain)	Low: 10~100 mrad/√Hz	Low: 10~100 mrad/√Hz
Monitored distance	~100 km without repeater ~1000 km with special repeaters	~250 km without repeater >10,000 km with repeaters	~250 km without repeater >10,000 km with repeater	10,000 km with repeater
Event localization	Spatial resolution: 1 m ~ 100 m	Cannot localize the event using optical method; Require ML-based signature recognition	Vibration bandwidth dependent: from 10 m to 100 km	Submarine fiber span length: 40 km to 100 km
Multi-vibration capture	Independently monitored points: 10,000 ~ 50,000 pts	Single “blended” signal from all vibration sources; Require ML-based method to detect multiple events	Dependent on noise/vibration strength: Likely <5 vibration events	Independently monitored spans: <200 fiber spans
Applications	Too many to list.	Earthquake, fiber cut prevention, telecom network protection	Earthquakes, fiber cut prevention, network fault identification	Repeater monitoring, OTDR, earthquakes, fiber cut prevention
WDM network compatibility **(Current)**	Separate fiber, or use guard band and proper power optimization	Already integrated into WDM transponder	Multi-span WDM possible with dedicated sensing channel	Multi-span WDM possible with using special reserved OSC channel slot
WDM network compatibility **(Potential)**	Multi-span WDM with new EDFA and ROADM design	Higher speed monitoring, but signal bandwidth still limited	Functionality integrated into transponder or OSC	Functionality integrated into OSC channel

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4. Use Cases

Due to the extensive benefits of the in-band forward transmission-based fiber sensing, many applications can be enabled. Below are a few examples.

4.1. Telecom network anomaly detection

The use of forward transmission-based fiber sensing technology offers a powerful solution for detecting early signs of physical stress, preventing potential fiber breaks, and ensuring proactive maintenance. This method is also highly effective for securing networks against unauthorized intrusions, animal proximity, and structural strain. By leveraging ML technology, the fiber sensing system can distinguish between natural disturbances and threats, providing enhanced security for both physical networks and data transmission. Overall, this technology plays a key role in maintaining network integrity and preventing environmental, economic, and safety issues.

For example, illegal or unplanned excavation near the buried cable route is a common reason for cable damage in terrestrial fiber optic networks, and optical fibers deployed in rural or remote areas are often vulnerable to damage from wildlife activity. By detecting optical characteristic and pattern changes in the received signal, network operators can be notified the excavation event or animal proximity and its location, so that they can proactively address issues before they escalate, ensuring continuous and reliable data transmission. This advancement significantly improves the accuracy and reliability of fiber monitoring and damage prevention systems, while simultaneously maintaining uninterrupted user traffic flow.

4.2. Telecom network risk assessment

The SoP capabilities of an optical transport network equipped with coherent APN transponder (cAPN-T) can be used to identify Shared Risk Link Groups (SRLGs) within fiber optic transport networks. The method leverages the detection of correlated perturbations between adjacent fibers to determine if they share the same physical duct or infrastructure. When a perturbation is introduced on one fiber, any corresponding perturbation detected on a neighboring fiber suggests that both run through the same duct and share common risks. The network operator can then assess their vulnerability to environmental and physical risks, and proactively manage risks associated with shared ducts or infrastructure, protecting critical data transmission routes from potential failures.

This operation is performed without interrupting high-capacity live traffic, avoiding costly downtime or disruptions during SRLG assessments and ensuring continuous operation.

4.3. Earthquake detection

One of the earliest forward transmission-based sensing application is large-area earthquake detection [8], because conventional discrete seismometer and backscattering-based DFOS have limited coverage area, and the required location accuracy and resolution for earthquake detection is not as high as other fiber sensing applications such as perimeter intrusion detection and highway traffic monitoring. This makes forward transmission-based fiber sensing an ideal solution for large-scale seismic activity detection, such as using submarine fiber optic network to monitor underwater earthquake in an ocean. Other seismic activities, such as landslide or volcano movement, can also be monitored using this technology.

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5. Forward Transmission-based Sensing for IOWN Global Forum's Open APN

5.1. Architecture

For backscattering-based DFOS systems, due to the different operation configuration and different optical characteristics of the signal, it is not straightforward to incorporate the sensing system in the WDM system, including IOWN GF's Open APN network. As shown in [1] and [2], several architectures have been proposed, with different levels of integration and different levels of technology maturity. Some modifications is required on the interconnect node to bypass the amplifier.

However, that is not the case for forward transmission-based sensing systems. As discussed earlier, a major advantage of forward transmission-based sensing is the easy/natural integration of the WDM network. Therefore, the existing architecture developed for Open APN can be directly applied.

5.2. Control

Similarly, the control of forward transmission-based sensing system is much simpler than backscattering-based sensing system. No special network control function is required. Additional control parameters can be set up to provide the information related to the sensing function, such as sensing route, event information, etc.

APN network controller can be configured to set up the sensing routes. On the other hand, the sensing results can be reported to the network controller in real-time for network reconfiguration and rerouting in case of anomaly events.

5.3. Key requirements

For SoP-based forward sensing system, no additional equipment is required since the cAPN-T is equipped with technology that not only supports high-capacity data transmission but also enables distributed fiber sensing functionality. Some cAPN-T can provide real-time phase information too.

The key requirements for the cAPN-T are:

- **Sensitivity and Resolution:** The system must demonstrate the ability to detect small changes in the monitored parameters.
- **Response Time:** The system is expected to facilitate rapid detection and timely reporting of physical changes, thereby enabling prompt and effective interventions.
- **Distance Coverage:** The fiber sensing system must maintain performance over the required monitoring distance, with minimal signal degradation.
- **Reliability and Accuracy:** The system's data must be accurate and reliable over time, with low false alarm rates and high repeatability.

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- **Operational Cost:** The fiber sensing-based solution must maintain cost-effectiveness over traditional monitoring methods.
- **Integration and Scalability:** The ability to integrate fiber sensing into existing monitoring systems and scale the solution as needed is a critical factor for wider deployment.

5.4. Work items to address

Even though there is no major fundamental technical issue to integrate forward transmission-based sensing with the Open APN developed by IOWN GF, several work items should be addressed by the forum before general commercial deployment becomes feasible. Here are some major work items:

- Develop a functional architecture that defines functional components with their functions and interfaces.
- Conduct techno-economic analysis to prove the economic/environmental advantages of this technology on each use case
- Develop organizational models to identify organizations involved in the deployment of this technology and the needed agreements between the organizations (such as data provider-consumer agreement, SLA, ..)

6. Conclusions

Forward transmission-based sensing presents a new way of distributed sensing in fiber optic networks. By monitoring the optical characteristics, such as polarization and phase, of the transmitted signal at the receiver, environmental events can be detected. With further optical, analytical, and ML processing, the events can be classified and localized. It works well with IOWN GF's Open APN architecture.

This technology offers many advantages compared to the conventional backscattering-based sensing, even though there are various limitations too. Forward transmission-based sensing enables many new applications, ranging from telecom network protection to global scale natural disaster monitoring. Therefore, it is an important technology to be adopted and incorporated into IOWN GF's network.

Several topics remain to be studied and addressed before commercial deployment of this technology, including functional architecture, techno-economic analysis, organization model and agreements. IOWN GF is a suitable organization to address these issues because of the broad range of technical expertise (including optical communication, networking, fiber sensing, data computation and analytics, etc.) and vast industries (including telecom, datacom, scientific, construction, financial, entertainment, etc.) among the members,

In order to adopt this technology earlier, IOWN GF should study these issues, and then quickly demonstrate the technical feasibility, system compatibleness, and business value through lab and field PoC experiments carried out by both equipment/system providers and application users. The successful outcome can drive IOWN GF to commercialize forward sensing technology in Open APN to offer fiber optic ISAC (integrated sensing and communication) service or stand-alone long distance sensing service to a broader customer base.

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Appendix I. Principle of SoP-based sensing

The electric field vector (**E**) can be described by its orthogonal components, $\mathbf{E}_x$ and $\mathbf{E}_y$. In elliptically polarized light, these components have different amplitudes and a phase difference that is not an integer multiple of π/2. The $\mathbf{E}_x$ and $\mathbf{E}_y$ values vary periodically but out of sync, spanning different ranges. When combined, the total field vector rotates around the propagation axis, with its length changing as it rotates. Viewed perpendicular to the $\mathbf{E}_x$,$\mathbf{E}_y$ plane, the tip of the vector traces the curve of a polarization ellipse. The figure below shows the decomposition of the electric field (**E**) into it is two orthogonal components, $\mathbf{E}_x$ and $\mathbf{E}_y$, with a δ, as the phase shift in between.

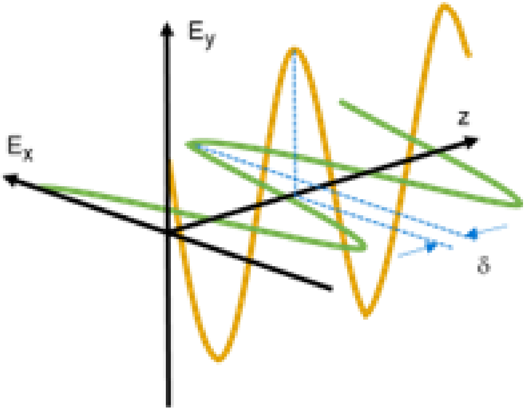

Figure 3 Decomposition of the electrical field E into two orthogonal vectors along the z-axis

The polarization ellipse is bounded by a rectangle whose sides are twice the amplitudes, $\mathbf{E}_{ox}$ and $\mathbf{E}_{oy}$, of the $\mathbf{E}_x$ and $\mathbf{E}_y$ components. This rectangle indicates the fraction of light in each component. To fully describe the polarization state, the phase delay between $\mathbf{E}_x$ and $\mathbf{E}_y$ must be considered. Key features include the major axis's rotation relative to the $\mathbf{E}_x$ axis and the ratio of the minor to major axis lengths. The angle (ψ) between the major axis and $\mathbf{E}_x$ axis, known as the orientation angle, varies between -90° and 90°, with ±45° when $\mathbf{E}_{ox}$ and $\mathbf{E}_{oy}$ are equal. The electric field vector's rotation direction, known as the handedness or helicity of light, defines right-hand (clockwise, positive helicity) and left-hand (counterclockwise, negative helicity) polarization. The figure below shows propagating light ray along an z-axis, and where the tip of the rotating electric field vector traces (**E**) out an ellipse. The ellipse is described in terms of angles Ψ and χ; with () to represent (/λ - ωt), in which λ is the material-dependent wavelength, ω is frequency, and t is time.

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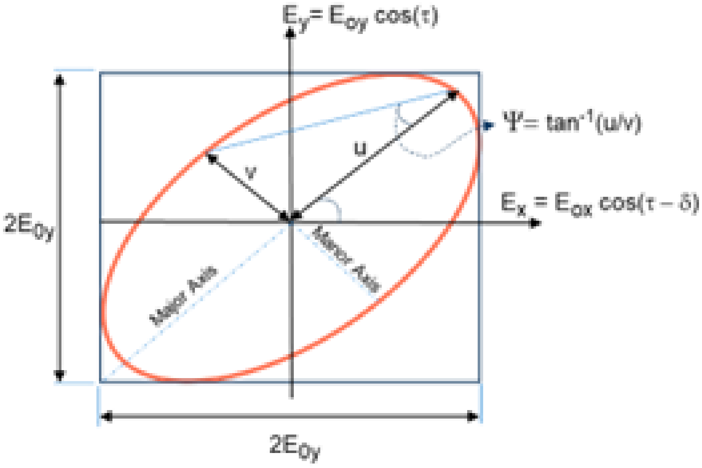

Figure 4 The Polarization ellipse

Polarization states are mapped to the Poincaré sphere using azimuth, ellipticity, and radius, similar to latitude and longitude on a globe. The azimuth and ellipticity derive from the polarization ellipse, while the radius, up to a maximum of one, indicates the degree of polarization. The Poincaré sphere simplifies calculations of polarization changes and provides a useful visual representation of polarization states and their evolution. The Figure below illustrates the mapping of the Polarization states to the Poincaré sphere based on the azimuthal and ellipticity angles, from the **S1** axis and the equator, respectively. The state's radius is largest when the light is completely polarized, when there is no remaining unpolarized part.

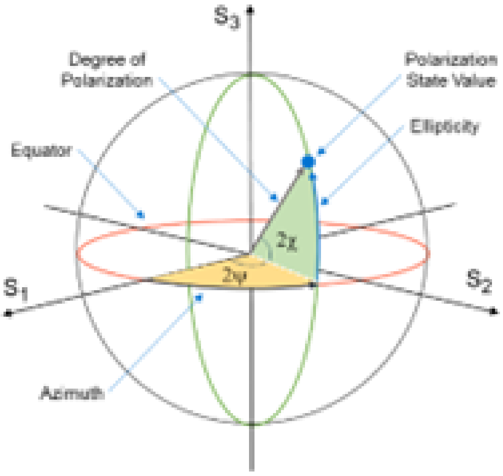

Figure 5 Poincare Sphere

The azimuthal angle (2ψ), also known as orientation, ranges between ±π/2 and is measured from the **S1** axis. The ellipticity (2χ) is an angle between ±π/4, measured from the sphere's equator. Points on the equator represent linearly polarized light, while points at the poles indicate circularly polarized light. Other elliptical polarization states are located elsewhere on the sphere. A radius of one corresponds to fully polarized light on the sphere's surface, while a decreasing radius indicates increasing unpolarized light. The degree of polarization (DoP) is the ratio of polarized light intensity to total light intensity. The polarization state's Cartesian coordinates are represented by the Stokes parameters, $\boldsymbol{S1}$, $\boldsymbol{S2}$, and $\boldsymbol{S3}$.

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The figure below illustrates that polarization states mapped on the orange circle, mapped to the equator of the Poincare sphere to be perfectly linearly polarized. Polarization states mapped on a green circle map to a value of ±1 on the **S3** axis are circularly polarized. All elliptical polarization states that are not linearly or circularly polarized are mapped to other regions of the Poincare spheres.

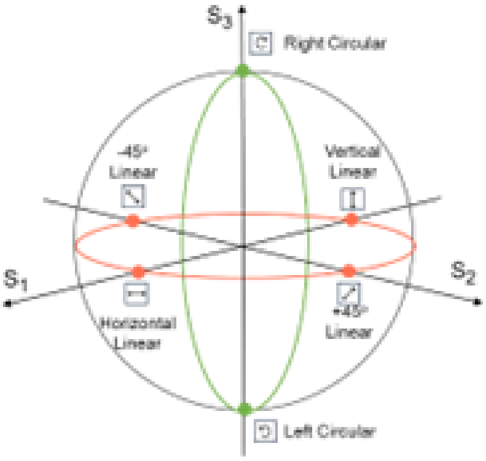

Figure 6 Polarization states mapped to the Poincare sphere

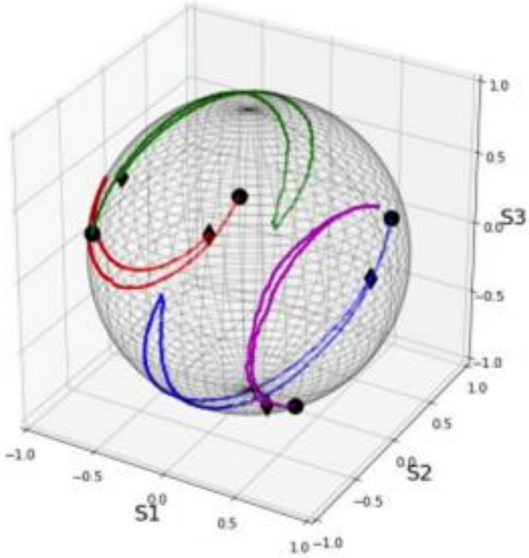

Figure 7 Interconnecting polarizations states on the Poincare sphere to helps predict light polarization after transversing polarization media, e.g. fiber

Two polarization states on the Poincaré sphere can be connected by an arc, and their azimuth and ellipticity differences calculated using spherical trigonometry. This helps predict light polarization after interacting with polarizing elements and design desired polarization states.

An SoP monitoring functionality incorporated into a coherent receiver is used to collect SoP fluctuations in real-time. Specifically, the Stokes parameters ($\boldsymbol{S1}$, $\boldsymbol{S2}$, and $\boldsymbol{S3}$) are recorded periodically. Each SoP recording is a multivariate time series of variable length , that incorporates the variation of Stokes parameters as a function of time. The SoP recordings are then sent for analysis to a remote-control system controller.

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History

Revision	Release Date	Summary of Changes
1	September 2025	Initial Release

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