# Fiber Sensing for Open APN

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# 1. Introduction

Distributed Fiber Optic Sensing (DFOS) refers to the technology of performing multi-point real-time and continuous measurement of change environmental conditions along the entire fiber optic cable with fine spacing between the measurement points. DFOS 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. Such sensing information acquired from the communications network is expected to be useful in many diverse areas, including traffic monitoring, earthquake detection, building health, and other applications unforeseen today.

The purpose of this document is to describe the benefits, basic technical features, and other issues of fiber sensing in communication networks, especially in the Open APN of IOWN Global Forum, and to serve as the basis for future discussions on the realization of fiber sensing in the APN.

## 1.1. Market dynamics

The global DFOS market is projected to grow at a CAGR (compound annual growth rate) of 15.0% during the forecast period, reaching $1,970.1 million by 2023 [1]. Since the DFOS technology is based on various types of backscattering mechanisms in an optical fiber, the DFOS market can be categorized based on the backscattering process type into Rayleigh scattering, Raman scattering, interferometric scattering, distributed fiber Bragg grating, Brillouin scattering, and several others. Among these, Raman scattering is expected to dominate the market during the forecast period. In contrast, the Rayleigh scattering process is projected to register the highest CAGR in recent predictions for the distributed fiber optic sensor market [1].

A major factor driving the growth of the global DFOS market is the increase in the worldwide demand for electrical power derived from oil and gas. This is primarily because DFOS systems have the ability to operate and optimize the resources in the oil and gas industry as they can monitor the entire length of the pipeline structure. Moreover, factors such as a surge in capital investments for thermal-enhanced oil improvement techniques, a growing focus on oil recovery, and the emergence of multi-lateral hydraulic fracturing technologies are aiding the growth of the oil and gas market. In conventional tank monitoring systems used in the oil and gas industry, the sensing element works as a separate physical device, commonly fastened at the end of the copper line, and is thus only capable of monitoring one single location. Unlike such devices, the DFOS system transforms the entire length of the fiber into thousands of individual sensing points to offer more accurate measurements.

Another area of great potential for DFOS technologies is the smart city application. Smart cities collect data from citizens, various devices, and assets to manage available resources more efficiently. A wide range of information and communications technology (ICT) is evolving to enhance knowledge and innovation, reduce costs and use of resources, improve living and working environments, and increase the communication between government and citizens. Global spending on smart cities in 2020 was $679 billion, and this is expected to reach $1 trillion by 2025 [2]. There are many different sensing devices such as acoustic sensors, cameras, flow sensors, strain sensors, and temperature sensors. However, most are discrete point sensors and often provide only a partial view of the asset. Optical fiber sensing technology enables the optical fiber to detect vibration, temperature, and stress like the nerves in a human body. Optical fiber networks can be compared to the nerves in the human body. The nerves give us accurate and real-time feedback about the health condition of our bodies. Similarly, optical fibers can be applied on or inside various physical structures and enable these structures to perceive internal and environmental information in real-time, such as vibration, strain, and temperature.

## 1.2. Objectives of Open APN fiber sensing task force

Conventional sensors depend on various sensors measuring at pre-determined points, whereas distributed sensing takes advantage of optical fiber rather than manufactured sensors. DFOS systems offer many benefits in surveillance solutions for the safety of critical assets, especially when deployed in remote locations or hostile environments (refer to Section 3.1). All these benefits offered by these sensors are expected to help the DFOS market to grow.

However, the high cost of a conventional DFOS system is one of the major factors hampering its market growth worldwide. The adoption of sensing technologies relies not only on accurate and dependable measurements but also on their installation and ease of use. The installation of DFOS systems is often impacted by technical constraints that occur in the process owing to the sensor packaging, optical loss, and breakage of the fiber cabling. Thus, the high product cost and technical constraints during installation are the key factors impacting the growth of the distributed fiber optic sensor market.

As a result, performing distributed fiber optic sensing over existing telecom networks becomes very attractive economically and practically. There is a growing technology trend to utilize the deployed fiber optic cables in existing telecom networks to perform distributed sensing. Adding fiber sensing capabilities to telecom networks brings additional value to existing network infrastructure. In fact, Open APN includes the fiber sensing function over the communication network as a new and unique feature, which is expected to bring new values to the Open APN. The Open APN Fiber Sensing Task Force (OAF) aims to study the use cases and the Open APN system architectures to add the new sensing capabilities with the emergence of DFOS. Performing optical sensing on/with the existing telecom network is a new research and development area, therefore there are no existing standards. IOWN Global Forum hopes to fill in this gap and establish the first standard and recommendations in this field.

The telecommunications networks can support a limited level of distributed sensing in their traditional form. Still, engineered enhancements to sensing aspects are increasingly available through advanced optical fiber and cable design. As such, this task force seeks to provide for open architectural support by leveraging traditional telecom network infrastructure, including the opportunity for game-changing telecommunications networks that combine distributed sensing while acknowledging the potential for emerging technologies with improved sensing.

The task force activities will include investigation and planning for the addition of distributed sensing to traditional telecom architectures and the integration of sensing capabilities within active equipment and passive cabling to enable dual-use equipment in future telecommunications infrastructure.

# 2. Fiber Sensing Technologies

## 2.1. Different types of fiber optic sensing technologies

In a broad definition, the term “fiber sensing” refers to any technology that uses optical fiber to detect some physical phenomenon. Fiber-sensing capabilities can be categorized by their physics principles, detectable physical parameters, scale, application, and so on. Based on their distribution (the number of sensing points and the ability to localize the signal), they can be roughly divided into the types shown in Table 2.1.

*Table 2.1:Comparison of different types of fiber-sensing technologies based on their distributive characteristics*

| TYPE | TECHNOLOGY EXAMPLE | NUMBER OF SENSING LOCATIONS | CAN THE EVENT BE LOCALIZED? | SENSING POINT IN THE FIBER | OPTICAL FIBER |
|---|---|---|---|---|---|
| **Optode sensor** | Chemical transducer coating | 1 point | N/A | Fiber tip or side surface | Regular fiber with special coated tip or surface |
| **Point sensor** | FBG | 1 point | N/A | 1 point on the fiber | Fiber with special structure (e.g., grating) |
| **Zone sensor** | Mach-Zehnder interferometer | 1 zone | No | Entire fiber | Regular fiber |
| **Semi-distributed sensor** | FBG array | A few points | Yes (among a few locations) | Several points on the fiber | Fiber with special structure (e.g., grating) |
| **Distributed sensor** | Forward SoP (State of Polarization) monitoring, or bidirectional phase interferometry | Many points | Maybe | Entire fiber | Regular fiber |
| **Distributed sensor** | Backscattering | Many points | Yes | Entire fiber | Regular fiber |

## 2.2. Backscattering based DFOS technologies

In this document, the term “fiber sensing” refers explicitly to the backscattering-based distributed fiber optic-sensing over standard communication fiber (the last type in Table

2.1). Even though some technical topics are also applicable to the other types, the focus of this report is distributed fiber optic sensing (DFOS).

As shown in Table 2.1, DFOS can interrogate a long section of optical fiber with fine spatial resolution and the ability to localize each event. All of these can be performed on a regular communication grade optical fiber without any special physical or chemical modification. Therefore it is suitable to be applied in fiber optic communication networks to realize Network-as-a-Sensor (NaaSr) functionality.

As the name indicates, the backscattering-based DFOS solutions are based on the backscattering signals of the probe light propagating in the core of the optical fiber. In such a system, pulsed probe laser light is sent down from the sensor (also called the interrogator) to the sensing fiber. As the light propagates along the fiber, a small amount of photon backscatter is generated due to various physical principles. These backscattering lights propagate in the reverse direction and are received and analyzed at the interrogator. If there is a perturbation in the environment, some characteristics of the backscattering signals will change, such as frequency shift or intensity variation. By detecting these changes, the environment condition is monitored. And by analyzing the different time-of-flight for the backscattering signals generated at different locations along the fiber, the event's location can be identified. Therefore this type of system is also called OTDR (optical time domain reflectometer). Figure 2.1 illustrates the operation principle of the DFOS.

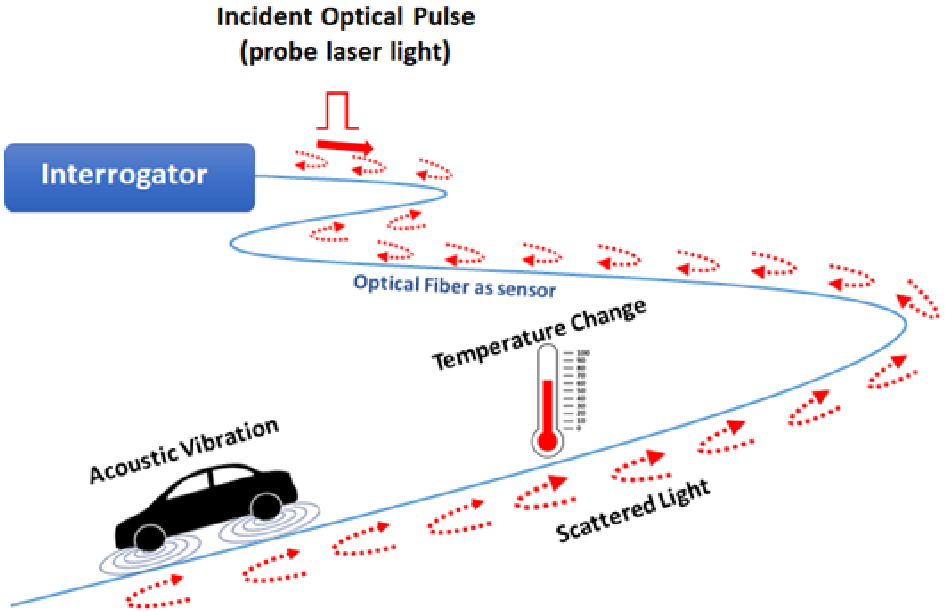

*Figure 2.1: Operation principle of backscattering based DFOS*

There are three major types of backscattering signals in an optical fiber, namely Rayleigh backscattering, Brillouin backscattering, and Raman backscattering. Each of these types of backscattering phenomena is caused by a different physical mechanism and is sensitive to different environmental conditions and stimulations, such as vibration, strain, and temperature. They also exhibit different characteristics, such as wavelength and optical power. Table 2.2 shows the comparison of some characteristics among the common backscattering-based DFOS technologies. Please note that the values in the table are typical values, not standard values.

*Table 2.2:: Comparison of the DFOS technologies based on different types of backscatterings in the fiber*

| SENSING TECHNOLOGY | | OTDR | DWDM-OTDR | C-OTDR | OFDR | B-OTDR | R-OTDR |
|---|---|---|---|---|---|---|---|
| Backscattering | | **Rayleigh** | | | | **Brillouin** | **Raman** |
| Application | | **Fiber cut and attenuation** | | **Vibration / acoustic** | **Strain / Temperature / Vibration** | **Strain / Temperature** | **Temperature** |
| **Probe laser light*** <br> **(forward)** | Center wavelength [nm] | 1550.12 nm | DWDM grid | 1550.12 nm *typical | | | |
| | Laser spectral linewidth | No restriction, but usually use LDs with 1MHz to 10MHz | | <= ~1 kHz | | ~1 MHz | No restriction |
| | Laser output power $P_{in}$ | >=4mW peak | | 100~200 mW peak | Tens of mW | 100~200 mW peak | >= 1W peak |
| | Pulse / CW | Pulse, pulse width: 10-200ns | | Pulse, pulse width: ~50 ns | Frequency modulated CW | Pulse, pulse width: ~50 ns | Pulse, pulse width: ~10 ns |
| | Signal bandwidth (FWHM) | Inverse of the pulse width: 5~100 MHz | | Inverse of the pulse width: ~20 MHz | Frequency modulation bandwidth | Inverse of the pulse width: ~20 MHz | Inverse of the pulse width: ~100 MHz |
| **Backscattering* (reverse)** | Analyzed signal | Intensity | | Phase or intensity | Scattered E field over optical spectrum | Brillouin frequency shift | Raman intensity |
| | Detected signal power | About 42 dB lower than $P_{in}$ | | | | About 50 dB lower than $P_{in}$ | About 70 dB lower than $P_{in}$ |
| | Signal bandwidth (FWHM) | Same as probe signal bandwidth | | | | ~±11 GHz | ± 100 nm |

* Typical values

Figure 2.2 shows the spectra of various types of backscattering light in an optical fiber.

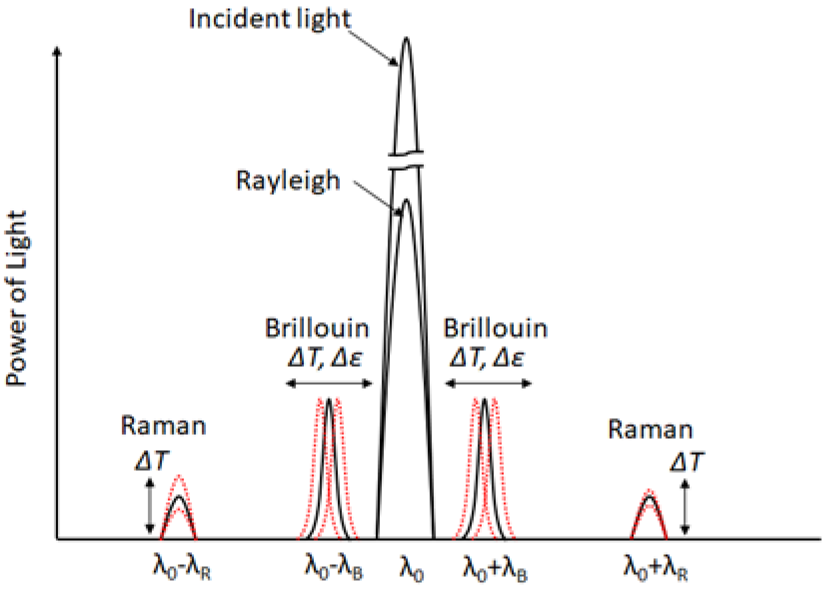

*Figure 2.2: The spectra of various types of backscattering light in an optical fiber*

## 2.3. DFOS by functions

Commercially, DFOS systems (notably, the DFOS interrogators) are usually categorized based on their functions rather than their respective sensing mechanisms. Therefore DFOS systems are usually called “DxS”, in which “D” stands for “distributed” and “S” stands for “sensing” or “sensor.” The “x” refers to the physical parameters that the sensor measures, such as temperature, strain, and vibration. Table 2.3 lists the major types of DFOS systems by function, as well as the backscatter mechanism. Conventionally, multimode optical fibers are used as the transmission waveguide for Raman backscattering-based DTS due to the larger amount of optical power that a network can carry. In recent years, single-mode fiber-based Raman DTS systems are also being developed to operate on the growing amount of single-mode fibers deployed in the field. For Brillouin and Rayleigh-based DFOS, single-mode fibers are usually used.

Due to the different mechanisms and the different backscattering light signal levels, the typical monitoring distance that different types of DFOS are capable of reaching also varies.

*Table 2.3: Different DFOS systems by function*

| FUNCTION | WAVEGUIDE (FIBER) | BACKSCATTER MECHANISM | TYPICAL MONITORED DISTANCE |
|---|---|---|---|
| **DTS – Distributed Temperature Sensing** | Single-mode & multimode | Raman | 15 km |

| | | | |
|---|---|---|---|
| **DTS – Distributed Temperature Sensing** | Single-mode | Brillouin | 50 km |
| **DSS – Distributed Strain Sensing** | Single-mode | Brillouin | 50 km |
| **DSTS/DTSS – Distributed Strain &Temperature Sensing** | Single-mode | Brillouin | 50 km |
| **DAS/DVS – Distributed Acoustic Sensing** | Single-mode | Coherent Rayleigh | 50 km |

# 3. Benefits and Use Cases

## 3.1. Benefits of Fiber Sensing over APN

### 3.1.1. General benefits of fiber optic sensing

Due to the characteristics of the optical fiber and the optical signal propagating in it, fiber-optic sensing technologies have many advantages over conventional types of sensors. Some benefits are:

- Long-distance sensing: The low attenuation in the optical fiber enables long fiber length. If the fiber is used as the sensing medium, the sensor range can be tens of kilometers or even hundreds of kilometers.
- High sensitivity: Using optical techniques such as interferometry, minute variations in the optical signal (such as the nanometer-level changes of wavelength or micro radian of phase) caused by slight environment disturbance can be detected.
- Low latency: The signal travels at the speed of light inside the fiber and can be detected in real-time.
- Compact and lightweight: The physical characteristics of the optical fiber make the sensing fiber compact and lightweight.
- Non-line of sight: Since the optical fiber is flexible and can be bent or curled, the fiber-sensing path does not require line-of-sight, unlike most free space optical sensors.
- Immunity to electromagnetic interference: Since there is no metal part in the optical fiber, it does not experience interference from electromagnetic interferences.
- Robustness: The optical fiber can be deployed in harsh environments and has outstanding durability against physical fatigue.

### 3.1.2. Additional benefits of distributed fiber optic sensing

Besides the benefits in general fiber optic-based sensing solutions, the DFOS solutions offer additional benefits:

- Large amount of sensing points: The entire optical fiber acts as the sensor, making it essentially equivalent to hundreds or thousands of integrated sensors.
- Synchronization of sensing data: Since the same optical source generates the signal collected from all locations in the fiber, these signals are naturally synchronized and do not require a complicated mechanism to synchronize them. This feature enables easy data analysis over large sensing area.

- Ability to localize the event: By performing the time-of-flight calculation on the backscattering signals, DFOS can pinpoint the location of every detected event. Multiple events can be identified and localized simultaneously.
- Use standard fiber: Unlike other fiber optic sensors that require grating fabrication or chemical transducer coating, the DFOS can operate on standard communication grade optical fiber without any special physical or chemical modification.
- No need for electric power supply: Except for the sensor interrogator in the central office, the sensing media of the DFOS (i.e., the sensing fiber in the field) does not require an electric power supply. This feature makes the deployment much easier and can provide sensing service to more areas faster.
- No need for data communication: Unlike the solutions with individual sensors in the field, with DFOS, there is no need for transmitting the sensing data from the field to the central office since all the signals collected from the field are received and recorded in the central office where the interrogator is located through the sensing fiber optic cable. This eliminates the requirement for WAN communication or dedicated wireline channels for sensing data communication.
- Low cost: By replacing thousands of individual sensors with a single interrogator and one fiber, the hardware cost of sensing over a large area is significantly reduced. The operation cost is also reduced due to easy monitoring and data synchronization.

### 3.1.3. Benefits of performing fiber optic sensing on communication networks

Even though there are many advantages in distributed fiber optic sensing, the DFOS systems are still not widely deployed. As mentioned earlier, a primary reason is the installation expense. Unlike standalone conventional sensors (such as an accelerometer or a thermometer) or wireless sensors, DFOS systems require the deployment of fiber optic cables, which include a significant amount of labor and cost to dig a trench, lay cable, and restore the ground condition (such as repaving or landscaping). In addition, there is the tedious process of applying for approval from various authorities and various losses during the cable installation process.

Therefore, it is beneficial to utilize the existing deployed optical fiber to perform sensing, especially the optical fibers in existing telecommunication networks. Optical fiber is the backbone of modern communication networks and is globally ubiquitous. Communication optical fibers can be found from intercontinental trans-oceanic networks to ultra-long-haul and long-haul networks, metro and regional networks, access networks, or even in-building networks. Suppose these fibers are used for distributed sensing purposes, in addition to the current communication function. In that case, the value of the network can be doubled, and more applications and revenue can be generated from the existing network. The cost of fiber sensing can be significantly reduced, leading to faster and broader deployment.

There are multiple stages of implementing fiber optic sensing over telecom networks. At the first stage, dedicated sensing fibers, such as the unlit fibers inside the optical cables in the field, will be used to perform the sensing function. This will avoid any interference between the sensing signal and the communication signal. Right now, there are usually spare, dark fibers available for this purpose. As the data volume continues to grow, more dark fibers will be used for data communication purposes in the future. As a result, despite the various advantages of systems with dedicated sensing fibers, it is helpful to enable the dual-use feature in existing fiber deployments. In other words, both data transportation and optical sensing will be performed over the same optical fiber. This will increase the utilization of the network resource and make the network operation more flexible. Allowing the dual-use function over the same fiber will increase the application and deployment of fiber-sensing technology in the network, especially in networks with a limited number of available fibers. More details of these options will be described in Section 5 below.

## 3.2. Use cases

For Communications Service Providers (CSP) and fiber optic network owners, ubiquitous fiber-optic infrastructure already exists. Therefore, if the fiber sensing technology system can sense vibration, temperature, and sound within tens of kilometers or more, with a fine spatial resolution such as 50 cm, the solution can help the CSP prevent damage and accidents and thus improve the reliability and operational efficiency of their networks. Also, the CSP can establish a new source of revenue by providing additional services to new customers based on fiber-sensing data. Recently, CSPs and fiber network owners have begun introducing fiber-sensing technologies to explore many potential applications leveraging the existing optical communication infrastructure.

Below are some examples of the current and potential use cases for fiber optic sensing over communication networks. Some of the applications are still at the research or proof-of-concept stage, and require thorough technical verification.

### 3.2.1. Improving the reliability of fiber optic network

#### 3.2.1.1. Link outage and fiber degradation detection

OTDR is a fiber optic instrument used to characterize, troubleshoot and maintain optical telecommunication networks. Unlike fiber-sensing devices that detect environmental parameters, OTDR provides detailed optical fiber end-to-end characteristic information on the location and overall condition of splices, connections, defects, and other features of interest. OTDR fiber monitoring solutions have proven to be the fastest, most efficient tool to identify and locate link outages. But conventional OTDR has a wide spectral width light source that cannot pass through DWDM components. DWDM OTDR with narrow spectral width tunable wavelength light source can verify network at the discrete ITU G.694.1 wavelengths. So it can test end-to-end loss through multiplexers, OADM, and de-multiplexers. If the fiber sensing can be applied in Open APN, DWDM OTDR is suitable to monitor and verify optical path characteristics and enhance the Open APN service quality by the following functions:

- Identify and locate link outages
- Find problems with wavelength-specific Open APN components in the fiber route
- Detect fiber degradation at an early stage and provide the fault information

#### 3.2.1.2. Aerial cable and telephone pole collapse prevention and repair

Telephone poles could collapse due to a hurricane, typhoon, or earthquake, causing significant damage nearby, even blocking traffic and preventing access to a serious accident. By sensing the abnormal vibration of the optical fiber of the aerial optical cable, the CSP can remotely locate the collapsed point and then perform related repair works more quickly and more efficiently. They can also notify the municipality, police station, or other first responders before the telegraph pole falls to prevent accidents before they happen.

#### 3.2.1.3. Underground cable damage detection

Underground fiber optic cable damage caused by road excavation is a common pain point for telecom carriers. Conventional Remote Fiber Test System (RFTS) using OTDR only detect the road excavation after the fiber is broken. By analyzing the vibration detected by the optical fiber, the vibration source that may cut the optical fiber, such as construction machinery, can be automatically characterized. This helps prevent accidental fiber damage by identifying abnormal vibrations caused by construction.

#### 3.2.1.4. Data center temperature monitoring

It is estimated that data-centers will use around 3-13% of global electricity in 2030 compared to the 1% consumption in 2010 and 2% of global greenhouse gas emissions [3]. The cooling systems required for these centers represent approximately 37% of the total power they consume [4]. As a result, temperature monitoring and regulation is a critical aspect of data center administration. Currently, conventional discrete thermal sensing systems are widely used, which requires a discrete device for each temperature measurement in the special domain. As the scale of the data center expands, this will lead to increased complexity and cost. According to the discrete thermal regulation model, increasing the density of these sensors can increase the efficiency of these systems. Optical fiber thermal sensing system composed of B-OTDR or R-OTDR can simultaneously measure thousands of discrete points along the length of the fiber under test. The temperature of individual servers and the ambient room temperature can be simultaneously monitored in real-time using a single optical fiber probe. Besides, distributed temperature sensing detects fires precisely and can accurately track the size and direction of a spreading fire with exceptional high-temperature endurance.

### 3.2.2. New applications and services

With the addition of fiber-sensing on the telecom network, the network infrastructure provides data communication and environmental information. Therefore, new services outside the traditional telecommunication field can be offered. Many facilities and infrastructure can be monitored by optical fiber sensing, including submarine optical cables, bridges, tunnels, road slopes, and much more.

The target objects being monitored must be close to existing network fibers. As a result, some examples of the promising applications and services are as follows:

#### 3.2.2.1. Utility health monitoring

Utilities, including electricity, telecommunications, water, and natural gas pipelines, are essential elements of cities, and monitoring them to ensure safety is vital. Power outages caused by cable failures, pipeline leaks, and telecommunications failures can have devastating consequences for the public. Therefore, ensuring the integrity of these networks is crucial for city planners.

#### 3.2.2.2. Traffic monitoring and management

Traffic is often considered to be one of the primary issues with city living. In very crowded cities, drivers waste a great deal of time daily sitting in traffic. Currently, traffic monitoring uses cameras and loop detectors to alleviate traffic flows. Since cameras are affected by weather and light intensity changes, and the loop detectors are single-point sensors and are thus difficult to install in multiple locations, the use of distributed optical fiber sensing to monitor traffic on existing optical fiber cables shows great potential. It can not only monitor the traffic congestion, but also improve the air pollution issue and contribute to carbon neutrality. According to International Renewable Energy Agency (IRENA), cities are responsible for about 67-76% of global energy demand and 71-76% of the energy-related CO2 emissions [5]. Smart traffic management systems can be put in place to mitigate CO2 and nitrogen oxides emissions, helping to improve air quality.

#### 3.2.2.3. Railways operation and safety monitoring

There is a common installation route of optical cable along railways. Trains need their movement monitored accurately to operate safely and provide a reliable and convenient service for passengers. The health of the track and rolling stock can also be monitored for a smarter and faster way to identify issues before failure. For example, sensing technology can detect broken rails and flat wheels or alert an operator for any unusual intrusion movement, such as a person, car, or landslide, indicating a potential issue or fatal security threat. The flow of passengers arriving and departing stations can also be monitored. Transport operators can then use the real-time information to optimize their schedules for rider demand and direct trains to where they are most needed. As a result, trains operate more efficiently, and maintenance crews deliver more effective repairs.

#### 3.2.2.4. Earthquake/tsunami warning

Earthquakes and tsunamis are fatal natural disasters. Earthquake early-warning systems need to detect the initial earthquake vibration and quickly estimate and notify people before imminent, destructive vibrations so that there is time to take measures to avoid or mitigate the damage and casualties. Today, earthquake early warning systems use discrete seismographs, so the denser the sensor coverage, the less the average elapsed time from the epicenter to the station. Fiber sensing can leverage existing optical networks, including continental and submarine optical cables, to sense seismic vibrations. Since the fiber network is much denser than seismograph networks, it can provide critical information much more quickly. Both fiber sensing and existing earthquake early warning systems can take advantage of the high-speed data processing of DCI and the low latency of Open APN to enhance their effectiveness.

# 4. Requirements and Challenges

## 4.1. Requirements of fiber sensing over APN

Optical fiber sensing technology has been widely used in pipeline monitoring, oilfield services, power cable condition monitoring, perimeter security and safety monitoring, structural health monitoring, landslide monitoring, and other fields, etc. Those applications use dedicated fibers for a specific purpose. For acquiring stronger signals from the target object, the fiber is installed as close as possible to monitored subjects so that the detected signals will be simple and straightforward. The signal generated by the monitored object is simple and unique and does not require complex data processing.

The most critical requirement when performing optical fiber sensing is that data communication and fiber sensing functions do not impact each other’s effectiveness.

The influence of fiber sensing on the performance of the communications network depends on the type of optical fiber used for fiber sensing. The architecture for using fiber sensing in communication optical fibers, particularly APNs, is described in Section 5.

## 4.2. Challenges of fiber optic sensing over APN

### 4.2.1. Challenges of performing fiber optic sensing on communication networks

This section describes general technical issues for reducing the impact of fiber sensing on fiber optic networks, including APNs.

In optical fiber sensing, the signal source is remotely and not near the fiber, so the phenomena that can be detected and their accuracy depend on the type of cable, the installation method, the location of the cable, and the environmental conditions at the site. In fiber communication networks, such conditions are determined by communication requirements rather than fiber sensing requirement. Therefore, in order to achieve the required sensing performance in a given optical fiber communication network, it is necessary to make complex adjustments to the hardware and software of the fiber sensing system according to the conditions. This is the most significant technical challenge.

Another major problem is that signals from fiber sensing interfere with communication data signals in a fiber communication network. A fiber sensing light source has a narrow spectral width and a large power, and when a fiber sensing signal from such a light source and a communication data signal are mixed, a noise such as a nonlinear phenomenon and a beat signal and mutual crosstalk occur, which adversely affects communication. To avoid this issue, operators must study the allocation of wavelength channels, the new technology of low-power optical fiber sensing, and the installation of interrogators for the proper propagation direction of the sensing signal.

Another problem is the direction of light propagation. In fiber sensing, the interrogator emits probe light into the fiber and detects backscattered light to detect signals. That is, the fiber sensing signal from the interrogator travels back and forth in the optical fiber being measured, i.e., propagates in both directions. However, in optical fiber communication networks, there are elements such as EDFAs (Erbium-doped fiber amplifiers) and isolators that transmit light only in one direction. This is a problem to be solved.

To route fiber sensing signals to extend the sensing range, WSS (wavelength selective switch) is required. The characteristics of WSS, such as insertion loss, return loss, and polarization, may affect the measurement range and optical fiber sensing signal. This may be an important issue that needs to be addressed.

Although fiber optic sensing can quickly sense various environmental parameters such as vibration, temperature, and strain, the delay time required to transmit information to the end-user may limit or deteriorate the efficiency of fiber optic sensing applications.

The fibers in existing telecom networks are common communication-grade fibers and are not specifically designed for fiber sensing. In addition, they are not laid in the manner that many fiber sensing applications may require. As a result, using existing fibers with DFOS will produce noisier signals that will reduce their effectiveness. The signal variation caused by the external environment is also less uniform because the bury depth, distance to the sensing area (such as the highway), and other installation conditions (such as direct burial vs. conduit) might vary along the sensing route.

There are even more technical challenges with the dual-use fiber configuration compared to sensing over dedicated fibers. The main issue is how to prevent the potential interference between the communication signal and the sensing signal since these two types of signals are likely to have different spectrum widths, different optimum power levels, different characteristics (e.g., pulsed vs. CW), different amplification requirements, different requirements of isolation and back reflection, and so on. If not planned properly, one type of signal might cause crosstalk, power fluctuation, or have a nonlinear effect on the other, thus reducing each other’s performance. It also makes wavelength management, switching and routing, and control more complicated.

### 4.2.2. Challenges in sensing data handling and processing

In distributed optical fiber sensing, the system acquires data in a long optical fiber at the speed of light and high resolution, which will generate a large amount of data. Environmental signals can be complex and require advanced data processing techniques to identify signal characteristics. Therefore, when fiber sensing is used in the APN, it is possible to realize more advanced sensing by utilizing much larger data transfer and processing power.

This section also describes technical issues related to data transfer and data processing in fiber sensing, taking into account the use of communication networks.

#### 4.2.2.1. Data volume from fiber sensing

Since the DFOS system can continuously monitor a long fiber distance with fine spatial resolution, it could generate an enormous volume of raw sensing data. The amount of data depends on several settings in the sensing system, such as the number of ports, the fiber length, the spatial resolution of the sensor, the repetition rate of the probe light, the internal averaging and processing, the number of bits for the data, and other variables. These variables are determined by the physical parameters that need to be monitored, the scale of the system, and the specific requirements from the user (such as the accuracy, the refresh speed, and so on). The change in the amount of raw sensing data produced within a given period of time can be several orders of magnitude between different sensors.

For example, if a distributed acoustic sensor (DAS) monitors ultrasound signals up to 20 kHz, the acoustic signal needs to be sampled at the Nyquist rate of 40 kHz or higher. Due to round trip propagation, the maximum distance of the sensing fiber is about 2.5 km. If the system has a spatial resolution of 0.5 m, there will be 5000 measurement points on the fiber. If each data is represented as a 32-bit integer (4 bytes), the raw data volume for one port is 800 MB per second or about 70 TB per day.

On the other hand, for temperature sensing, sub-second monitoring is typically not required due to the slower temperature variation. Also, the raw data is very noisy due to the low intensity of the Raman backscattering signals; therefore, a large amount of averaging is usually performed to smooth out the result. The result is that the refresh rate in a distributed temperature sensor (DTS) is generally relatively low, such as one measurement every 1 or 5 minutes. Some applications only require one temperature measurement every hour. Also, in most environments, the temperature difference between two physically adjacent locations is minimal; therefore, the spatial resolution can be coarser. So for a DTS system with 10 km fiber and 5-meter spatial resolution (i.e., 2000 measurement points), if the temperature is measured once every minute, and each temperature reading is recorded in the unit of millidegree Celsius and represented by a 16-bit integer, the data volume for one port is less than 6 MB per day.

#### 4.2.2.2. Local processing vs. centralized processing

Another important issue to consider is where and how the sensing data are processed and stored.

For some users and some applications, all the raw data needs to be stored for records or future processing. That means a large amount of data needs to be stored locally or remotely. Off-site data backup might also be required for some essential applications. This leads to the need for a large volume of data transportation between the interrogator site and the data storage site.

For other applications, the users are only interested in higher-level information extracted from the data by processing and analysis. Examples might include vehicle traffic history, intrusion logs, abnormal event alarm records, etc. This type of information usually has a much lower volume and can be quickly sent to more users. If the users do not require the raw data for further analysis, the raw data can be deleted after the analysis is completed; therefore the bandwidth requirement of the network is much less.

Conventionally, the sensor data is processed locally at the interrogator site. As machine learning and artificial intelligence technology develop, more and more sensing applications utilize these technologies to analyze the data and extract insights and trends easily interpretable by human beings. Such processing requires a large amount of computation resources. Instead of performing the data analysis locally, it might be advantageous to analyze it on centralized processors with more powerful computation resources, such as those in cloud data centers. As fiber optic sensing evolves from individual discrete systems to networked sensor systems, performing the analysis at a centralized location also helps coordinate the data from multiple interrogators and enables a higher level of information extraction. Centralized processing also makes information distribution and system response easier. Therefore cloud computing is a good option for fiber sensing over communication networks. However, it also requires a more considerable amount of data transportation compared to local processing and will experience more latency. A compromise is to process the sensing data at the edge and only send processed data, which has a much lower volume, to the cloud for centralized information management and response.

# 5. Fiber Sensing for Open APN

In today's networks, the fiber sensing function is generally conducted using a standalone sensing system with specialized sensing fiber, an interrogator, and a local server for analysis. This function is performed in a local area network because sensing raw data is too large and costly to transfer to the cloud. In addition, most sensing systems identify and/or locate only one specific phenomenon, the data for which is used locally. In contrast, fiber sensing interrogators connected to an Open APN will be distributed in a wide area to collect sensing data in cooperation with the APN to provide higher value and more widely usable information by DCI. The special feature of the sensing function implemented in Open APN is the ability to share data collected over a wide area for multiple use cases.

When we want to collect data from various locations, it is desirable to use existing communication optical fiber as a sensing fiber. In some use cases for which increased sensitivity or specialized sensing functions are desired, separate fiber or separate cable may be used. Whether common or separate optical fibers are used, transport of both communication and sensing data requires attention to a switching function in the APN.

In this section, possible fiber sensing architectures for conducting sensing function with APN are described. The essential point is that those architectures will consider how to eliminate (or compensate) mutual influence between sensing and communication light.

## 5.1. Usage of Open APN and DCI for Fiber Sensing

Figure 5.1 shows the complementary relationship between fiber sensing and the Open APN and the DCI.

The fiber sensing interrogator is connected to the Open APN for two purposes. One is to use the existing communication fibers that make up the Open APN as a sensor medium. The other is to transfer a large amount of data obtained by sensing for processing. By connecting the interrogator to the Open APN and using the communication fiber as a sensing medium, infrastructures, e.g., fibers and switches, etc., can be shared between communication and sensing. Fiber sensing can improve the Open APN service quality by avoiding accidental excavation and cable breakage by monitoring and can also create new value for existing optical networks by utilizing them as urban nervous systems.

With the help of the Open APN with high-speed, ultra-reliable, and low-latency connection functions, fiber sensing can immediately transfer large amounts of measurement data to the Data-centric infrastructure (DCI) for processing, recognition, and storage. The DCI can provide powerful and high-speed data processing and AI data analysis environments.

Thanks to these functions, fiber sensing systems can process a large amount of data more quickly and efficiently. These features of the Open APN and the DCI may enhance the use case for fiber sensing.

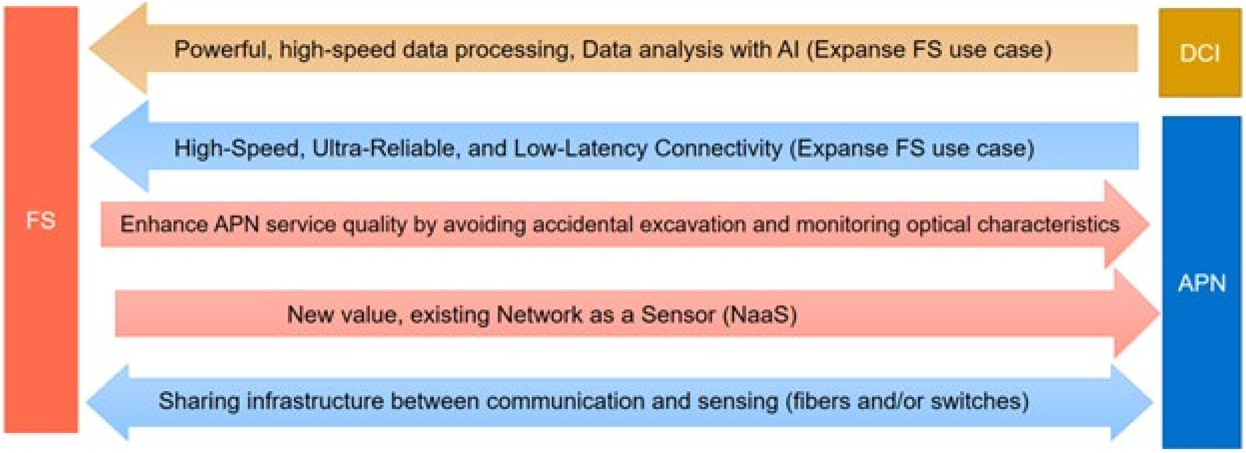

*Figure 5.1: Complementary relationship between fiber sensing and Open APN and DCI*

## 5.2. Usage form of sensing fiber, cable, and optical switch for selecting sensing path

When considering the architecture of the connection to the APN, it is necessary to clarify how to use the communication optical fiber of the APN as a sensor medium and utilize the open APN gateway, which is the switching function of APN. In connection to the APN, optical fibers are considered based on whether or not communication fibers are shared. As for the switching function, various types of switches can be considered following the specifications of the APN. The sensing fiber switches need to be considered based not only on whether they are shared or not, but also on the characteristics of the communication switches used therein when they are shared.

Based on the concept of exclusive use and sharing, optical fibers are used in the following ways:

F-1) Fiber assigned for sensing only. Telecommunication use is prohibited. This usage form is “dedicated fiber.”

F-2) Fiber is used for both sensing and data communications, but the fiber transmits only one application signal at a time, which means both application signals cannot co-exist in one fiber simultaneously.  This usage form is “Time separated applications fiber.”

F-3) Fiber is used for both sensing and data communications, and optical signals of both applications simultaneously propagate in the fiber. This usage form is “dual-use fiber.”

Fiber(s) in a deployed cable will be assigned as a sensing fiber. In addition to the fibers listed above, there are also two types of optical fiber cables as follows.

C-1) Separate cable dedicated for sensing only

C-2) Common cable carries both telecom and sensing fibers

The required switching function is based on whether it is shared with the APN function and whether crosstalk exists.

S-1) Switch is prepared externally for sensing only. The requirement to SW could be determined only by fiber sensing requirements.

S-2) Switch in Open APN gateway is prepared in APN and shared with communication service. The SW does NOT have crosstalk between sensing and telecom. All devices in the optical path of the sensing signal also do NOT have crosstalk.

S-3) Switch in Open APN gateway is prepared in APN and shared with communication service. They have negligible crosstalk between sensing and telecom.

Hereafter, the symbols F-1 to F-3, C-1 to C-2, and S-1 to S-3 described above will be used as a property of sensing fiber and switch in APN.

## 5.3. Fiber sensing architectures

Using the following cables, fiber types, and switch requirements, we can describe multiple architectures for connecting a fiber sensing network to the APN, as shown in the following table.

*Table 5.1: Sensing architecture types*

| TYPE | SWITCH REQUIREMENT | EXAMPLE OF SWITCH TYPE | FIBER USAGE FORM | CABLE USAGE FORM | POSSIBLE FIBER | TECHNICAL ISSUES | STAGE |
|---|---|---|---|---|---|---|---|
| **I** | S-1 | Various types applicable | F-1 | C-1 | Standard SMF(existing) in both cables<br>Special sensing fiber in sensing cable | Interface for transferring control signal and sensing data | Initial |
| | | | | C-2 | Standard SMF(existing)<br>Special sensing fiber | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **II-1** | S-2 | Mechanical fiber selector (without crosstalk)<br>Others | F-1 | C-1 | Standard SMF(Existing) in both cables<br>Special Sensing fiber sensing cable | *In addition to Type I,*<br>SW type and its specification in APN | Early |
| | | | F-2 | C-2 | Standard SMF (existing) | | |
| **II-2** | S-3 | MEMS (with crosstalk)<br>Others | F-1 | C-1 | Standard SMF(existing) in both cables<br>Special sensing fiber in sensing cable | *In addition to Type II-1,*<br>Assessment of crosstalk in SW<br>Clarification of sensing probe light condition | Next |
| | | | | C-2 | Standard SMF (existing)<br>Special sensing fiber | | |
| | | | F-2 | C-2 | Standard SMF (existing) | | |
| **III** | S-3 | MEMS (with crosstalk)<br>Others | F-3 | C-2 | Standard SMF (existing) | *In addition to Type II-2,*<br>Assessment of nonlinear phenomena in sensing fiber | Final |

The following sections describe each type in detail. The following figures illustrate the Fiber sensing architecture types based on the high-level reference architecture discussed in the Open APN Functional Architecture draft.

### 5.3.1. Sensing architecture type I

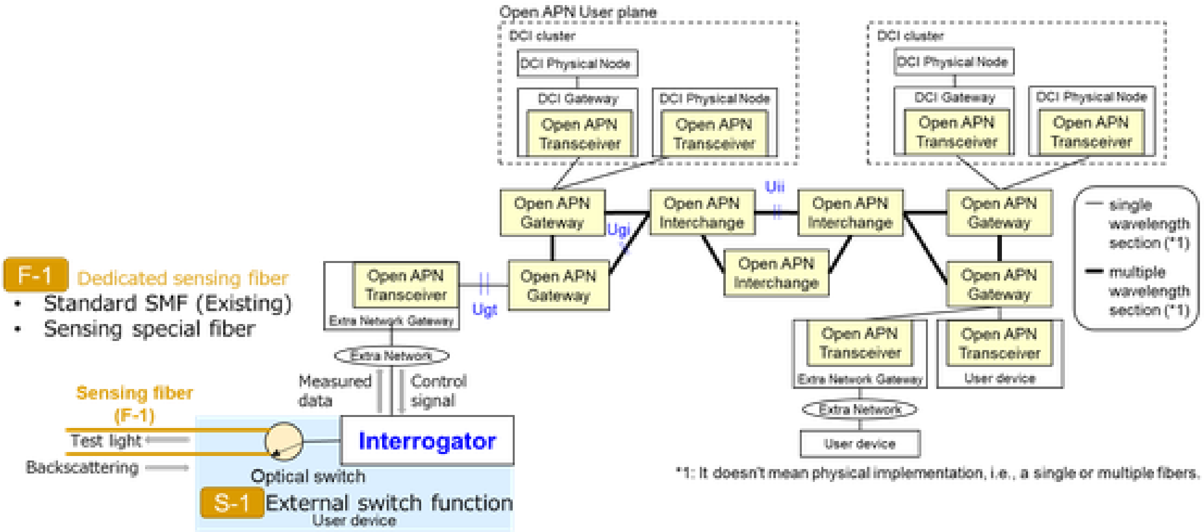

*Figure 5.2: Sensing architecture type I*

Type I is shown in Figure 5.2. Basically, fiber sensing uses the APN for two purposes: sensing medium and measured data/control signal transmission. However, only Type I utilizes the APN just for transmission of measured data and control signal of the interrogator. Therefore, this type provides optical fiber and an external switch as a sensor medium, completely independent of the APN. Thus, the switch's performance and the optical fiber can be wholly decided based on only requirements from the fiber sensing side.

In this type, the optical fiber used as a sensor medium is in the form of F-1, a dedicated optical fiber used only for sensing. As for the optical switch, an external switch used only for fiber sensing is in the form of S-1.

As for transmission with the APN, measured data is transferred to the DCI by the ultra-high-speed communication service of the APN. The generated data volume might be tens of gigabits per second at maximum, but it depends on sensing conditions. This is described in section 4 in detail.

This type is the most straightforward architecture for fiber sensing with the APN because fiber sensing is the most independent and flexible. Therefore this should be the first step to implement the sensing function in the APN.

### 5.3.2. Sensing architecture type II-1 and II-2

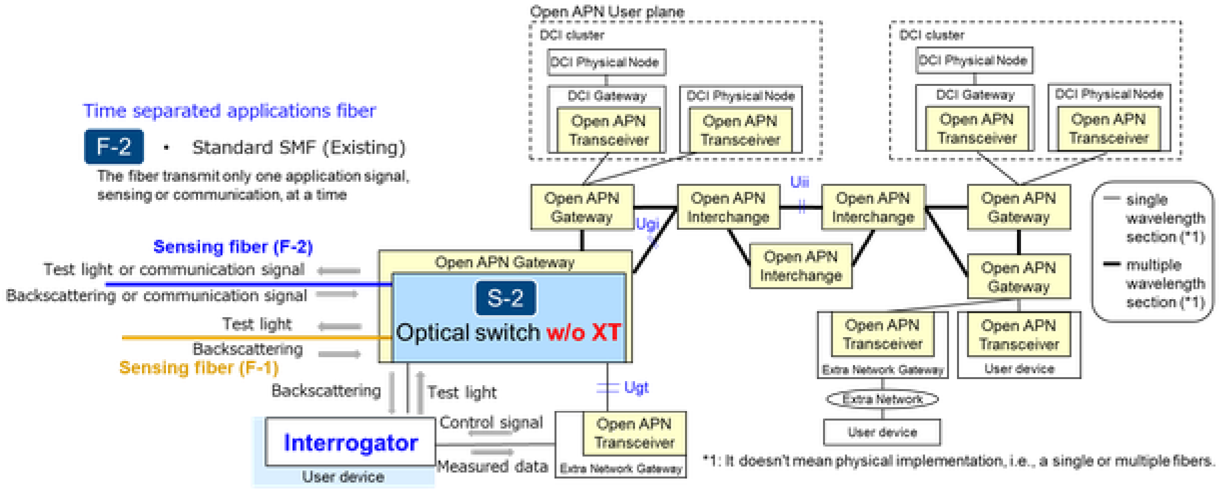

*Figure 5-3: Sensing architecture type II-1*

Type II -1 is shown in Figure 5.3. The optical fiber used as a sensing medium is classified into F-1 and F-2, namely dedicated fiber and time separated applications fiber. The switch is S-2, that is, having no crosstalk.

In this type, when the fiber dedicated for sensing is used, the performance of the fiber can be decided entirely based on only requirements from fiber sensing as in Type I. When the time separated applications fiber is used, the fiber used for communication service of the APN is utilized as the sensing fiber, but both signals do not co-exist in the fiber.

When the switch which has no crosstalk is used, the switch for data communication of the APN is utilized for fiber sensing. Here, communication signals and sensing signals do not have mutual interference. The switch itself is provided as a function of the APN, and fiber sensing must match the control determined by the APN when sharing fibers and controlling the division of usage time through the switch.

As for transmission with the APN, measured data is transferred to the DCI by the ultra-high-speed communication service of the APN. The generated data volume might be tens of gigabits per second at maximum, but it depends on sensing conditions. This is described in Section 4 in detail.

This type does not have mutual interference between communication and sensing, so it is the second easiest type to implement the sensing function to the APN.

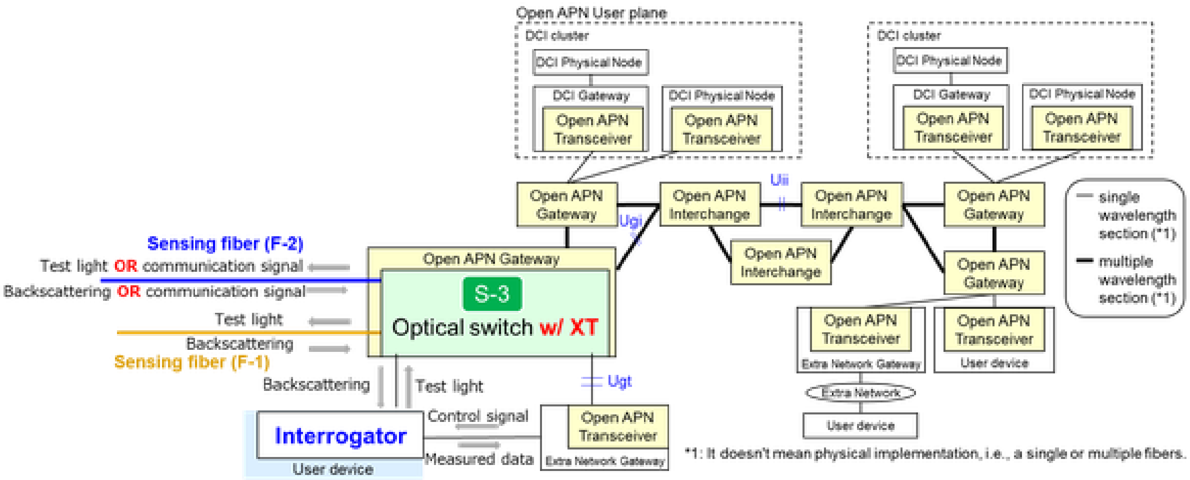

*Figure 5.4: Sensing architecture type II-2*

Type II -2 is shown in Figure 5.4. This Type is similar to Type II -1, but the switch has crosstalk, which is the pattern of S -3. The fiber used as a sensing medium is classified into two patterns of F -1 and F -2.

In this type, the fiber is as same as that of Type II -1, namely dedicated fiber and time separated applications fiber.

Many studies, such as evaluation of crosstalk, evaluation of mutual interference between communication and sensing signal, and noise immunity of communication signals, are necessary for adopting this type as fiber sensing architecture with the APN since fiber sensing light may affect the communication service due to crosstalk of the switch.

As for transmission with the APN, measured data is transferred to the DCI by the ultra-high-speed communication service of the APN. The generated data volume might be tens of gigabits per second at maximum, but it depends on sensing conditions. This is described in Section 4 in detail.

The introduction of this type will be the next stage in time because this type has a lot of technical issues for consideration mentioned above.

### 5.3.3. Sensing architecture type III

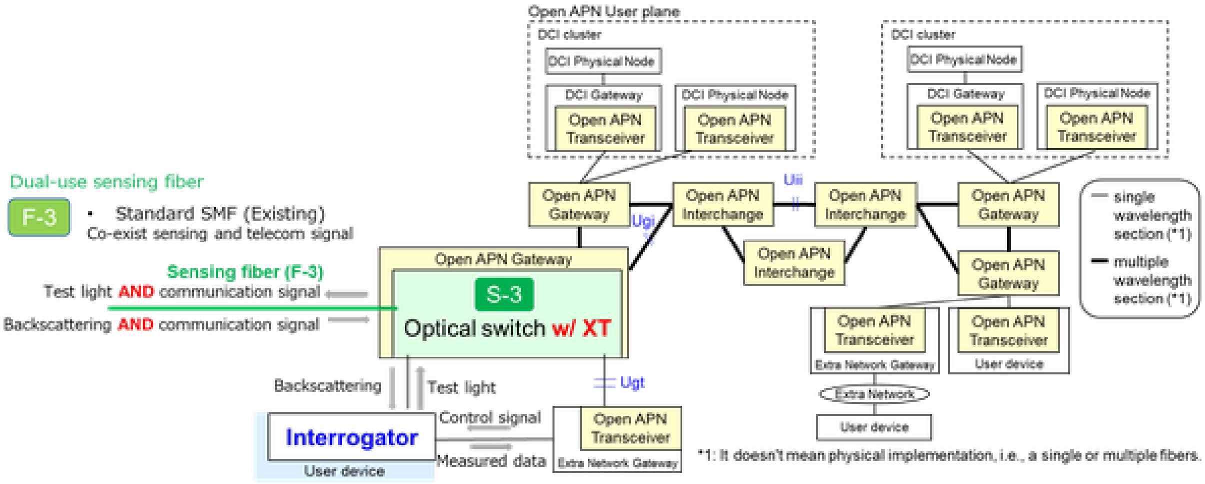

*Figure 5.5: Sensing architecture type III*

Type III is shown in Figure 5.5. In this type, the usage form of the optical fiber is F -3: dual-use fiber. The switch is a pattern of S-3.

Both the fiber and the switch are shared with the communication service of the APN, and optical signals of both applications simultaneously propagate in the fiber.

In this type, since the communication service signal and the fiber sensing light exist in the same fiber simultaneously, it is essential to use multiplexing technologies such as WDM. Therefore, in addition to technical issues of Type II-2, it is necessary to evaluate the influence of the nonlinear optical effect caused by the high power feature of the sensing light in the fiber. Then it is necessary to determine the specifications of the fiber sensing light from the viewpoint of whether the required performance of the fiber sensing can be satisfied by the sensing light specification and whether the communication signal of the APN is not affected.

As for transmission with the APN, measured data is transferred to the DCI by the ultra-high-speed communication service of the APN. The generated data volume might be tens of gigabits per second at maximum, but it depends on sensing conditions. This is described in section 4 in detail.

As described above, this type has the most technically difficult issues caused by co-existing with APN communication service. Therefore this type should be considered the last stage of the development of fiber sensing with the APN.

## 5.4. Fiber sensing data handling and processing over Open APN

As discussed above, the fiber sensing system might generate a large volume of data, which needs to be transported to other locations for processing and/or storage. This is a technical challenge for many conventional sensors since it is difficult to access high bandwidth data transportation resources. This also imposes additional expenses for the user.

Such problems will not occur if fiber sensing is performed over Open APN. Because the sensing system is part of the fiber optic communication network, high bandwidth data communication is available locally. Also, Open APN is designed to accommodate large data volume with low latency, which fits the needs for fiber optic sensing applications. Furthermore, IOWN GF's Data-Centric Infrastructure (DCI) will also help the sensing data processing be more efficient and secure.

# 6. Conclusions

In summary, performing fiber sensing, particularly distributed fiber optic sensing, on/with the existing telecommunication network is a new and unique feature for Open APN. It has many benefits and brings new functions, applications, and values to the network and its operators. There are also new challenges such as implementing the fiber sensing function on the existing telecommunication network, which must be investigated and addressed. This can be done in several stages, with different architectural designs. These designs have different levels of interactions with the communication part of the network and have different levels of technical issues. The IOWN Global Forum will work to solve these technical issues so that the fiber sensing function can be realized in the Open APN.

## 6.1. Future study items

In the next step, the physical parameters for the Open APN related to fiber sensing will be studied quantitatively for recommendation to the Working Group. These will be part of the standards for the field of fiber sensing over telecom networks.

The parameters include:

- Wavelength and spectrum arrangement
- Optical power level
- Span design and loss budget
- Repeater design and isolator configuration
- Switching and add/drop device
- Fiber design parameters
- Cable design parameters
- Etc.

The control and management scheme for the networked fiber sensing hardware will also need to be designed and specified according to the Open APN network management protocols.

After implementing the backscattering-based DFOS technologies in Open APN, the OAF task force can continue to study the forward-based sensing technologies (such as SoP monitoring and bidirectional phase interferometry) for longer distance applications in the telecom networks.

## 6.2. Experiment testbed and verification proposal

Since fiber sensing over telecommunication networks is still a relatively new concept, and only research content has been published, testing and verifying the performance experimentally before issuing the recommendations or specifications is necessary.

Therefore, it is proposed that after the Open APN testbed is set up, various options of fiber sensing subsystem will be implemented in the testbed, and quantitative performance for both the communication and sensing part of the network will be collected and analyzed. Further improvement and modification will be conducted based on the experimental results.

The experiment testbed can also serve as a proof-of-concept system for the potential customers to demonstrate the benefits of fiber sensing over Open APN.

# Definitions and Abbreviations

| TERM/ACRONYM | DEFINITION | SOURCE |
|---|---|---|
| **Acoustic Bandwidth [DAS]** | The range of frequencies over which the fiber optic sensing, usually DAS, measures over. The bandwidth can be described by the maximum detectable frequency to the minimum detectable frequency. | https://www.fiberopticsensing.org/page/glossary |
| **APN** | All Photonic Network. | IOWN Global Forum |
| **Asset [all DFOS]** | The physical object to be monitored using fiber optic sensors. The asset is considered to be separate from the optical fiber, and therefore a mapping is usually required from fiber to the asset. Examples: Pipelines, Power Cables, Tunnels. | https://www.fiberopticsensing.org/page/glossary |
| **Backscatter** | In physics, backscatter (or backscattering) is the reflection of waves, particles, or signals back to the direction from which they came. | https://en.wikipedia.org/wiki/Backscatter |
| **B-OTDA** | Brillouin optical time-domain analysis. B-OTDA is a method that uses Stimulated Brillouin Scattering (SBS) to probe the gain spectrum as a function of distance along the fiber. B-OTDA involves launching light from both ends of a single fiber where one of the optical signals is continuous wave (pump), and the other is pulsed (probe). | Hartog, Arthur H. (2017). An Introduction to Distributed Optical Fiber Sensors, CPC Press, Chapter 5, p. 197 ISBN 13: 978-1-138-08269 (pbk) |
| **B-OTDR** | The term Brillouin optical time-domain reflectometer (BOTDR) is used for systems based on time-domain interrogation of spontaneous Brillouin scattering (SpBS).* Due to its single-ended nature, B-OTDR is the most common method used in DSS, long-distance DTS, DTSS, and DSTS sensing systems. | *Hartog, Arthur H. (2017). An Introduction to Distributed Optical Fiber Sensors, CPC Press, Chapter 5, p. 161 ISBN 13: 978-1-138-08269 (pbk) |
| **Brillouin Frequency [DSS]** | Frequency shift of light caused by Brillouin scattering. | https://www.fiberopticsensing.org/page/glossary |
| **Brillouin Scattering [DSS]** | Inelastic scattering of light involving energy transfer to or from acoustic phonons. | https://www.fiberopticsensing.org/page/glossary |
| **Channel [DAS]** | Range of adjacent fiber locations used for evaluating acoustic signals. | https://www.fiberopticsensing.org/page/glossary |

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| **C-OTDR** | Coherent Time Domain Reflectometry - utilizes coherent Rayleigh backscatter to detect acoustics and vibrations along the axis of an optical fiber. C-OTDR is the primary method used in DAS systems. C-OTDR interrogators include phase-OTDR (measures only intensity) and differential phase-OTDR (phase-based or quantitative) | Hartog, Arthur H. (2017). An Introduction to Distributed Optical Fiber Sensors, CPC Press, Chapter 6, p. 239 ISBN 13: 978-1-138-08269 (pbk) |
| **Cycle time [all DFOS]** | Time for measuring a complete sequence of channels where multiple fiber channels are available on the instrument. | https://www.fiberopticsensing.org/page/glossary |
| **DAS vs. DVS** | Although the terms distributed acoustic sensing (DAS) and distributed vibration sensing (DVS) are both used interchangeably, some make a distinction as “acoustic” is etymologically related to pressure waves, whereas what is usually measured is the strain on the fiber caused by a mechanical wave that is not necessarily a pressure wave: shear waves and surface waves commonly exert a stronger influence on the fiber than pressure waves do. The term distributed vibration sensing (DVS) is preferred as a more general description of this class of distributed sensing. | Hartog, Arthur H. (2017). An Introduction to Distributed Optical Fiber Sensors, CPC Press, Chapter 6, p. 232 ISBN 13: 978-1-138-08269 (pbk) |
| **DAS [DAS]** | See Distributed Acoustic Sensing. | https://www.fiberopticsensing.org/page/glossary |
| **Dedicated fiber** | An optical fiber within a cable or telecommunications architecture where the fiber is assigned a single task communications or sensing. | |
| **DFOS [DAS, DSS, DSTS, DTS]** | See Distributed Fiber Optic Sensing. | https://www.fiberopticsensing.org/page/glossary |
| **Distance Range [all DFOS]** | The maximum length of optical fiber to be measured. | https://www.fiberopticsensing.org/page/glossary |
| **Distributed AcousticSensing [DAS]** | Distributed Acoustic Sensing (DAS) is a sensing technology that delivers real-time spatially resolved acoustic and vibration output from virtually unlimited points along a fiber optic cable. The technology effectively turns common optical fiber (or specially optimized cables) into a series of thousands of sensitive virtual microphones or vibration sensing devices. DAS produces thousands of channels of acoustic output from these virtual microphones – in real-time. | https://www.fiberopticsensing.org/page/glossary |

| | | |
|---|---|---|
| **Distributed Fiber Optic Sensing [DAS, DSS, DSTS, DTS]** | Distributed fiber optic sensing (DFOS) are systems that connect opto-electronic interrogators to an optical fiber (or cable), converting the fiber to an array of distributed sensors. The fiber becomes the sensor while the interrogator injects laser energy into the fiber and detects events along the fiber. | https://www.fiberopticsensing.org/page/glossary |
| **Distributed Strain and Temperature Sensing [DSS]** | Distributed Strain and Temperature Sensing (DSTS, also known as DTSS) is a fiber optic sensing technology that delivers spatially resolved measurements of changes to both strain and temperature at any point along the length of a fiber optic cable. This allows a single optical fiber to replace thousands of individual strain or temperature sensors. | https://www.fiberopticsensing.org/page/glossary |
| **Distributed Strain Sensing [DSS]** | Distributed Strain Sensing (DSS) is a fiber-optic sensing technology providing spatially resolved elongation profiles along a fiber-optic sensing cable. By combining multiple sensing cables at different positions in the asset cross-section, DSS is used to compute the asset (device under test) elongation (strain), shape (bending radius and bending direction), twist, etc. | https://www.fiberopticsensing.org/page/glossary |
| **Distributed Temperature Sensing [DTS]** | Distributed Temperature Sensing (DTS) is a fiber-optic sensing technology for measuring spatially resolved temperature profiles along fiber-optic sensor cables. Sensor cables may be installed near-linear assets and on 2- or 3-dimensional objects for measuring their temperature profiles. | https://www.fiberopticsensing.org/page/glossary |
| **Distributed Vibration Sensing** | See DVS | |
| **DSS** | See Distributed Strain Sensing. | |
| **DSTS, also known as DTSS [DSS and DTS]** | See Distributed Strain and Temperature Sensing. | https://www.fiberopticsensing.org/page/glossary |
| **DTGS - Distributed Temperature Gradient Sensing** | In the very low-frequency range, phase-based C-OTDR systems enable the highly sensitive measurement of transient temperatures due to the elongation/compression of the fiber with temperature changes. This measurement mode is called Distributed Temperature Gradient Sensing | https://www.apsensing.com/technology/distributed-acoustic-sensing-das-dvs |

| | | |
|---|---|---|
| **DTS [DTS]** | See Distributed Temperature Sensing | https://www.fiberopticsensing.org/page/glossary |
| **Dual-use fiber** | A single optical fiber within a cable or telecommunications architecture that is assigned two tasks - communications and sensing. | |
| **DVS** | Distributed Vibration Sensing, commonly used interchangeably with Distributed Acoustic Sensing. | |
| **DWDM OTDR** | DWDM OTDR or Wavelength-Tunable OTDR is special category of OTDR. It does not use broadband lasers like traditional OTDRs, but uses narrow linewidth tunable lasers to test through mux/demux channels to provide complete end-to-end DWDM link characteristics. | Ping Gong , Xiaokang Jiang , Jian Zhou, and Liang Xie , “Wavelength-Tunable OTDR for DWDM-PON Based on Optimized Wavelet Denoising”, IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 33, NO. 24, DECEMBER 15, 2021 |
| **Fiber Bragg grating** | A fiber Bragg grating (FBG) is a type of distributed Bragg reflector constructed in a short segment of optical fiber that reflects particular wavelengths of light and transmits all others. This is achieved by creating a periodic variation in the refractive index of the fiber core, which generates a wavelength-specific dielectric mirror. | https://en.wikipedia.org/wiki/Fiber_Bragg_grating |
| **Fiber channel [all DFOS]** | Length of fiber connected to one optical output of an interrogator. | https://www.fiberopticsensing.org/page/glossary |
| **Gauge Length [DAS]** | Length of a fiber section used to evaluate changes of length or phase. | https://www.fiberopticsensing.org/page/glossary |
| **Interrogation Rate [DAS, DTS, DSS]** | See Pulse Repetition Frequency. | https://www.fiberopticsensing.org/page/glossary |
| **Measurement time [all DFOS]** | Time required for taking a measurement from one fiber. | https://www.fiberopticsensing.org/page/glossary |
| **OFDR** | Optical Frequency Domain Reflectometry - used to detect temperature, strain, beat length and high order mode coupling in optical fibers. | https://www.sciencedirect.com/topics/engineering/optical-frequency-domain-reflectometry |
| **Optical Loss Budget [all DFOS]** | The optical loss budget establishes the total amount of tolerable loss attributable to the fiber/cable loss and loss through connectors and splices. | https://www.fiberopticsensing.org/page/glossary |

| | | |
|---|---|---|
| **OTDR (Optical Time Domain Reflectometer)** | An OTDR is the optical equivalent of an electronic time-domain reflectometer. It injects a series of optical pulses into the fiber under test and extracts, from the same end of the fiber, light that is scattered (Rayleigh backscatter) or reflected back from points along the fiber. The scattered or reflected light that is gathered back is used to characterize the optical fiber. | https://en.wikipedia.org/wiki/Optical_time-domain_reflectometer |
| **Pigtail [all DFOS]** | A pigtail is a short optical fiber cable with an optical connector on one end and a length of exposed optical fiber at the other end. | https://www.fiberopticsensing.org/page/glossary |
| **Pulse Rate, also known as Pulse Repetition Rate [all DFOS]** | Number of laser pulses per second. | https://www.fiberopticsensing.org/page/glossary |
| **Pulse Repetition Rate, also known as Pulse Rate [all DFOS]** | Number of laser pulses per second. | https://www.fiberopticsensing.org/page/glossary |
| **R-OTDR** | Raman Optical Time Domain Reflectometry - principle tool used in Raman DTS, relies upon temperature sensitive Raman bands and Stokes/anti-Stokes ratio. | Hartog, Arthur H. (2017). An Introduction to Distributed Optical Fiber Sensors, CPC Press, Chapter 1, p. 13-25 ISBN 13: 978-1-138-08269 (pbk) |
| **Raman Scattering [DTS]** | Inelastic scattering of light involving energy transfer to or from optical phonons or molecular vibrations. | https://www.fiberopticsensing.org/page/glossary |
| **Rayleigh Scattering [DAS]** | Elastic scattering of light at particles or inhomogeneities that are smaller than its wavelength. | https://www.fiberopticsensing.org/page/glossary |
| **Sampling Interval [all DFOS]** | Distance between measuring data locations along a fiber. | https://www.fiberopticsensing.org/page/glossary |
| **Single-Ended Measurement** | A measurement taken from only one end of an optical fiber. Example: measurements on a subsea power cable where access to the subsea end of the fiber is not possible. | https://www.fiberopticsensing.org/page/glossary |
| **Spatial Resolution [DTS, DSS]** | Length of a temperature or strain event required for 90% reading response. | https://www.fiberopticsensing.org/page/glossary |
| **Temperature Accuracy [DTS]** | Deviation between the average measured temperature and true temperature. | https://www.fiberopticsensing.org/page/glossary |
| **Temperature Resolution** | The standard deviation of local temperature data taken in a measuring sequence. | https://www.fiberopticsensing.org/page/glossary |

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| **Time separated application fiber** | A single optical fiber that can be used for multiple applications without interference through use of time windows to separate and distinguish the applications. E.g., a fiber that can be used to communicate in one time window and detect vibration events in a second time window. | |
| **Warmup Time** | Time between power-on and readiness to take measurements according to the specification. | https://www.fiberopticsensing.org/page/glossary |
| **Zone [all DFOS]** | Range of adjacent fiber locations used for triggering events according to common alarm criteria. | https://www.fiberopticsensing.org/page/glossary |

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# Annex A: Suggested Readings

| SUGGESTED READINGS |
|---|
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| "Smart sensing redefined: the invisible backbone for smart cities, Fotech Co., Available: https://www.fotech.com/media/1581/fotech-smart-sensing-redefined-final.pdf |
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# History

| Revision | Release Date | Summary of Changes |
|---|---|---|
| 1.0 | January 27, 2022 | Initial Release |