White Paper

NEC Solution: NEC Fiber Optic Smart Sensing Solutions for Telecom Network Infrastructure

NEC Laboratories America

Orchestrating a brighter world

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Overall, NEC FOSS solutions can interrogate a long section of optical fiber, providing fine spatial resolution and the ability to localize each event accurately and instantly.

1. Introduction

NEC FOSS (NEC Fiber Optic Smart Sensing) is a product suite that consists of sensor interrogator equipment for measuring different physical parameters over a long distance of fiber, application-specific artificial intelligence (AI) analytic engines, and intuitive graphical user interfaces (GUI) across multiple device platforms. The NEC FOSS product suite provides solutions for a broad range of applications over fiber optic networks. It offers a unique value proposition to network infrastructure operators by enabling them to efficiently manage and operate their pool of deployed fiber network fields and leverage it to create new non-transport service offerings.

In the age of the bandwidth-intense metaverse, OpenRAN 5G disaggregation, and residential broadband, the investment in optical fiber infrastructure is expected to grow exponentially. NEC's industry-first, AI-based NEC FOSS solutions provide a way to protect that investment and ensure increased ROIs by opening up new revenue streams.

The NEC FOSS solutions combine NEC's decade of experience in transoceanic fiber optic transmission, our expertise with machine learning (ML)-based AI and advanced distributed fiber optic sensing technologies to provide unobtrusive, low-maintenance detection capabilities.

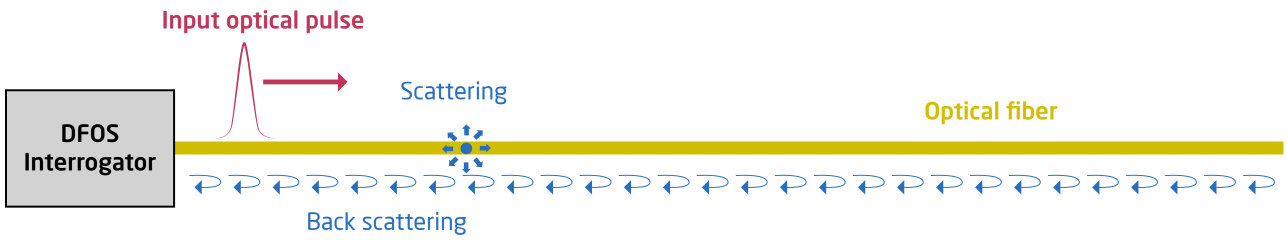
2. Technology Background

2.1 Distributed fiber optic sensing technology

NEC FOSS solutions uses backscattering-based distributed fiber optic sensing (DFOS) technology over standard communication fiber. The technology's operation principle is based on the backscattering signals of the probe light propagating in the core of the optical fiber as illustrated in Figure 1. In this system, pulsed probe laser light is sent from the sensor/interrogator and travels down the sensing fiber. As light propagates along the fiber, a small number of backscatters are generated due to various physical principles.

There are three major types of scattering signals in an optical fiber—Rayleigh scattering, Brillouin scattering, and Raman scattering. Each type of scattering phenomena is caused by a different physical mechanism and is sensitive to different environmental conditions and stimulations, such as vibration (including acoustic signal), strain, and temperature. Part of these scattering lights propagate in the reverse direction—called the backscattering—and travel back to the interrogator. They are received by photodetectors at the interrogator and then digitized for signal processing and analysis. 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 exact location of the event can be identified.

Figure 1: Operational principle of Distributed Fiber Optic Sensing technology



2.2 Benefits of DFOS

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. Benefits include:

- **Long distance** – The low attenuation in the optical fiber enables the light to propagate over an optical fiber with a large length. If the fiber is used as the sensing medium, the sensor range can be tens of kilometers without repeaters, or hundreds of kilometers with repeaters.
- **High sensitivity** – Use of 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 light weight** – The physical characteristics of optical fiber, such as small diameters and no metal parts, 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 in the optical fiber, it does not experience electromagnetic interferences.
- **Robustness** – The optical fiber can be deployed in harsh environments and has very good fatigue durability.

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

- **Large amount of sensing points** – The entire optical fiber acts as the sensor, making it equivalent to hundreds or thousands of sensors integrated together, so the total capital expenditure (CAPEX) is significantly reduced compared to equivalent numbers of discrete sensors.
- **Passive field requirement** – All the active elements that require electricity in the DFOS system are located at the interrogator, which is usually installed at the central office, and the signal is communicated through the sensing fiber itself. Therefore, the need for communication hardware and power supply in the field is eliminated, and operation expenditure (OPEX) for power consumption, is greatly reduced.
- **Intrinsic synchronization** – Since signals received from these individual sensing points are generated by common input pulses, these signals are intrinsically synchronized. This is unlike other integrated sensor systems that require complex synchronization schemes.
- **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.
- **Ability to detect multiple events** – Since these sensors are detected individually and independently, multiple events can be identified and localized simultaneously.
- **Use standard fiber** – Unlike some fiber optic sensors that require grating fabrication or chemical transducer coating, the DFOS can operate on standard communication-grade optical fiber without special physical or chemical modification.

NEC FOSS solutions uses backscattering-based distributed fiber optic sensing (DFOS) technology over standard communication fiber.

2.3 Applying DFOS over the telecom network infrastructure

Despite of all the advantages listed above, DFOS systems do not yet have large-scale deployment, with the main reason being the installation expense. Unlike stand-alone conventional sensors such as an accelerometer, a thermometer, or wireless sensors, DFOS systems require deployment of fiber optic cables, and cable deployment is labor intensive—dig trenches, lay cable, and restore the ground condition (repaving or landscaping)—and incurs significant costs. In addition, gaining construction approvals from various authorities can cause delays that result in lost worker productivity, increased costs, and significant traffic disruption during the cable installation process.

It is therefore beneficial to use existing deployed optical fiber to perform sensing, especially the optical fibers in telecommunication networks. As the backbone of modern communication networks, optical fiber is ubiquitously deployed throughout the world. Communication optical fibers can be found from intercontinental trans-oceanic networks to ultra-long-haul and long-haul networks, to metro and regional networks, to access and campus networks, or even in-building networks. If optical fiber cable is used for distributed sensing in addition to its current communication function, the value of the fiber network will increase as more applications and revenue can be generated from the existing fiber. With the DFOS, the cost of optical fiber sensing can be significantly reduced, leading to faster and broader deployment. Clearly, there are viable business benefits to applying DFOS over an existing telecom network infrastructure.

However, there are technical challenges to performing fiber optic sensing on existing communication networks. Firstly, the optical fiber in existing telecom networks is regular communication cables and not specifically designed for optical sensing, so they are not as sensitive as specially enhanced sensing fibers. In addition, these field fibers typically are not in ideal condition: They usually have many splicing points and/or fiber adapters in the route that cause non-uniform losses at multiple points along the sensing route. This is problematic for DFOS systems since most of them have single-ended operation and thus cannot properly handle the additional step loss in the field, especially for temperature monitoring applications.

Also, fiber optic cables in the field are not laid for sensing applications. Aerial or buried deployment, in-conduit or direct burial, burial depth, and/or proximity to the sensing environment all affect optical sensing performance. Performing sensing over these existing fibers will produce noisier signals. The signal variation caused by the external environment is also less uniform because installation conditions may vary along the sensing route. This is irrelevant for data communication; however, is critical for optical sensing purposes.

Furthermore, there is a mismatch in the repeater setup between the communication network and sensing system. For example, the span length for regular long-haul or submarine optical networks is usually 60 km or 80 km. However, the reach of a conventional DFOS system is usually 10-to-20 km and cannot be extended by optical repeaters. Therefore, it is not trivial to apply DFOS directly over an existing telecom network infrastructure.

3. Technologies and features of NEC FOSS solutions

Built upon decades of expertise and experience in ultra-long-distance optical transmission and ML-based-AI data analytics, NEC developed various innovative technologies to make DFOS function over the telecom network infrastructure feasible. These technologies are applied in the NEC FOSS solutions and become the differentiators to the conventional DFOS systems.

signals at different polarizations and in the quadrature plane, more signal information can be obtained, which helps to reduce impairments such as the Rayleigh fading effect. This improves the quality and increases the stability of the sensing signal.

3.1 Extending the distance

Conventional DFOS interrogator uses a single photodetector or pairs of balanced photodetectors to detect the received backscattering light. The NEC FOSS interrogator uses the polarization-diverse digital coherent receiver with advanced high-speed digital signal processing (DSP) technologies to detect the backscattering signal. This is based on the high-speed digital coherent transponders used for long-distance transmission. By monitoring

Various technologies are developed and implemented to extend the reach of the sensing system. A combination of Erbium-doped fiber amplifiers (EDFAs) and Raman amplifiers are used to provide the optimum optical power profile while minimizing noises. To further extend the transmission reach, remote optically pumped amplifiers (ROPAs) are used to supply power at the extended distance without requiring electrical power supply in the field.

Due to the fiber nonlinearity, it is not possible to keep improving the signal to noise level by increasing the optical signal power. In order to further extend the signal reach without increasing the optical power, an advanced DSP technique is applied. Through appropriately designed signal processing algorithms, sensing signal recondition is implemented and NEC FOSS sensing distance gains are significantly increased.

3.2 Increasing the accuracy

Different DSP techniques are also applied in the NEC FOSS solutions to improve output quality, including refining the spatial resolution, combined spatial-temporal domain de-noising, phase recovery from weak signal, and so on.

Multiple application-specific AI models are developed based on the special features of the sensor data and the targeted events to monitor. Accurate high-level information can be extracted and reported to the user in real time for quick notification and responses. These AI technologies simplify the complex fiber sensing measurements into actionable insights for convenient customer applications.

To compensate for the losses at the splicing points and fiber adapters in the field and to mitigate the computation error occurred at these locations, a multi-calibration point scheme is developed, with automatic drift correction and a user-friendly interface for additional manual adjustment functions.

3.3 Enhancing the flexibility

The NEC FOSS product suite offers different form factors for different customer needs. Besides the standard 19” rack-mount and ETSI V400 rack form factor for installation on telecom equipment racks, the NEC FOSS interrogator can also be used as a stand-alone desktop instrument. Detachable handles are available to facilitate easy transportation. The interrogator can use the standard telecom 48V DC power supply or work under 90V to 264V AC through the included AC adapter.

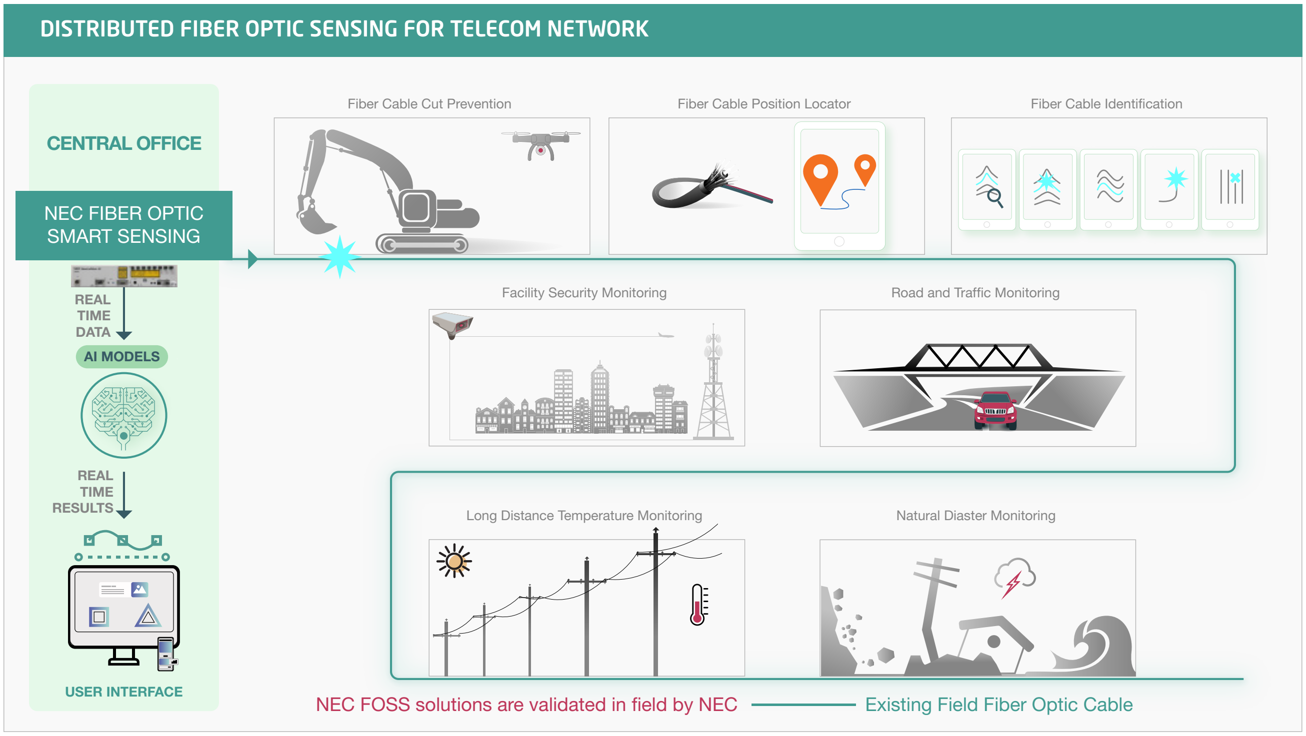
In terms of the processing of sensor data, the user also can select from different options, such as having data processing performed in the cloud, at a local on-premises server, or at the integrated on-board computer. Raw sensor data are stored so that, besides real-time analysis, the user can also select the option to have offline processing in the future.

The GUI of the NEC FOSS product suite provides an intuitive, user-friendly visual tool. The GUI is highly customizable for different applications in different fields. Flexibility across different operation systems and platforms is also offered. Besides the high-level information, such as the event logs and alert notifications, the user can also access the raw data. Users can also monitor information and manage the system locally at the central office, on the integrated monitor of the portable sensor, or through a handheld device connected through WAN network.

4. Applications of NEC FOSS solutions

Thanks to the technology innovation and feature enhancement in NEC FOSS product suite, many new or improved application solutions are available. These applications improve operational efficiency for the network operators and create new capabilities for the existing network infrastructures, bringing new business opportunities and revenues for the network owners. Figure 2 illustrates some of the applications supported and enabled by NEC FOSS solutions that have been validated in the field by NEC, including commercially available products.

Figure 2: Examples of NEC FOSS Applications



Fiber Cable Cut Prevention – Cable cut is a common problem for network operators. Not only does it cause service interruption, but it also requires costly repair efforts. Cable cut usually occurs when some unauthorized construction activity occurs in the area of buried optical cables. Existing solutions can only detect a cable cut after it occurs. The NEC FOSS solutions can provide early warning to network operators before the accident occurs. This is achieved by constantly analyzing activities along the cable routes to detect any abnormal activities—such as when a construction machine starts operation—and identifying possible events at those locations. The network operators will be notified and have the opportunity to take appropriate action before cable damage occurs.

Fiber Cable Position Locator – Detailed information on the installed optical network is crucial to network operators, who rely on this information for network management and maintenance. However, quite often the cable information in the operator's database is inaccurate. For example, additional lengths of fiber optic cable might be added during a repair work, or the cable might be relocated to the opposite side of the street during area redevelopment. Although the traditional tool, the optical time domain reflectometer, can report the distance along the fiber route when an accident happens, the field technician cannot properly associate this distance information with the actual physical location using an inaccurate database. The NEC FOSS solution utilizes a coordinated system of fiber sensor, signal generator, GPS, and area map to enable easy updates to cable position information with high precision.

Fiber Cable Identification – In many urban fiber optic networks, it is typical that each manhole or hand hole contains multiple optical cables, and each cable usually contains tens or even hundreds of fiber strands. It is very difficult to identify one particular cable or one particular fiber since they look identical in the field and usually do not have specific markings. Identifying one specific cable or fiber for field operations often require a large amount of time and effort, which often causes service delay or interruption. The intelligent analytic tools within NEC FOSS solutions enable field technicians in the field to easily identify the cable/fiber of interest and instantly obtain the information sought while using a mobile device app that communicates with the sensor at the central office.

Facility Security Monitoring – NEC FOSS allows continuous monitoring over the perimeter of critical facilities and campuses with accurate location reports. The ML-based analytic software can classify events accurately and quickly. The user can also customize event alerts, designating what events to be alerted and what events to be treated as normal . With their long-distance sensing capability, NEC FOSS products can deliver a wide range of security monitoring solutions, ranging from the perimeter of a 5G wireless tower to a data center site to harbors and national borders.

Road and Traffic Monitoring – Since large amounts of optical fibers are deployed along major roadways, it is advantageous to use them for traffic monitoring. The NEC FOSS solution can provide a broad range of traffic information, such as the vehicle count, vehicle speed, illegal driving activities, traffic accident, and other information Roadway operators can use the obtained information for rapid response to traffic accidents, to schedule maintenance, and to manage traffic patterns to reduce congestion, which can reduce economic loss incurred from on-road delays. Operators also can use the solution to monitor, manage, and reroute traffic to ward off traffic jams and the emissions produced by idling vehicle engines, thus reducing air pollution. Besides monitoring traffic, the NEC FOSS solution can also monitor road conditions, providing information on potholes, rain or snow, and even bridge infrastructure health.

Long-Distance Temperature Monitoring – Combining the distributed sensing feature of DFOS and advanced signal processing schemes, NEC FOSS can provide accurate temperature monitoring over long distances with fine spatial resolution. It can use used for many applications, such as monitoring for overheating in server blades and racks in large data centers, refrigeration condition monitoring in large supermarkets or storage facilities, and high-power electric cable condition monitoring (overheating, ice, or strong wind). Constant temperature monitoring inside roadway tunnels can also provide early warning before smoke and fire becomes visible.

Natural Disaster Monitoring – Earthquake monitoring is an emerging application for DFOS technologies. It is useful to detect earthquakes in the middle of an ocean in real time; however, it is very difficult and expensive to deploy millions of sensors to cover the sea floor. With the long-distance sensing capability and specifically designed AI analytic engines of NEC FOSS, existing submarine optical cables can be turned into earthquake sensors, and the interconnected submarine networks can provide detail locations of earthquake activity in real time. Besides earthquake monitoring and related tsunami warning, NEC FOSS also provides solutions to monitor other natural disasters such as landslides and flooding over river embankment.

5. Summary and Benefits

NEC FOSS suite of products use a toolset of distributed vibration-, acoustic-, and temperature-sensing technologies. Applied to existing fiber optic network infrastructures or a dedicated fiber optic sensing network, it monitors various types of environmental conditions and events. A user-friendly and customizable GUI denotes the location of events-of-interest and provides actionable data in real-time. When an environment disturbance like physical movements, temperature variations, or acoustic vibrations reach the optical fibers, the sensor interrogator instantly detects and locates the signal. The solution's ML-based AI analytic engine simultaneously analyzes and classifies the multiple physical events. Integrate software immediately triggers silent or audible alarms and/or sends actionable alerts. Actionable data, such as date, time, location, and event classification can be stored locally or remotely for future reference and data analysis.

Overall, NEC FOSS solutions can interrogate a long section of optical fiber, providing fine spatial resolution and the ability to localize each event accurately and instantly. These features enable many new applications that make fiber cable network operations more efficient and yield additional network value and uses, such as smart cities, smart transportation, smart power distribution. When NEC FOSS solutions are applied to a fiber optic communication network, the entire network becomes a giant sensor for various applications and actualizes the new Network-as-a-Sensor paradigm.

Finally, NEC FOSS solutions are CAPEX friendly, as they are compatible with existing deployed infrastructure; they are OPEX friendly, because they reduce or replace large amounts of manual labor and; they are environmentally friendly, thanks to the DFOS' low energy consumption compared to the use of hundreds of discrete sensors.

Corporate Headquarters (Japan)
NEC Corporation
nec.com

North America (USA & Canada)
NEC Corporation of America
necam.com

NEC Enterprise Solutions
NEC Europe Ltd
nec-enterprise.com

APAC
NEC Asia Pacific Pte Ltd
sg.nec.com

Latin America
NEC Latin America
latam.necam.com

NEC Corporation of America

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