# More Than Communications: Environment Monitoring Using Existing Optical Fiber Network Infrastructure

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**Abstract:** We propose reusing existing optical cables in metropolitan networks for distributed sensing using a bidirectional, dual-band architecture where communications and sensing signals can coexist with weak interaction on the same optical fiber. © 2020

## 1. Introduction

The optical fiber network is an important telecommunications infrastructure which supports high-speed Internet. In addition to its intended function of facilitating data transmission, optical fibers can also be used to monitor a cable's ambient environment. An optical fiber sensor is a passive sensor where the glass medium acts as the transducer. When an interrogator launches a sensing pulse with short temporal duration into the fiber, a weak return light is generated at every position due to Rayleigh, Brillouin and Raman backscattering. Rayleigh backscatter is at the same frequency as the launched sensing pulse, whereas Brillouin and Raman scattering are nonlinear processes which generate return light at frequencies around ±10.7 GHz and ±13 THz from the launched pulse. Scattering at frequencies below and above that of the launched pulse denotes "Stokes" and "anti-Stokes" processes respectively. By co-locating a receiver at the same end of the fiber as the interrogator, both accessing the fiber via a circulator, it is possible to filter one of these backscatter components for optical time-domain reflectometry (OTDR) measurement. The backscatter generated at position $z$ along the fiber is received with delay $\Delta\tau = \left(2n_{eff}/c\right) z$ equal to the round-trip propagation time, where $n_{eff}$ is the group index. Changes in the ambient environment around the cable created by vibration, strain or temperature fluctuation will change the local properties of the optical fiber, causing either a change in optical path length manifesting in optical phase shift of the received backscatter, or change in the Brillouin or Raman frequency shift. Since events at different fiber positions can be discriminated by round-trip delay, the optical fiber can serve as a distributed sensor with sensitivity along its entire length.

Optical fiber sensors have many advantages. Firstly, its distributed nature allows the ambient environment to be sensed continuously at a spatial resolution $\Delta z = \left(c/2n_{eff}\right) T$ set by the duration $T$ of the sensing pulse. This contrasts with Bragg grating-based fiber sensors which can only sense the ambient environment at discrete locations. Another advantage is that it is possible for the sensing pulses to coexist on the same fiber carrying data traffic by allocating different parts of the spectrum to these functions. This allows reuse of the existing optical fiber network for a new application. The ubiquity of optical cables in metropolitan areas provides plentiful opportunities for distributed sensing over wide geographic area, and create new revenue sources for telecom operators.

In order for data transmission and sensing to coexist, it is necessary that their signals do not interfere. In this paper, we propose a bidirectional, wavelength-division multiplexed (WDM) scheme where data transmission and sensing systems coexist in the low-loss C band (~1530 to 1565 nm). Bidirectionality reduces nonlinear interaction between sensing and the data signals. With this architecture, we demonstrate distributed vibration sensing (DVS) of vehicular traffic over a deployed cable carrying live data traffic. Machine learning (ML) on the raw data captured with DVS allows determination of vehicle flow condition, average vehicle speed, and even pavement deterioration. The paper is structured as follows: Section 2 describes our bidirectional architecture, and Section 3 describes field experiments of several distributed fiber-optic sensing (DFOS) application.

## 2. Bidirectional Dual-Usage Architecture

Fig. 1(a) shows the architecture of our bidirectional dual-usage system where data transmission and DFOS coexist on the same optical fiber. The system comprises of a fiber-pair supporting two-way data traffic between two nodes. These nodes can be in two data centers or at two add-drop/repeater sites. The data channels and sensing pulses propagate in opposite directions in each fiber to reduce their mutual nonlinear interference, allowing both systems to coexist in the low-loss C-band. Diplexers (DXR) are used to multiplex/demultiplex data signals and sensing signals. This is to prevent out-of-band amplified spontaneous emission (ASE) noise of the booster amplifiers from swamping the backscatter of the DFOS system, which co-propagates with the data channels at substantially lower power (inset of Fig. 1). Normally, only one fiber sensing interrogator is needed per cable. It is possible to insert a second DFOS interrogator on the return fiber as shown in Fig. 1, either as a backup system, or as a different DFOS system that senses a different environmental variable, e.g. Brillouin-based temperature sensor.

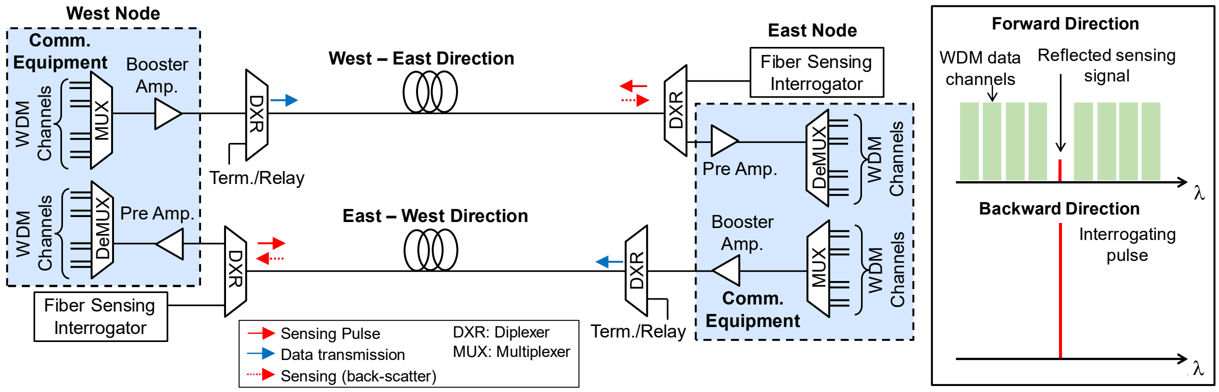


Fig. 1. Bidirectional dual-usage architecture, where data transmission and distributed fiber-optic sensing coexist on different wavelengths. The sensing and data signals counter-propagate in each optical fiber to reduce their nonlinear interaction.

## 3. Optical Fiber Sensor Applications

*Intrusion detection*

An important application of DFOS is detection of unauthorized intrusion at protected facilities. By laying an optical fiber cable along a perimeter fence (Fig. 2(a)), it is possible to monitor any micro-movement of the fence. The key challenge is to discriminate between real intrusion events, and false alarms caused by natural perturbations such as wind and rain, or by the movements of small animals. Fortunately, different types of vibrations can be distinguished by their different telltale vibration signatures, as shown in Fig. 2(b) for a DVS system based on direct detection of Rayleigh backscatter conducted at NEC. Machine learning (ML) algorithms can be used to classify these different events. Once the artificial intelligence (AI) has been trained, a single interrogator can discriminate "harmful" vibration caused by intrusion (e.g., shaking, cutting) along the entire optical cable. The combination of DFOS with AI thus provides an inexpensive intrusion detection solution compared with deploying large numbers of security cameras.

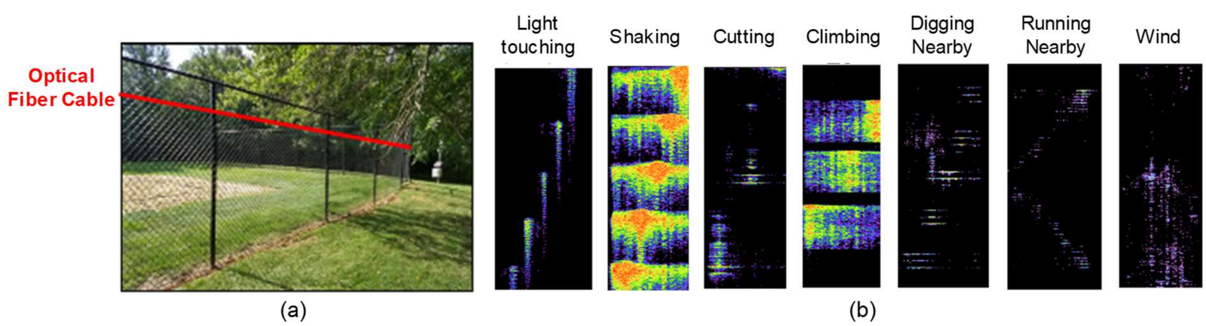


Fig. 2. (a) DFOS system mounted on a fence, (b) "Waterfall" plots for different vibration events which can be classified by machine learning.

*Vehicular traffic monitoring*

A second application is monitoring of vehicular traffic. This is feasible as deployed optical cables are often buried next to major arterial roads. Vehicular traffic creates vibration whose position varies with time [1]. Fig. 3 shows a waterfall plot recorded using Rayleigh-based DVS on a 55-km fiber cable in the Dallas metropolitan area [2]. The horizontal and vertical axes denote fiber position and time, respectively. The speed of a vehicle can be inferred by the slope of the vibration features: a steep slope denotes slow traffic (congestion), while a shallow slope denotes fast traffic (smooth flow). Positive and negative slopes indicate different directions of travel. As with intrusion detection, waterfall plots like Fig. 3 can be used to train an AI to isolate individual vehicles and estimate their speeds. In this field trial, the DFOS system coexisted with full C-band 38-Tb/s transmission of dense WDM (DWDM) traffic where each of the 92×48-Gbaud channels carried PS-144QAM at a net data rate ≥400-Gb/s, at an average spectral efficiency (SE) of 8.3 b//Hz. To facilitate the DFOS system, a block of three 50-GHz channels were left unused in Fig. 1(a). Fig. 2(b) shows the constellation diagrams of one of the PS-144 QAM channels in back-to-back configuration and after 110-km propagation (two 55-km spans concatenated, with the bidirectional dual-usage scheme in Section 2 implemented on one of the spans). The launch power of the sensing pulse was adjusted for optimum operation of both the data transmission and DFOS systems. The presence of the sensing pulses did not produce perceptible difference in signal quality on the data channels. Error free operation (pre-FEC BER < $2.2\times10^{-2}$) was achieved, demonstrating the feasibility of the scheme outlined in Section 2.

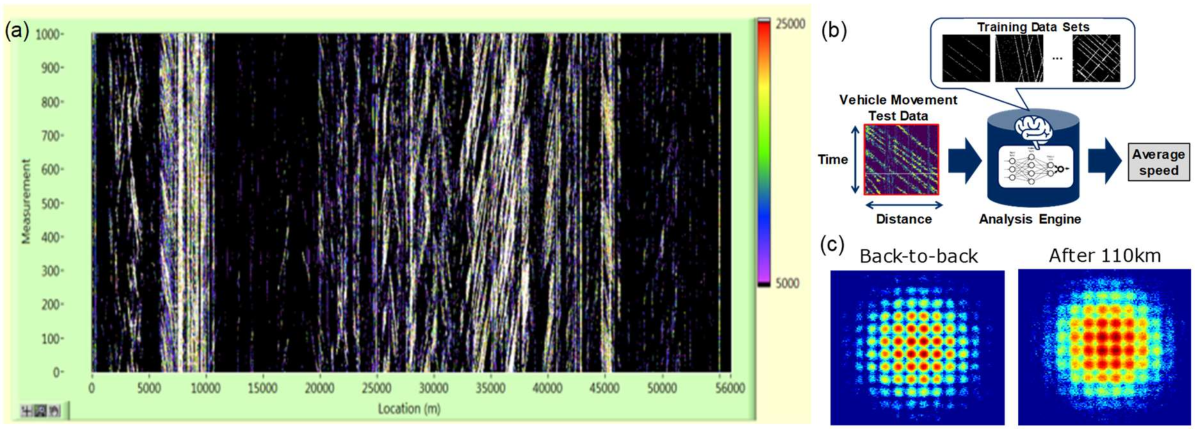


Fig. 3. (a) "Waterfall" plot showing vehicular traffic pattern, (b) Machine learning to determine vehicular direction and average speed, (c) Constellation diagrams of PS-144QAM channels which counter-propagated against the DFOS system.

*Infrastructure health monitoring*

A third application is monitoring the health of key infrastructure such as bridges. The natural frequencies of the monitored structure, as well as the damping characteristics at each natural frequency changes with physical deterioration. It is thus possible to use DFOS to detect changes in vibration characteristics in real-time. Initially, human inspection is required to generate training data sets for different states of deterioration of the reference structure. Once the AI is trained, it is possible to simultaneously monitor a cascade of similar structures when they are all traversed by the same optical cable. Such a DFOS-based monitoring scheme is low cost. Fig. 4(b) shows field data recorded for a railway bridge in Japan. A clear difference is observed between the distribution of "anomaly scores" before and after renovation, allowing 1-class classification of structural health using RAPID machine learning [3].

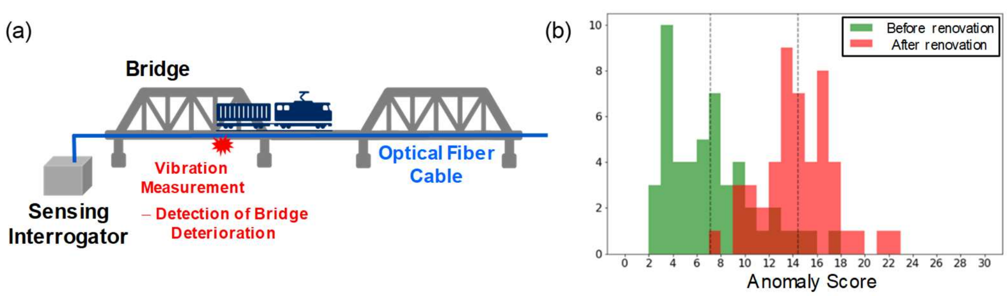


Fig. 4. (a) Bridge structural health monitoring using DFOS, (b) ML classification of bridge health showing distribution of "Anomaly score" before and after renovation.

## 4. Conclusions

In this paper, we have demonstrated the feasibility of reusing existing fiber optic cables for distributed fiber-optic sensing (DFOS). We outlined three applications that can be performed using DFOS: intrusion detection, vehicular traffic monitoring and infrastructure health monitoring. DFOS combined with artificial intelligence (AI) enables accurate classification of events, reducing the likelihood of false alarms, and facilitates low-cost environmental monitoring across wide geographic area.

## 5. References

[1] Kanno et al., "Research on highway traffic flow observation using optical fiber sensing technology," Proc. 39th Traffic Engineering Conf., Paper 50, Tokyo, Japan (2019).

[2] G. Wellbrock et al., "First field trial of sensing vehicle speed density and road conditions by using fiber carrying high-speed data," OFC'19, Paper Th4.C.7, San Diego, CA, USA (2019).

[3] NEC Online TV: RAPID machine learning detects abnormalities with high accuracy using only normal data! Available at: https://jpn.nec.com/ad/onlinetv/ai_rapid.html