Distributed Acoustic Sensing Over Passive Optical Networks Using Enhanced Scatter Fiber

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Abstract: Simultaneous fiber-optic sensing and NG-PON data transmissions over a 1x16 splitter is demonstrated by enhanced scatter fiber. Acoustic signals from a single distribution fiber are identified. The crosstalk between sensing and data channels is studied. © 2024 The Author(s)

1. Introduction

Recently, the use of telecom fiber infrastructure for distributed fiber-optic sensing (DFOS) is gaining a lot of attention as it can provide a variety of new applications such as perimeter intrusion detection, and infrastructure health monitoring [1-2]. The telecom operators are not only interested in using this for monitoring their telecom fiber infrastructure integrity, but also interested in gaining new business opportunities. On the other hand, with the wide adoption of 5G mobile network and cloud computing, and introduction of artificial intelligence (AI), there is increasing demand for structural health monitoring and security surveillance, which can enhance public safety, increase sustainability, and improve basic services [3]. The passive optical network (PON) [4] has been widely deployed in both traditional fixed access networks and modern centralized radio-access networks for 5G mobile. Integrating the PON fiber infrastructure with DFOS is an important step to realize such new applications, especially for realization of future smart city architectures. It is well known that the distributed acoustic sensing (DAS) techniques have been used in wide-ranging sensing applications [5]. In DAS, an interrogator launches an optical pulse train into the fiber and measures dynamic strain along the fiber, typically using Rayleigh backscatter. The round-trip nature of backscatter measurement makes DAS more susceptible to signal propagation loss than data transmission, as losses of the DAS links are doubled in dB. The backscatter signal will be very weak after a typical PON splitter due to the losses from the passive splitter plus the short length in the distribution fiber (DF). This makes DAS over PON extremely difficult. Recently simultaneous data transmission with DFOS on DF was demonstrated by using reflective semiconductor optical amplifiers at optical network units (ONUs) [6] and the data transmission and vibration monitoring under PON was also reported by using interferometry-based sensing interrogator with two fibers and Faraday Rotator Mirrors (FRM) at ONU [7].

In this work, we explore the possibility of using DAS over PON infrastructure for civil structural health monitoring. We consider an application case where the DAS and optical line terminal (OLT) are co-located in central officer (CO) that is connected to each ONU via a 1xN optical splitter. As shown in Fig.1, one DF employing enhanced scatter fiber (ESF) [8] is for both sensing and PON data transmission, another one DF with ESF is dedicated for sensing. The rest of DFs using single-mode fiber (SMF) connecting each ONUs carry PON data only. Using intensity-based DAS interrogator, we first discover a significant benefit when using ESF in PON splitter compared to using SMF. We then demonstrate that the DAS signals from two DFs can be distinguished. This feature can be used for discrimination of the DAS signal from individual DF. Finally, we successfully demonstrate co-existing DAS signal and transmission of 4x10Gb/s NG-PON signals over 1x16 splitter with 10km feeder fiber (FF). We further show that transmission penalties of both down-stream (DS) and up-stream (US) 4x10Gb/s NG-PON signals are negligible from the DAS channel, however some degradation of the DAS signal is observed in the case of co-existence of the fiber sensing and PON systems.

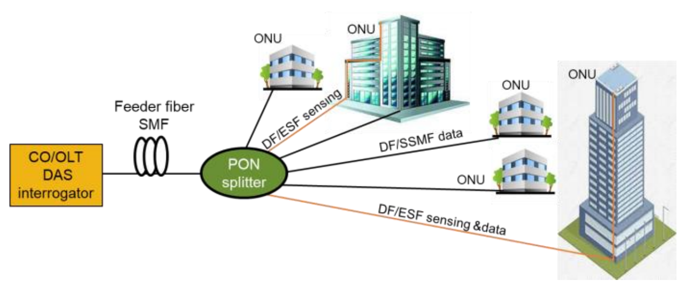

Fig. 1 Schematic of DAS over PON architecture. One DF using ESF is only for sensing, another DF using ESF is for sensing and PON data transmission, the rest of DF using SSMF are for PON data communication.

2. Co-Existing DFOS and Data Transmission over NG-PON

Fig.2 shows a schematic of a co-existing DFOS and data transmission over next generation PON (NG-PON) [4, 9] architecture. At CO with OLT, the DAS channel and four 10Gb/s DS and US channels are combined by using WDM-Mux or DeMux [4,9]. Here the PON consists of a 10km SMF as FF which is connected to 1xN splitter followed by DFs to each ONU. In this demonstration, the DF1 using 2.2km ESF was designed for both sensing and data communication between OLT and ONU1. The DF2 using 1.6km ESF was only for dedicated sensing. Other DFs using SMF were designed to carry NG-PON data only. In the experiment, the four 10Gb/s DS and four 10Gb/s US channels were operated with 100GHz spacing at 1596.34-1598.89nm and 1532.23-1534.56nm, respectively. A Fotech intensity-based DAS interrogator (model:H3242) was used for sensing measurement, and the pulse rate and width were set to be 10kHz, and 50ns respectively. Two piezoelectric transducers (PZT1 and PZT2), each of them wrapped by a 22m ESF, were spliced to the end of ESFs in DF1 and DF2 to stimulate vibrations. The PZT1 was then connected to the ONU1 comprising of four US transmitters (Tx) and DS receivers (Rx) and a WDM to combine them. The end of DF2 after PZT2 was inserted into the index-matching oil to avoid reflection. The PZT1 and PZT2 were driven with the same voltage of 0.6V at 100Hz and 134Hz to stimulate a maximum fiber stretching of ~1.3μm, respectively. This value was set just enough to estimate signal-to-noise ratio (SNR) of the sensing signal, but not generate any high harmonic noises. The SNR is estimated as the ratio of sensing signal powers at 100Hz and 134Hz over the noise power averaged within ±25Hz of the modulation frequency respectively. To properly assess the DAS performance, five ~ ten measurements were usually conducted in experiments, 5 positions on PZT ranges were selected for each measurement. The ESFs used in this work are the same as those of [8], with backscattering ~ 21.5dB above Rayleigh scattering. Inset of Fig.2 shows the reflection spectra of ESFs, and the spectra of DS/US channels, and sensing channel.

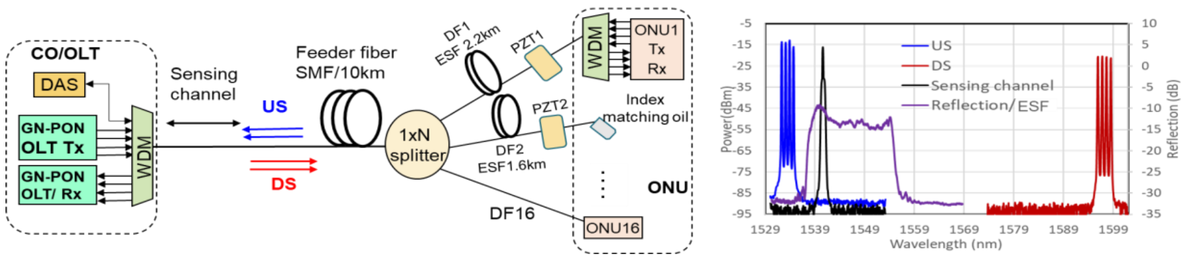

Fig. 2 Experimental set up for DAS over NG-PON. WDM combines the DS, US and sensing channel at CO/OLT, Inset: optical spectra for US, DS and sensing channel and reflection spectrum of the ESF.

3. Experimental Results and Discussion

We first assessed the DAS performance without data transmission by only connecting 2.2km ESF or 2.2km SSMF in DF1, and other DFs are terminated with AC/APC connectors. The Fotech DAS is connected to 1xN splitter through

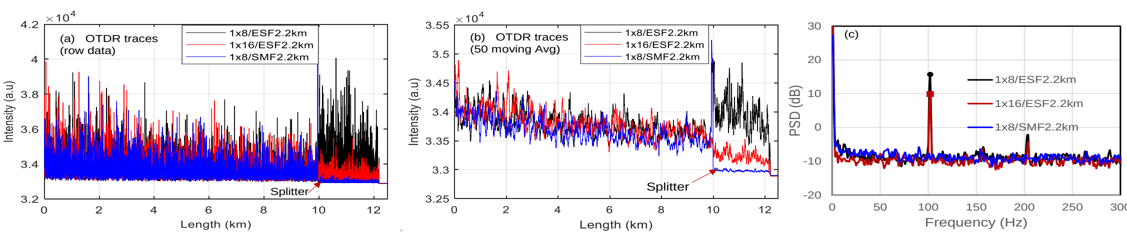

Fig.3. (a) Reflection intensities (raw data) vs distance for 1x16, 1x8 splitters using 2.2km ESF and 1x8 splitter using 2.2km SMF in DF; (b) 50-point moving average plot of (a), (c) Acoustic PSD spectra for these three cases.

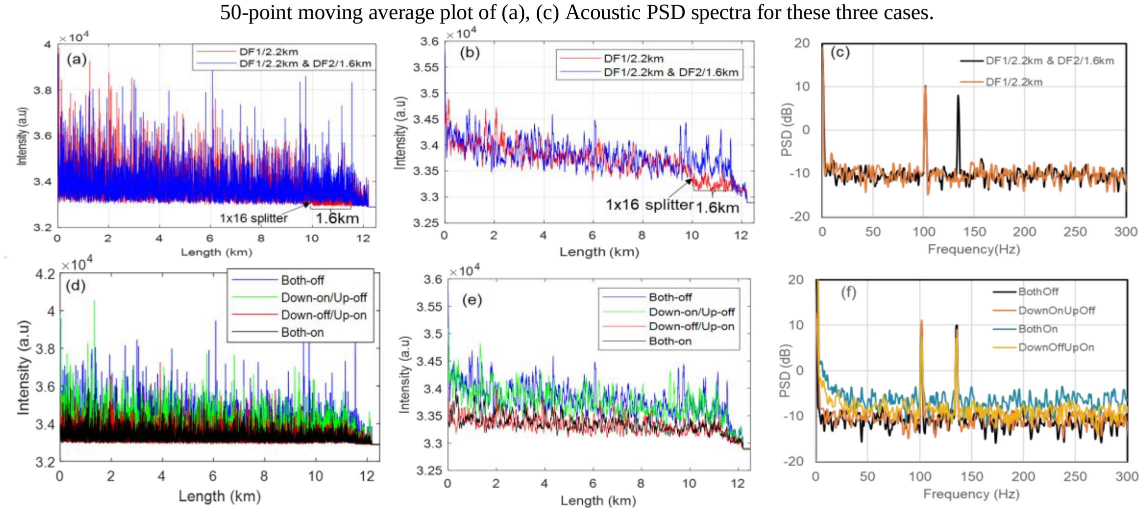

Fig. 4. a) OTDR traces from PON with 10km FF & 1x16 splitter with one DF1/2.2km ESF vs with two DF1/2.2km+DF2/1.6km ESF), b) 50-MA of a). c) DAS signals PSD spectra of Fig. 4a), d) OTDR trances of DAS signal co-existed with NG-PON e) 50-point MA of d); f) PSD spectra of Fig. 4d.

10km SSMF as FF and the splitter ratios are either 1x16 or 1x8. The end of DF1 with 2.2km ESF or 2.2km SSMF is connected to PZT then inserted into an index-matching oil. Fig. 3 (a) plots the OTDR traces vs distance in a 10km SSMF FF via 1:16 or 1:8 spitters with 2.2km ESFs, as well as a 10km SMF FF via 1:8 splitter with 2.2km SMF in DF1. The well-defined reflection traces through 10km FF with 1:16 or 1:8 splitter using 2.2km ESF in DF1 are clearly seen in Fig. 3 (a), however almost no reflection signals after 1:8 when using 2.2km SSMF in DF1. This difference can be easily seen in the plot in Fig.3 (b) which shows a 50-point moving average (MA), corresponding to ~29m in fiber length. The power spectral density (PSD) spectra of the three cases are shown in Fig.3 (c), and the measured SNRs are about 20 dB and 26dB for 1x16 and 1x8 splitter using 2.2km ESF respectively, however no 100Hz frequency signal was recovered when using 2.2km SMF in DF1, clearly showing significant benefit of using ESF in PON splitter.

We then connected DF2 with 1.6km ESF to the 1x16 splitter. Both ends of DF1 and DF2 were inserted in index - matching oil to avoid reflections. The OTDR traces vs distance in 10km FF with 1:16 splitter connecting only DF1/2.2km ESF and connecting both DF1/2.2km and DF2/1.6km ESF are plotted in Fig.4 (a). The reflection intensity was increased slightly after 1:16 splitter in 1.6km range when both DF1/2.2km and DF2/1.6km ESF are connected. The difference between these two cases can be seen in the 50-point MA plot (Fig.4 (b)). By employing different lengths in DFs, the reflection traces can be distinguished from two different DFs. This feature can be used for discrimination of individual DFs. The PSD spectra derived from successive coherent traces are shown in Fig.4 c.

To investigate the crosstalk in the co-existing DAS with NG-PON system, we compared the OTDR intensities for four cases i) both US and DS turned off, ii) DS on, US turned off, iii) DS off and US on, and v) both US and DS all turned on. As shown in OTDR trances (Fig.4 (d)), the relative intensities are reduced when US channels were turned on (cases iii and v), these results can be easily seen in the 50-point MA OTDR traces (Fig.4 (e)). Fig.4 (f) plots one example of the acoustic PSD spectra, and the SNR of DAS signal at 100Hz and 134Hz were estimated, and average values are shown in Table 1. It is indicated that US data channels have a large impact on the sensing performance. This can also be seen in Fig.4 (f), the acoustic noise levels at low frequency were increased when US channels turned-on. The BER receiver sensitivities of the DS and US channels with and without sensing channel were measured (Fig.5), showing negligible penalties from the DAS channel. From OTDR traces, PSD spectra and SNR values, some degradations of the DAS signal are observed from the US data channel. One of the reasons is that the US signals propagated forward to the receiver of sensing channel and the wavelength of US channels are too close to the sensing channel. Nevertheless, simultaneous DFOS with 4x10Gb/s NG-PON transmission was demonstrated. Separating the DAS and US channels far away, or use of a narrow bandwidth optical filter in front of DAS can be used to mitigate crosstalk.

Table 1 SNRs of the sensing signal co-existing with NG-PON

	Both off	DS-on US-off	DS-off US-on	Both on
SNR (100Hz) [dB]	20.9	20.3	18.3	16.1
SNR (134Hz) [dB]	19.7	20.1	17.6	16.3
SNR Average [dB]	20.3	20.2	18.0	16.2

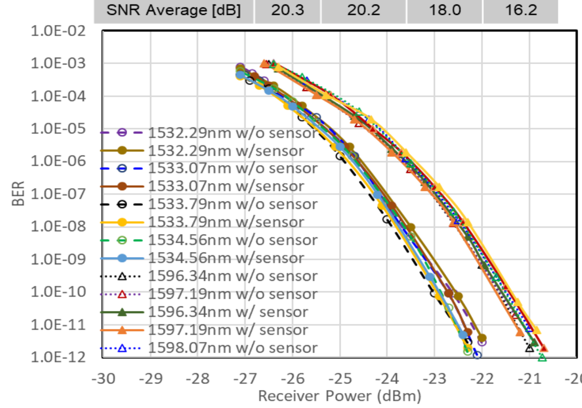

Fig.5 plot the BER of DS and US channels as a function of receiver power with and without sensing signal.

4. Summary

We have investigated the possibility of using DAS over NG-PON infrastructure. We have demonstrated a significant benefit for improvement of DAS reflection signals when using ESF in PON architecture compared to SSMF. By employing different lengths of ESF in DFs, the reflection features from individual DFs connected to the ONU can be discriminated. Using intensity-based DAS interrogation, co-existing DAS signal and transmission of 4x10Gb/s NG-PON signals over 1x16 splitter with 10km feeder fiber has been demonstrated by using ESF. The crosstalk between sensing and data channels has been investigated.

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