Simultaneous Optical Fiber Sensing and Mobile Front-Haul Access over a Passive Optical Network

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Abstract: We demonstrate a passive optical network (PON) that employs reflective semiconductor optical amplifiers (RSOAs) at optical network units (ONUs) to allow simultaneous data transmission with distributed fiber-optic sensing (DFOS) on individual distribution fibers. © 2020

1. Introduction

Centralized Radio Access Networks (C-RAN) will play a key role in providing 5G mobile front-haul access. Using a passive optical network (PON), a centralized baseband unit (BBU) can be connected to a cluster of remote radio heads (RRHs) [1, 2]. Deploying a C-RAN every few square miles enables 5G coverage across large populated areas such as cities and suburbs. Telecom operators are interested in monitoring the health of the network infrastructure, as well as new business opportunities from collecting ambient environmental data using the deployed fibers. Distributed fiber-optic sensing (DFOS) can facilitate a wide range of applications such as infrastructure health monitoring, traffic identification and earthquake detection [3, 4]. In distributed acoustic sensing (DAS), an interrogator launches an optical pulse train into the fiber and measures dynamic strain along the fiber using Rayleigh backscatter [4, 5]. The round-trip nature of backscatter measurement makes DAS more susceptible to signal propagation loss than data transmission, as losses are doubled in dB. This makes DAS over PON difficult, as PONs typically use large splitter ratios (e.g., 1×32 or 1×64) to distribute the signal from a feeder cable to as many customers as possible via “last mile” distribution fibers (DFs). The round-trip loss of a 1×32 splitter is ~30 dB. DFOS systems thus need to overcome round-trip losses on the order of 40 dB between the optical line terminal (OLT) and optical network units (ONUs).

Since it is costly to deploy a DFOS interrogator at every ONU, pulse signal coding was proposed to boost signal-to-noise ratio (SNR) to overcome round-trip loss and allow interrogation from the OLT [6]. This approach is unable to discriminate individual DF after the passive splitter, however. In [7], a DFOS system based on Brillouin backscatter was proposed to allow individual DFs to be discriminated as long as each DF uses a different type of fiber with a different Brillouin frequency shift. Such a scheme is costly and impractical to implement, and is also incompatible with PONs which have already been deployed.

In this paper, we show that it is possible to make PONs compatible with DFOS by placing low-cost reflective semiconductor optical amplifiers (RSOAs) at the ONUs. By using a time-domain multiplexing (TDM) scheme where RSOAs at different ONUs are turned on/off sequentially, it is possible to interrogate individual DFs. Our experimental results show we can overcome round-trip loss of almost 40 dB, as we successfully conducted DAS at a spatial resolution of 10 m, and were able to measure the vibration of two piezoelectric (PZ) fiber stretchers inserted at two different DFs simultaneously without any interference. We were also able to use the same system to detect vibrations from pedestrian and vehicular traffic on a buried cable next to a roadway. Our DAS coexisted with bidirectional 10-Gb/s transmission link based on 4-ary pulse-amplitude modulation (PAM4), which is compatible with XGS-PON supporting symmetric 10G-10G mobile front-haul using time-domain multiple access (TDMA) [8].

2. Overlaying Data Transmission / Sensing PON Architecture

The overlaying transmission/sensing PON architecture is shown in Fig. 1. At the OLT, the sensing channel (1550.12 nm) and two 6-Gbaud PAM4 upstream (1561.12 nm) and downstream (1546.12 nm) channels are combined using a wavelength-division multiplexer (WDM). The PON consists of a 4.4-km spool of feeder fiber connected to cascaded splitters forming a 1×32 split, followed by DFs that are 1.6 km long. The ONU comprise of a WDM whose upstream (US) and downstream (DS) ports are connected to PAM4 transmitters (Tx) and receivers (Rx), respectively, while the sensing port is terminated by an RSOA. When the RSOA is turned on at an ONU, the forward-propagating sensing pulse is amplified and reflected, becoming a backward-propagating sensing pulse which generates its own optical time-domain reflectometry (OTDR) signal due to Rayleigh backscatter. This secondary OTDR signal initially propagates in the forward direction. Upon impinging the RSOA, it is amplified and reflected back towards the OLT. A sample OTDR trace measured at the OLT is shown in Fig. 2(b). In each “frame” corresponding to the RSOA of one ONU being turned on, the first part of the OTDR trace (A) is Rayleigh backscatter of the feeder fiber. The second part of the OTDR trace (B) is the weak backscatter of the 1.6-km DF which has been attenuated by the 1×32 splitter. The last part of the OTDR trace (C) is amplified backscatter of the DF created by the backward-propagating sensing pulse. The RSOAs have single-trip small signal gains of ~ 5 dB.

Using the architecture shown, we can selectively interrogate each DF by turning on the RSOA in that ONU. During interrogation of a particular DF, the RSOAs in all other ONUs must be turned off so they do not interfere with the OTDR of the desired DF. Since timing synchronization between the ONUs can assumed in a TDM-PON, it is possible to perform synchronized sequential switching of the RSOAs. We note that Rayleigh backscatters of the 31 other DFs will create interference which overlaps with (B) in the OTDR frame (Fig. 2(b)). By making all DFs have similar length (adding fiber at an ONU if its DF is too short), we can ensure interference from other DFs do not extend into the relevant portion (C) of the OTDR frame. To emulate interference at the correct power level without all 32 DFs present, we concatenated a 1×4 splitter with a 1×8 splitter in Fig. 1. The Rayleigh backscatter of DF 3 is around −12 dB weaker than that of the feeder fiber. In a full 32-fiber implementation, the combined backscatter of 31 DFs will be around −15 dB weaker that of the feeder fiber.

In our experimental setup, the 6-Gbaud PAM4 communications channel is launched into the PON at 3.8 dBm. The DAS system transmits 100 ns pulses (spatial resolution ~ 10 m) at peak power of 7.6 dBm at a repetition rate of 10 kHz. The total signal loss from OLT to ONU is around 19 dB (roundtrip loss ~ 38 dB).

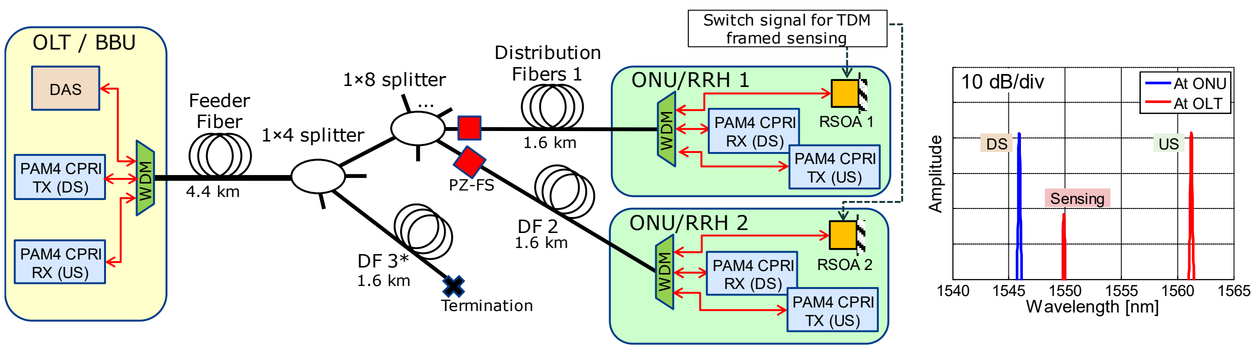

Fig. 1. Experimental setup for DFOS-compatible PON. Wavelength MUX/DEMUX combine the upstream (US), downstream (DS) and sensing channels, and the RSOA at each ONU enables DFOS on each individual distribution fiber. Inset shows spectra measured at the OLT and ONU.

3. Experimental Results

We first evaluated transmission performance for the 6-Gbaud PAM4 data channel. Fig. 2(a) shows bit-error rate (BER) vs received power sweep in back-to-back configuration, as well as for US/DS transmission with and without the sensing signal present. Due to low accumulated chromatic dispersion (CD), no transmission penalty is observed. In addition, the sensing pulse train had no impact on performance, proving the compatibility of data transmission with sensing. At nominal received power of −17 dBm, the PAM4 system achieved BER below the threshold of 3.8×10^{-3} for 7% overhead hard-decision forward-error correction (FEC), so a net data rate >10 Gb/s was achieved.

To test the operation of the DAS, we connected two 12-m long piezoelectric fiber stretchers (PZ-FS) between the splitter and two DFs (Fig. 1). The fiber stretchers are driven with sine waves at frequencies of 100 Hz and 133 Hz, respectively. The RSOAs at the two ONUs are toggled on/off sequentially so one sensing pulse measures DF 1, the next pulse measures DF 2, etc., achieving an acoustic sampling rate of 5 kHz for each fiber, allowing acoustic frequencies up to 2.5 kHz to be measured. The OTDR from Rayleigh backscatter was coherently detected and captured by a digital sampling scope (DSO) at the OLT. Offline digital signal processing (DSP) was used to estimate dynamic changes in optical phase caused by vibration at every fiber position. The DSP operations include resampling, filtering, and DSP emulation of an interferometer with differential length of 20 m. We normalized the power of the differential beat signal at every distance, followed by bandpass filtering to create "waterfall plots" showing the time-evolution of optical phase amplitude induced by vibration at every fiber position.

Fig. 2(c) shows the optical phase evolution measured at the position of the PZ-FS at each DF. Sine waves of high fidelity with amplitudes of ~ 4.3 rad are observed when the PZ-FS drive signal was set to 5 V amplitude. Fig. 2(d) shows the phase spectrum at the same fiber positions. The noise floor corresponds to a strain level of ~ 0.35 $n\epsilon/\sqrt{\text{Hz}}$. We swept the amplitude of the PZ-FS drive signal on DF 1 and measured the amplitude of the optical phase. The results are shown in Fig. 2(e).

Finally, we used the DAS to measure real world vibrations by replacing the PZ-FS on DF 1 with a 100-m long outdoor optical fiber cable which was buried below ground at a depth of ~ 30 cm. We measured vibrations generated by (a) walking and (b) cycling at a distance of ~ 1 m from the buried cable, and (c) driving at a distance of ~ 5 m from the cable. Fig. 3 shows waterfall plots recorded by the DAS, and optical phase evolution at the positions shown. The speed of the vibration source can be inferred from the slope of the waterfall plot: steeper/shallower slopes correspond to slower/faster movements, respectively. The speeds of walking, cycling and driving were around 1.0 m/s, 3.5 m/s and 10 m/s, respectively.

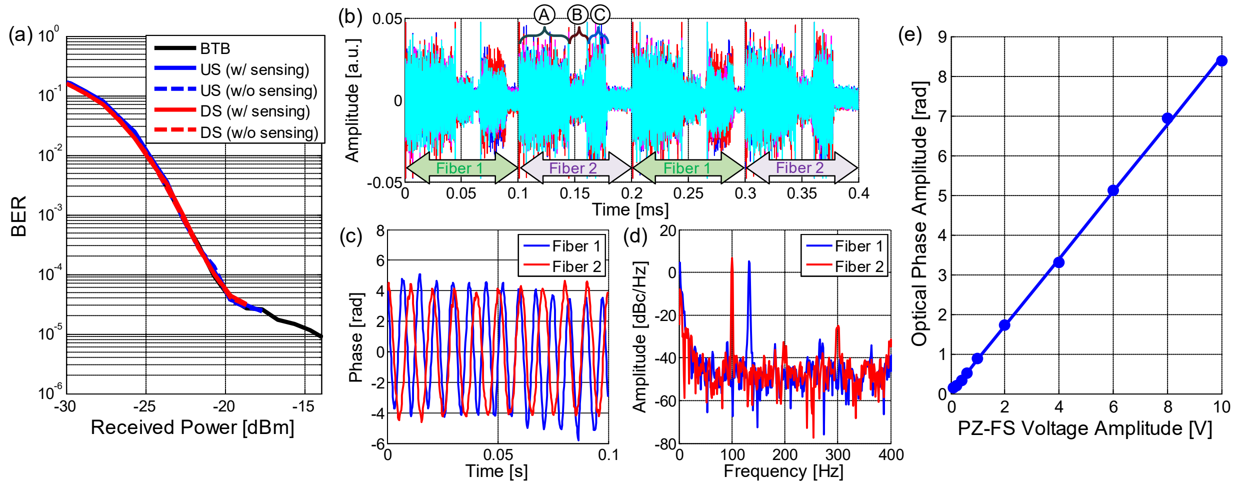

Fig. 2. (a) BER vs received power for 6-Gbaud PAM-4 signal; (b) OTDR trace measured at the OLT when the SOAs at ONU 1 & 2 are switched on sequentially; (c) Optical phase evolution and (d) phase spectrum on DF 1 & 2; (d) Optical phase amplitude vs PZ-FS voltage amplitude.

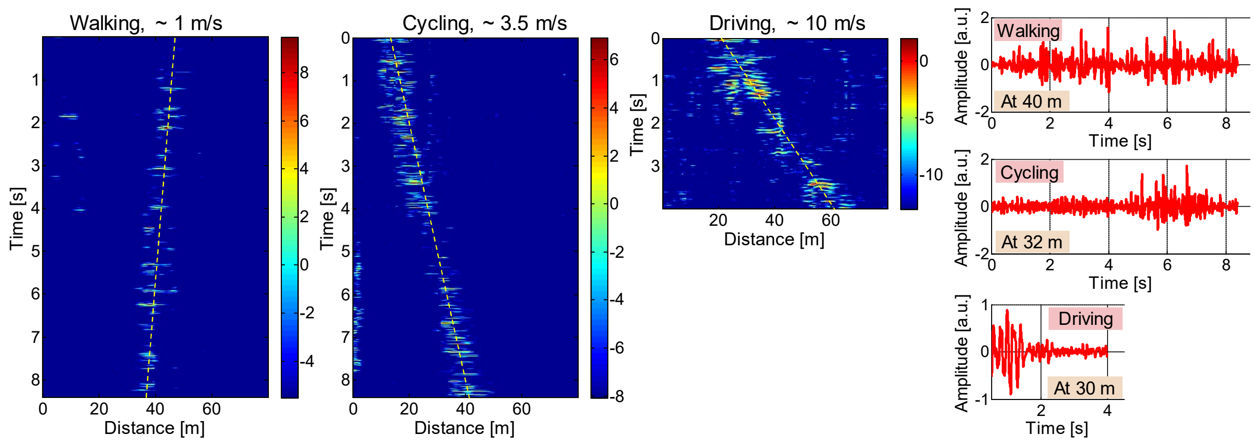

Fig. 3. Waterfall plots recorded for walking, cycling and driving, using DAS based on coherent detection of Rayleigh backscatter; and phase amplitude traces at fiber positions impacted by the vibration. The speed of the vibration source can be inferred by the slope of the waterfall plot.

4. Conclusions

We demonstrated a PON architecture which allows simultaneous mobile front-haul transmission and distributed fiber-optic sensing of each individual distribution fiber. The enabling technologies are RSOAs placed at ONUs which can be sequentially turned on/off to generate a backward-propagating sensing pulse that can interrogate its distribution fiber. The sensing channels and the upstream/downstream data channels coexist on three different wavelengths. We successfully demonstrated Rayleigh-based distributed acoustic sensing (DAS) using this architecture.

5. References

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