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Sensing Applications in Deployed Telecommunication Fiber Infrastructures

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Abstract *TLC-compatible coherent interferometric strategies applied to already deployed fiber networks are presented to provide not only civil structures health monitoring and traffic sensing, but also diagnostic and surveillance of the infrastructure integrity and damages localization, demonstrating fruitful synergy between telecommunication and sensing applications. ©2022 The Author*

Introduction

The ubiquitous optical fiber infrastructure installed for telecommunication purposed is becoming such as a "utility" to interconnect all the users to the Internet. This infrastructure, already deployed not only for the core networks and also in the metropolitan context, represents a precious asset for a pervasive and smart monitoring: its value can be enhanced by introducing novel potential sensing applications, leveraging the existing optical communication network. The exploitation of the fiber plan can be useful to control and supervision of the telecom fiber infrastructure integrity, considering that today 60% of OPEX is spent for physical maintenance; to monitor different aspects of traffic (car speed, congestion) and facility safety in railways and motorways; for detection of large breaches and damages in civil structures (buildings and bridges); for early earthquake detection for preventative operation; for utilities health monitoring (leak and fault in water and oil/gas pipelines); for distributed diagnostics and surveillance in "smart city" scenarios (landslides, digging, border intrusion).

Interrogation systems based on the well-known fiber Bragg gratings (FBGs) are devoted just to monitor a limited number of measurement points and need the invasive introduction of special sensing components. In case of a significant number of measurement points in the link, complex solutions such as distributed acoustic sensing (DAS) systems based on phase-resolved time domain reflectometry are currently employed. At the research level, DASs have been successfully applied to seismic monitoring [1]. In the metropolitan environment, few examples have been proposed so far [2-6] to monitor in real-time the vehicle speed and car density in a road and mechanical perturbations in civil buildings, by using directly the installed telecommunication network as sensing medium. The coherent detection scheme employed to receive the telecom data signals in very high capacity coherent systems in the core network is an alternative approach to effectively achieve the spectral analysis of light polarization: some examples [7,8] employing commercial transcontinental submarine cables have been recently proposed to detect seismic waves in a very-low environmental noise context.

For an extensive application of optical sensing in the pervasive fiber infrastructure installed in the urban and sub-urban area it is mandatory to apply sustainable solutions, in terms of cost, energy efficiency and reliability, guaranteeing also the transparency with the propagation of the telecom data signals. The adoption of interferometric approaches allows to develop simple sensing solutions, assuring good resolution and accuracy without requiring complex digital signal processing and expensive apparata. The capabilities of sensing interferometric solutions are here demonstrated, exploiting them in some fiber infrastructures already deployed by Italian operators in the city of Turin and along with the rail line in the North of Italy to monitor the traffic and to detect and even localize the onset of dynamic events in civil structures and in the entire infrastructure itself.

Michelson interferometer based solutions for buildings health monitoring, traffic sensing and integrity surveillance

An interferometric approach based on the Michelson scheme can be adopted for pervasive monitoring of health of civil buildings and facilities in order to identify anomalies that may indicate the beginning of a structural failure. We consider the application of this scheme to the passive optical network (PON), as reported in Fig. 1 right, where each building is directly fiber-to-the-home (FTTH) connected to the central office (CO). At the user side, two optical ports of the last PON splitter are not devoted for network units (ONUs), but for monitoring the building integrity [9].

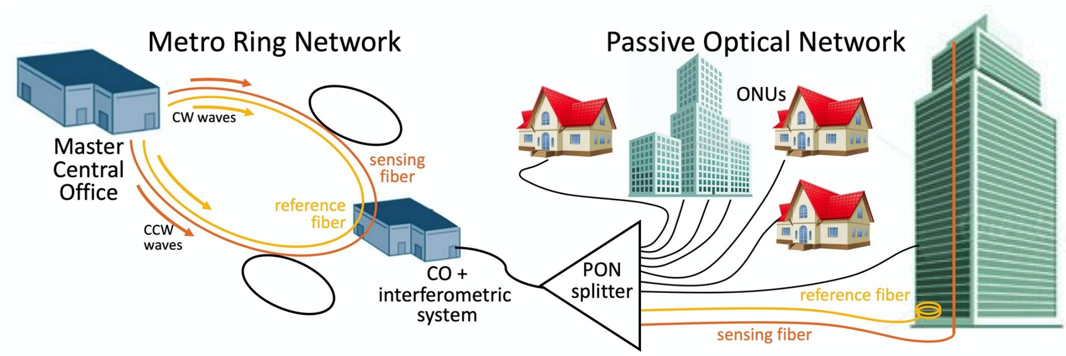

Fig. 1: On the right the PON, where two splitter output fibers terminated with FRMs are reserved to sensing, operating as a Michelson interferometer. On the left the metro ring network, operating as a dual MZI in a loop configuration for the wavelength reserved to sensing, enabling localization.

The fibers connected to these two outputs constitute the sensing and reference arms of the Michelson interferometer. The sensing fiber is laid on the structure to be monitored, while the reference arm is isolated. The sensing and reference fibers are terminated with Faraday rotator mirrors (FRMs) to back-reflect the radiation, retracing the signal polarization [10]. The trunk fiber connecting the CO to the splitter is common to the sensing and reference arms and hence does not introduce any phase noise contribution. According to the standard, the downstream telecom data traffic remains in the O band, while the wavelengths in the C band can be exploited for the sensing signals reflected by the FRMs.

A preliminary assessment of this interferometric solution was performed using an urban infrastructure of single-mode fiber (SMF), 11-km long, deployed in the city of Turin, Italy, by one of the Italian FTTH operators for telecom applications. At the CO the CW radiation at 1550 nm is added to the downstream 10-Gb/s NRZ signal at 1310 nm and the reflected sensing signal is here directly detected. The impact of the PON splitting ratio on the accuracy in the vibration monitoring was evaluated, also in presence of Rayleigh and Brillouin backscattering [11]. For 1x16 splitter, 17% of strain accuracy was achieved, still acceptable for the evidence of the onset of a critical event in the monitored building. Thanks to this interferometric solution, many buildings and skyscrapers, already FTTH-connected to the access network, can even operate simultaneously as seismologic optical “antennas” for the early earthquake detection in the urban area.

The same interferometric sensing scheme was experimented in a fiber infrastructure deployed along the railway in the north side of the Lake Iseo, Lombardia, from an Italian telecom provider, to achieve traffic monitoring and the surveillance of the rail integrity with early warning of possible risks. Two SMF fibers of the 48-fiber cable installed in a conduit under the sidewalk that runs alongside the railroad tracks (Fig. 2) are used to realize the Michelson interferometer, operating as sensing and reference arms.

Fig. 2: 48-fiber cable in the conduit under the sidewalk running along the railroad tracks.

In this configuration, the two fibers accumulate the same common mode environmental noise, cancelled out at the receiver. Actually, also the reference arm is affected by the events to be measured, yet a slight difference in the geometrical arrangement of the two fibers inside the cable is sufficient to still reveal them. In particular, events such as rockfall, travelling trains, pedestrians crossing the track can be discriminated from the temporal evolution of the signal energy evaluated by two different integration steps, called respectively short- and long-term energy (STE and LTE) [12]. We tested a link of 7 km, connecting two railway stations, in one of which the monitoring system [13] was placed. Fig. 3 reports an example of LTE of the signals acquired with the Michelson-interferometer based solution, in correspondence of the passage of two trains travelling in opposite directions, showing a similar shape, but reversed in time on the way back. The considered 7-km railway section also includes several railroad crossings, where the passage of cars can be monitored to get an indication of the traffic. Fig. 4 shows the STE of the acquired interferometric signal indicating the crossing of a car, where the characteristic 4-peak pattern is visible, caused by the contact of the two tracks with the front car wheels first and then with the rear car wheels. The sensing system is able to detect also the rock fall, dangerous for the passage of the train: from the station the measured data are sent via Ethernet to be remotely processed in real time in order to notify possible alarms.

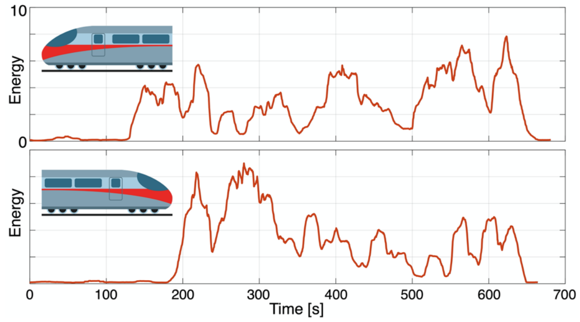

Fig. 3: LTE signals corresponding to the train passage on the way there (top) and on the way back (bottom).

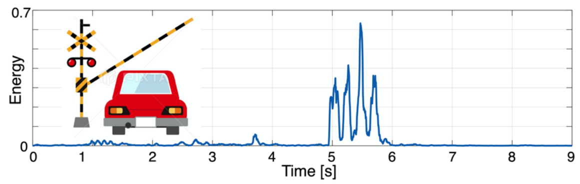

Fig. 4: STE signal corresponding to the car passage on a railroad crossing.

Mach-Zehnder interferometer based solutions for dangerous events localization

Thanks to a ring topology, also the localization of the onset of a dangerous event causing a possible damage or breakage of telecommunication fiber infrastructure can be detected. We exploit a dual Mach-Zehnder interferometer (MZI) arranged in a loop configuration [14], where two fibers of the same ring cable operate as sensing and reference arms (Fig. 1 left). For localization purpose, not only the clockwise (CW) waves travelling in the two arms of the interferometer, but also the counter-clockwise (CCW) waves counterpropagating in the MZI are considered. The event localization is achieved evaluating the time delay between the two counterpropagating signals at the receivers.

This MZI scheme was experimented in a 32-km SMF ring in Turin deployed metropolitan network, where WDM 50-GHz spaced telecom data channels at 10 Gb/s in the C band propagate in the ring. Just one WDM wavelength is devoted to the sensing signal. The arrangement of the sensing and the reference fiber in the same embedded cable cancels the strong common mode noise due to the city environment. By employing very simple off-the-shelf components and instruments, such as a programmable 20Msample/s sampling board, 10-m spatial resolution in the event localization was demonstrated without the need of complex and expensive distributed sensing systems [15]. Fig. 5 shows an example of localization of the onset of the dynamic even (corresponding to a sudden blow to the floor, under which the fiber cable is deployed). The same dual MZI loop scheme can be adopted in the railway monitoring described above, in case of request of localization of the dangerous event with a resolution of few meters.

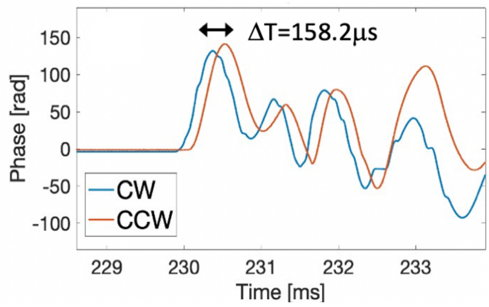

Fig. 5: Localization after 1 km of the onset of a dynamic event through the measure of the time delay in the 32-km long deployed ring.

Conclusions

Unconventional TLC-compatible sensing strategies based on interferometric schemes are applied to provide a real-time pervasive monitoring by employing already deployed telecommunication fiber links. The exploitation for sensing applications of the installed fiber network, in future even constituted by special fibers, such as multi-core fibers, gives an added value to the optical telecom asset. Some examples able to monitor the traffic and to detect and localize the onset of dynamic events in FTTH-connected structures and in the entire infrastructure itself have been presented, experimenting fiber cables already deployed in the urban and suburban area. The sensing monitoring is achieved preserving the coexistence with high-speed telecom data transmission. Reliable embedded sensing systems based on a simple interferometric implementation, without the necessity of complex and expensive solutions, are possible, providing a sustainable and fruitful synergy between TLC and sensing.

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