Chao Lu, Chair Professor and Director, Photonics Research Institute, The Hong Kong Polytechnic University

Prof. Chao Lu is currently Chair Professor of Fiber Optics in the Department of Electrical and Electronic Engineering, The Hong Kong Polytechnic University as well as director of the PolyU Photonics Research Institute. He has served as a faculty member in Universities in Singapore and Hong Kong for the past 33 years. Over the years, he has published extensively in major international journals such as Optics Express, Optics Letters, IEEE Photonic Technology Letters and IEEE/OSA Journal of Lightwave Technology. He has been organizer or technical program committee member of many international conferences. His current research interests are in the area of high capacity transmission techniques for long haul and short reach systems and distributed optical sensing systems. In addition to academic research work, he has had many industrial collaborative research projects and has a number of awarded patents. He is a fellow of the Optical Society(OSA).

ITU Workshop on “Evolution of Optical Networks for IMT2030 and Beyond”

Charles K. Kao Auditorium, Hong Kong Science and Technology Park (HKSTP)

20 November 2024, 15:00 - 18:00

Integrated Optical Communication and Sensing Systems

Chao LU

The Hong Kong Polytechnic University

Motivations

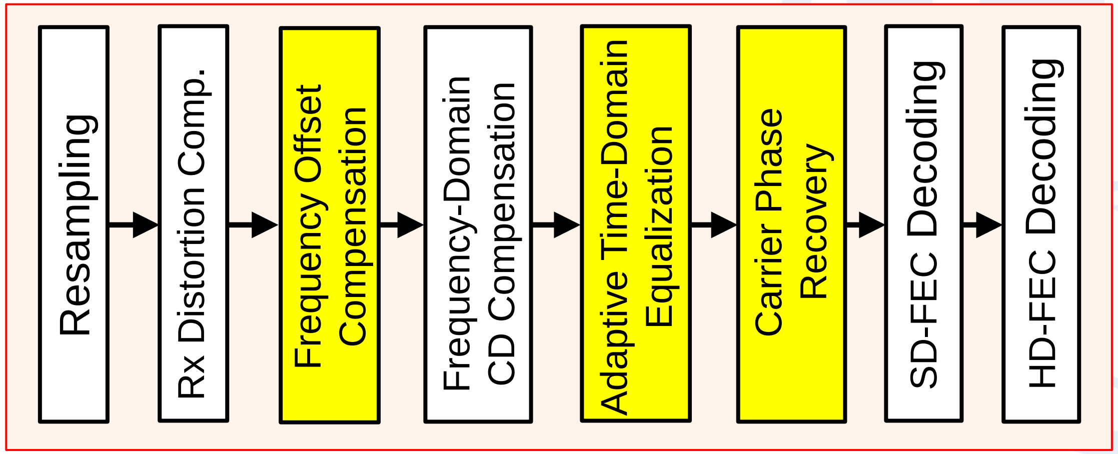
- There exists 5 billion kilometer of installed optical fiber worldwide.
- Wide amount of terrestrial fiber and submarine fiber as well as fiber for data centers and fiber to the home systems(FTTH)
- There are two main motivations for integrating sensing functionality into optical communication systems:
    - Using the communication fiber to provide additional functionality in addition to communication services. This may bring extra revenue for service providers or other owners of optical fiber.
    - Due to the huge amount of data carried by communication fiber, any disruption to communication services will result in significant amount of data loss. Many problems in optical networks are due to variation of physical parameters, such as unauthorized digging, vibration caused by strong wind or fast polarization variation due to lightning. The ability to have early detection of these activities will prevent service disruption.

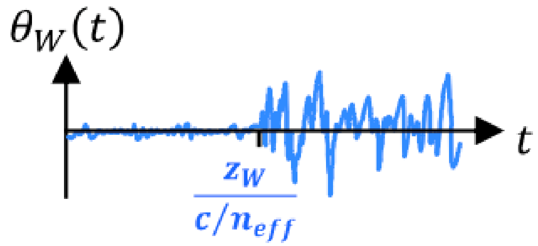
E. Ip et al., "Using global existing fiber networks for environmental sensing," Proc. IEEE, 10(11), 1853-88 (2022).

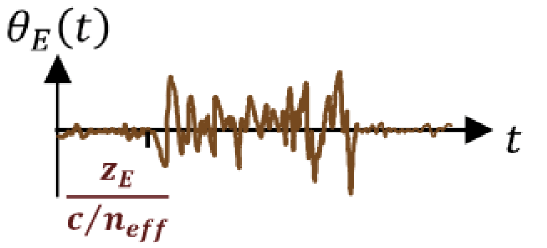
How to Achieve It?

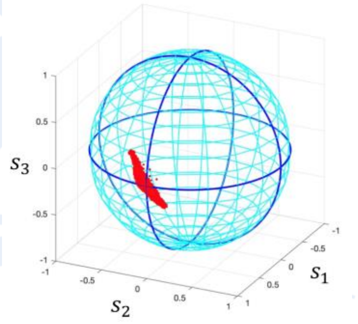
- External disturbance will affect phase and polarization of light in optical fiber, since in current coherent optical communication system, data is encoded into phase and polarization of transmitted light. Through detecting variation of light phase and polarization, external disturbance can easily be detected.

Generic Coherent RX DSP Architecture







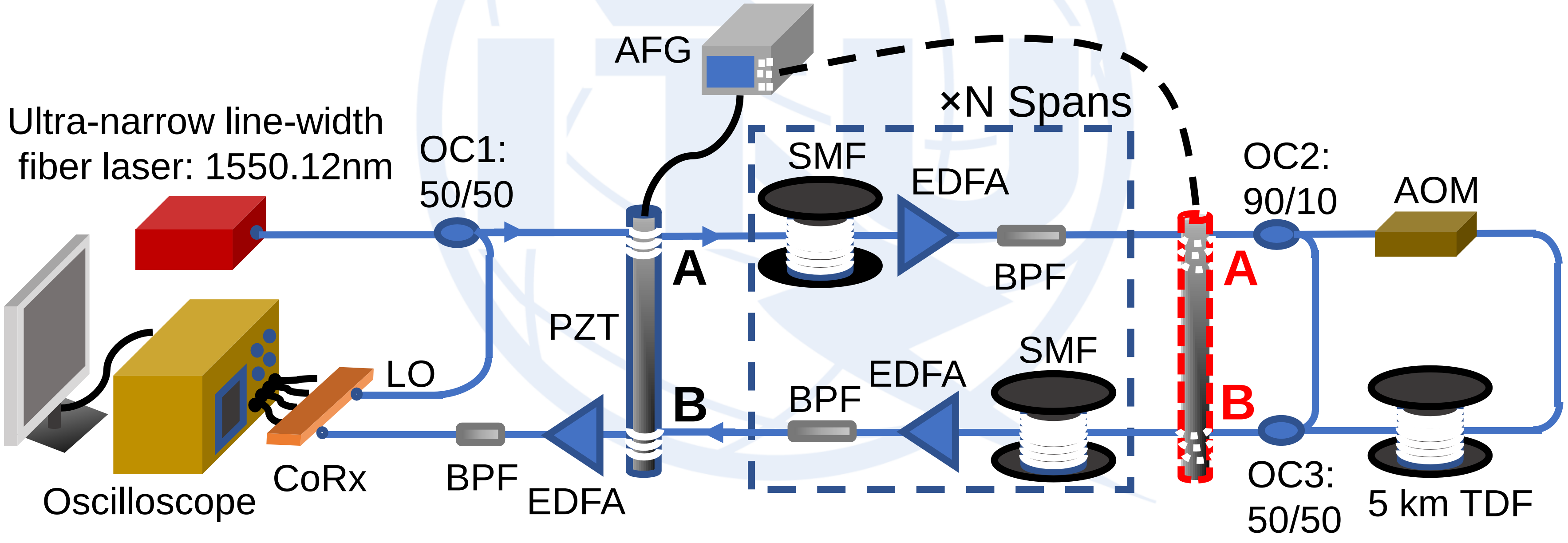


Stokes vector variation for an x-polarized input with vibration[2]

1. Ezra Ip, Yue-Kai Huang, Glenn Wellbrock, Tiejun Xia, Ming-Fang Huang, Ting Wang, and Yoshiaki Aono, "Vibration Detection and Localization Using Modified Digital Coherent Telecom Transponders," J. Lightwave Technol. 40, 1472-1482 (2022)
2. Mecozzi, A., Antonelli, C., Mazur, M., Fontaine, N., Chen, H., Dallachiesa, L., & Ryf, R. (2023). Use of optical coherent detection for environmental sensing. Journal of Lightwave Technology, 41(11), 3350-3357.

How to Achieve It?

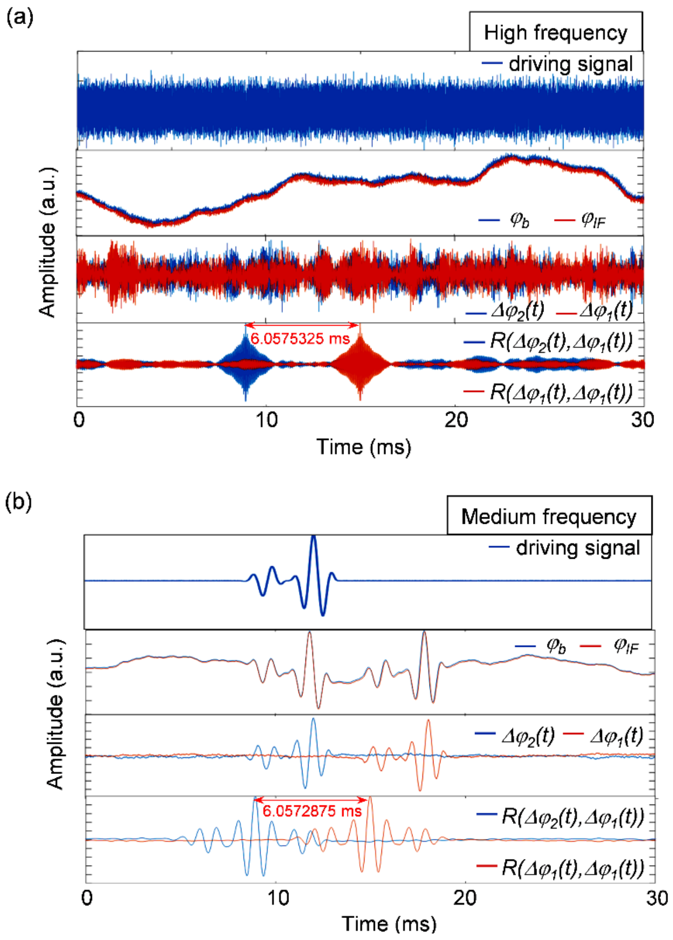
- Through detecting variation of light phase and polarization, external disturbance can easily be detected. To provide position information, we can use two bidirectional transmission fiber, by calculating correlation of two phase changes at the same location, location information can be obtained. However, transmission capacity in one direction will be wasted.



Y. Yan, F. N. Khan, B. Zhou, A. P. T. Lau, C. Lu and C. Guo, in *Journal of Lightwave Technology*, vol. 39, no. 7, pp. 2241-2249, 1 April1, 2021

Forward Transmission Based Scheme

- Construct two differential phase signals:



Δt: time difference introduced by the TDF

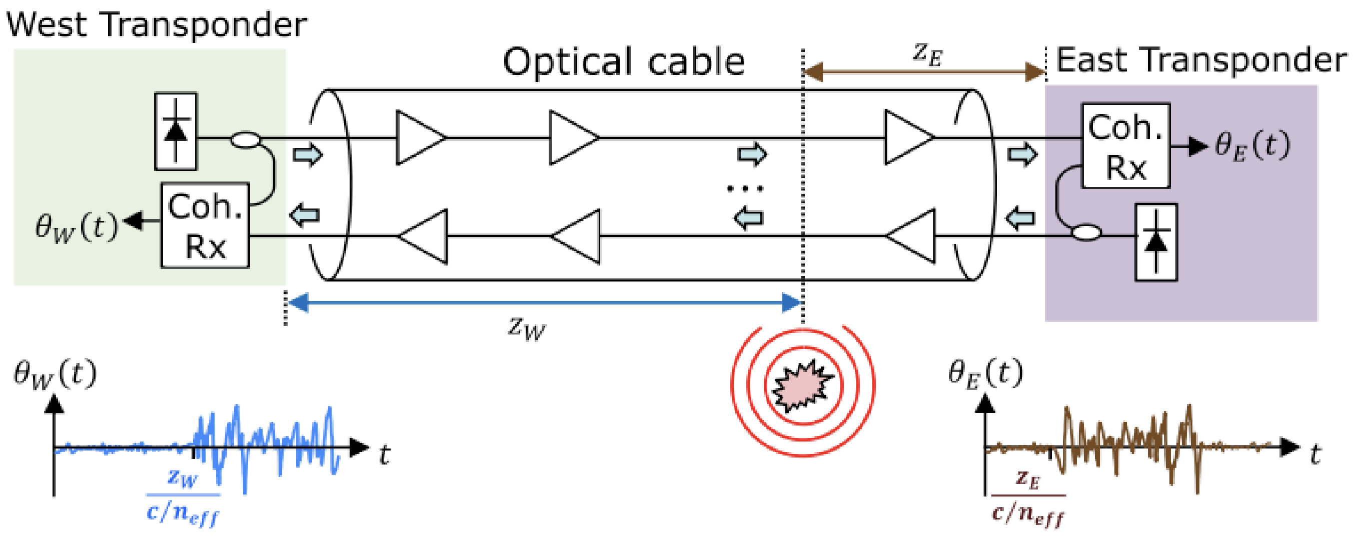
The length of the TDF should be smaller than the coherent length of the light source. In that case, the influence of the carrier phase noise can be neglected.

Two constructed phase differential signals:

Y. Yan, F. N. Khan, B. Zhou, A. P. T. Lau, C. Lu and C. Guo, in *Journal of Lightwave Technology*, vol. 39, no. 7, pp. 2241-2249, April, 2021

Forward Transmission Based Scheme

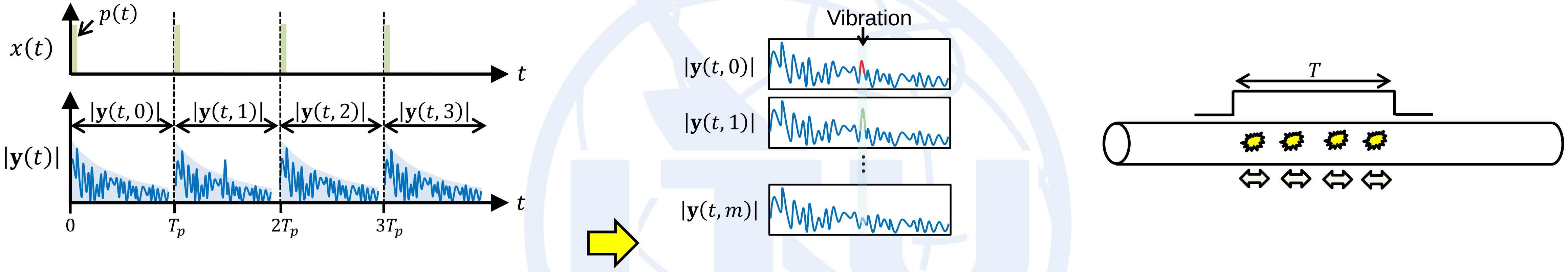
- Further work has shown it is possible to detect phases of communication signals in both directions and through perfect synchronization and correlation, sensing function can be realized.
- No realtime sensing is possible though.



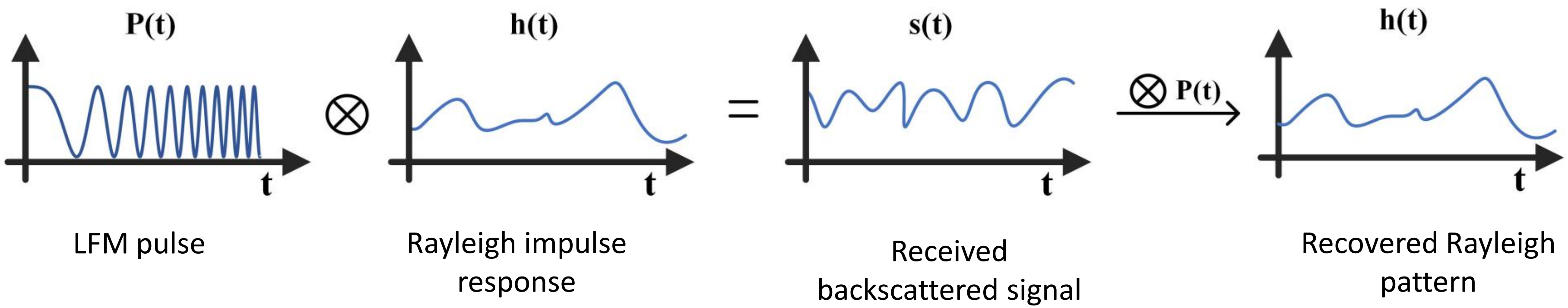
Ezra Ip *et al.*, "Vibration detection and localization using modified digital coherent telecom transponders," *J. Lightw. Technol.*, vol. 40, no. 5, pp. 1472–1482, Mar. 1, 2022

Distributed Acoustic Sensing(DAS) Based on Rayleigh Scattering

- Can be realized in time domain as a one dimensional LIDAR.



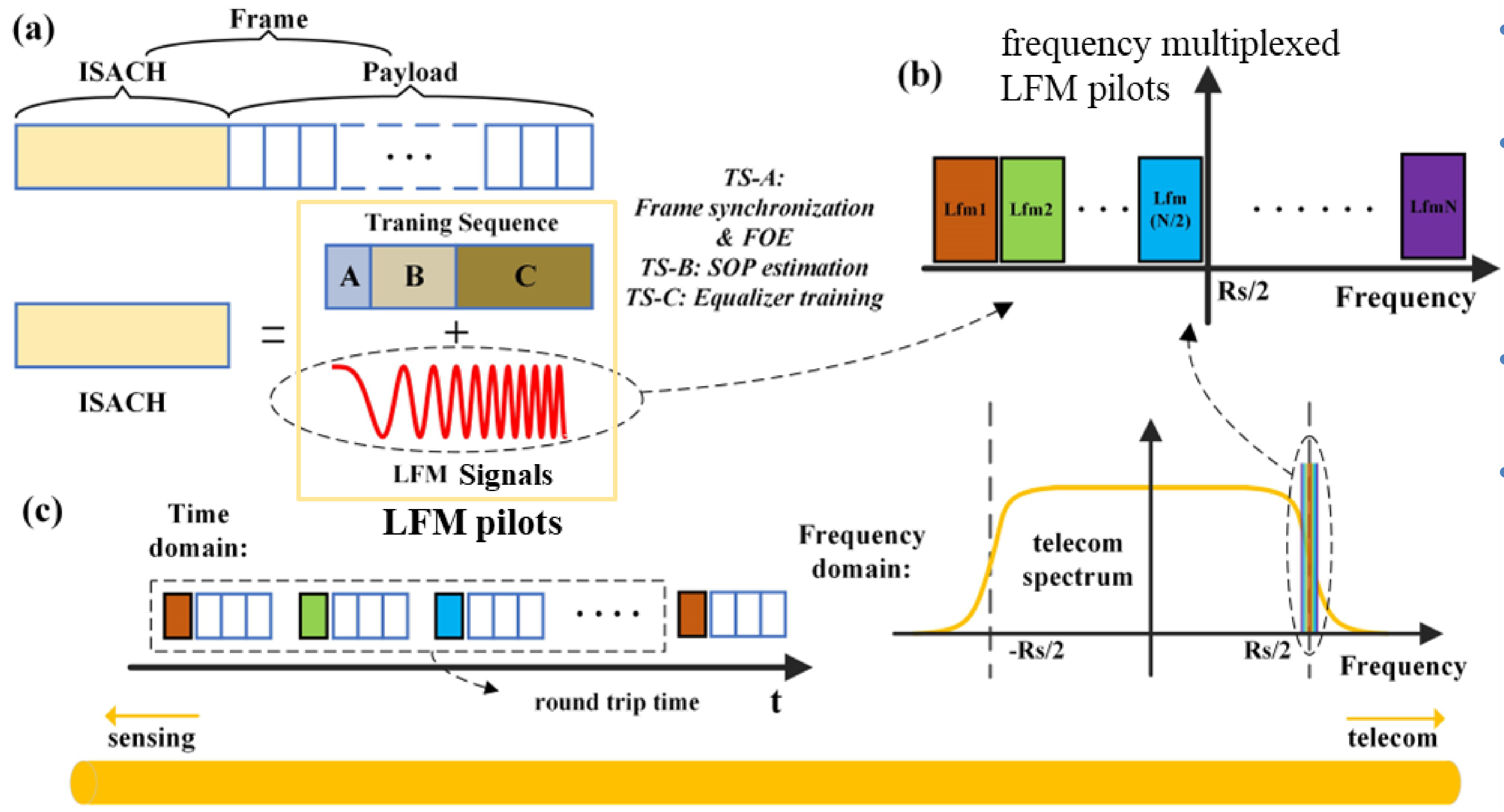
- Or through linear frequency modulated(LFM) pulse, like FMCW LIDAR



Ezra Ip, et al, "Using Global Existing Fiber Networks for Environmental Sensing," Proceedings of the IEEE, 111(11), pp. 1853-1888 (2022).

Integrate Communication and Sensing Signals

- Frame structure of integrated sensing and communication header (ISACH)

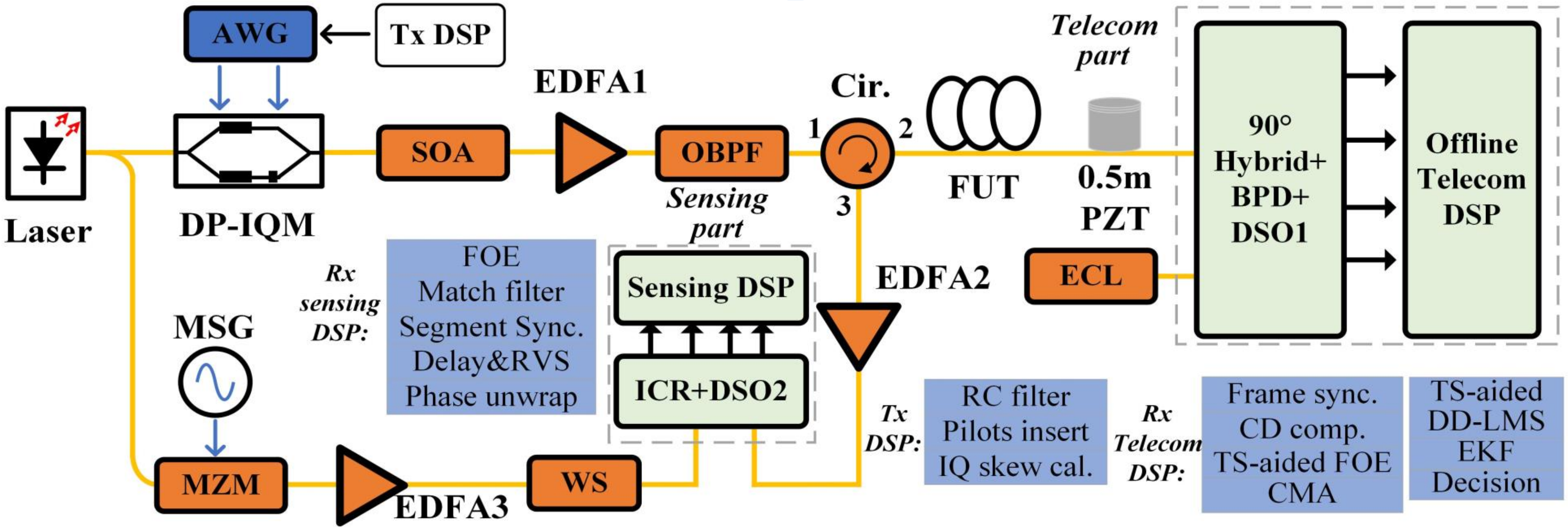


- Frequency division multiplexed DAS
- LFM pilots with different LFM center frequencies can be inserted in all the frames during a round trip time.
- Make use of the roll-off area of the telecom spectrum
- Help improve the sensing performance

Wang, J., Lu, L., Wang, L., Yan, Y., Tao Lau, A. P., & Lu, C. (2024). High-efficiency ISAC to enable sub-meter level vibration sensing for coherent fiber networks. In *2024 Optical Fiber Communications Conference and Exhibition, OFC 2024*

- Comm./Sensing realized in the same transmitter
- The crosstalk is suppressed as much as possible.

Integrate Communication and Sensing Signals



SOA: semiconductor optical amplifier. MSG: microwave signal generator. WS: waveshaper. OBPF: optical bandpass filter.

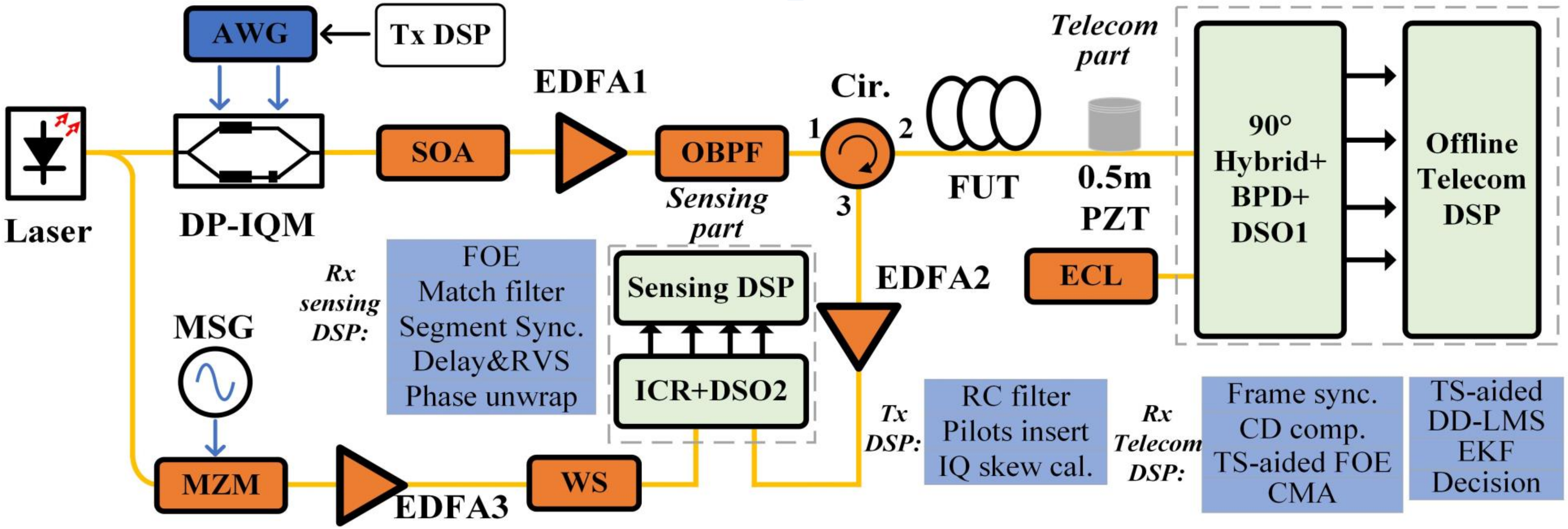
Laser linewidth	<100 Hz
AWG	92 GSa/s
DSO1	80 Gsa/s:
DSO2	2 Gsa/s

- Round trip time of 10 km fiber is 100 µs.
- An SOA is used to cut off the signal to avoid the superposition of Rayleigh backscattered signals.
- A PZT is used to stimulate vibrations

TS-A	256 periodic QPSK symbols	frame sync. & FOE estimation
TS-B	128 QPSK symbols followed by128 zeros	SOP estimation
TS-C	2048 QPSK symbols	taps pre-convergence

- ISAC head duration is 182 ns.
- Telecom: dual polarization 60 GBaud 16QAM with a roll off factor of 0.02
- Sensing: LFM signals centered at different frequencies with 250 MHz bandwidth (corresponding to 0.5m resolution).

Integrate Communication and Sensing Signals



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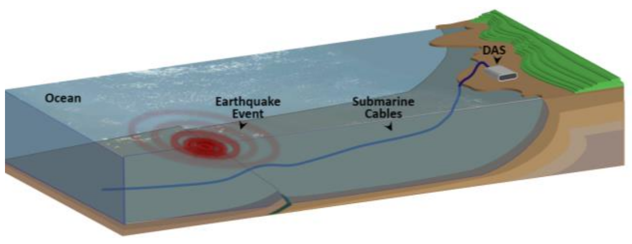
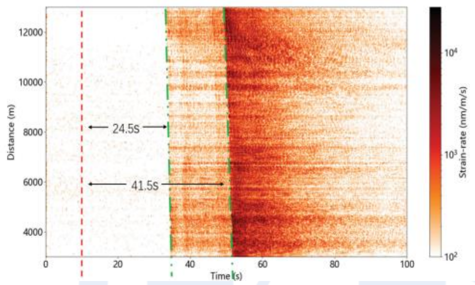
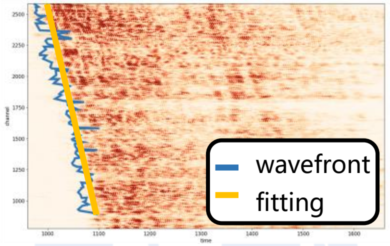
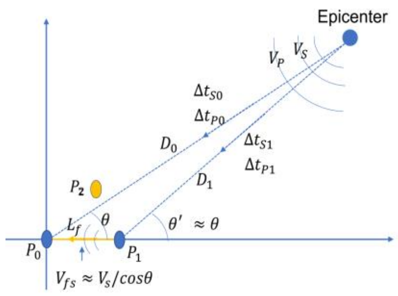
Integrate Communication and Sensing Signals

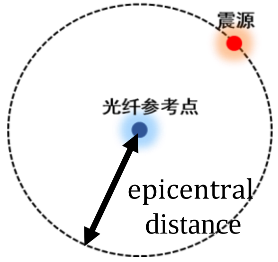
- Sensing using submarine communication cable.

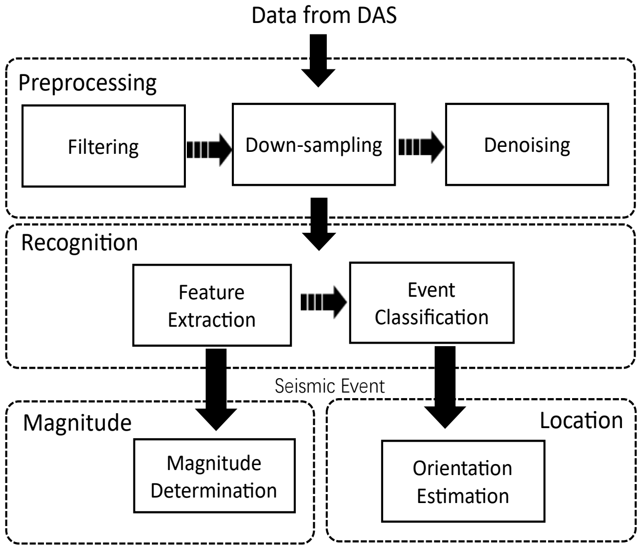










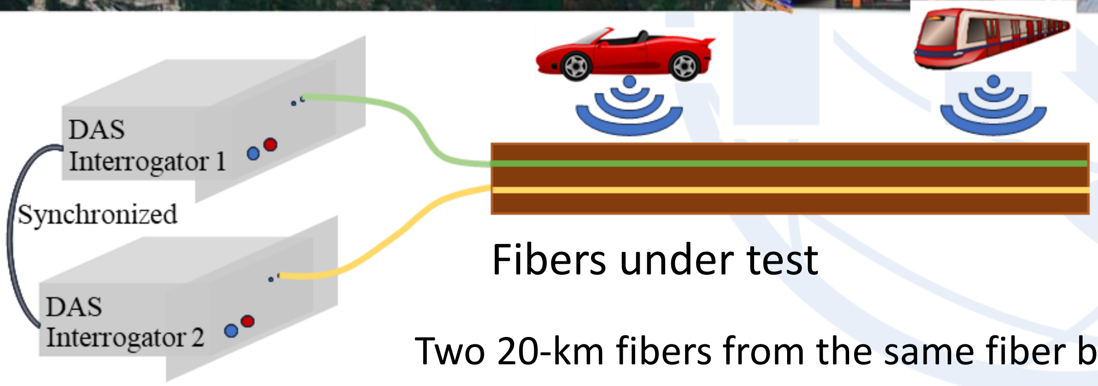


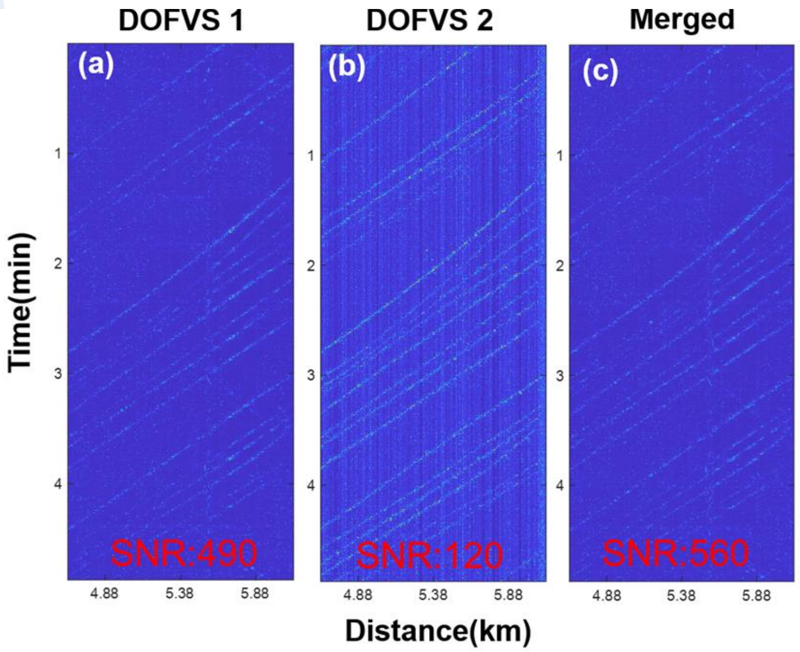
No.	Location	Time	Mag.	Reported coordinate	Estimated coordinate	Error
1	Huizhou	22/3/14 02:28:48	4.1	(22.48°, 115.07°)	(22. 60°, 114.96°)	(0.12°, -0.11°)
2	The South China Sea	21/9/30 11:21:09	1.7	(21.84°, 115.06°)	(21.79°, 114.98°)	(-0.05°, -0.08°)
3	Zhongshan	22/2/20 06:11:00	1.4	(22.50°, 113.48°)	(22.59°, 113.54°)	(0.09°, 0.06°)
4	Dongyuan	22/8/16 20:39:44	2.4	(23.91°, 114.47°)	(23.90°, 114.39°)	(-0.01°, -0.08°)
5	Dongyuan	21/9/24 12:34:00	2.5	(23.91°, 114.50°)	(23.84°, 114.53°)	(-0.07°, 0.03°)
6	Dongyuan	21/9/4 15:51:52	2.5	(23.85°, 114.51°)	(23.84°, 114.53°)	(-0.01°, 0.02°)

S. Y. Chen, Z. H. Li*, et al. JLT, 2023.

Integrate Communication and Sensing Signals

Tunnel	Vehicles per day
Lincoln Tunnel [1] (New York)	120000
Cross-harbour tunnel [2] (Hong Kong)	103832
Kingsway Tunnel [3] (Liverpool)	45000





Two 20-km fibers from the same fiber bundle tube diameter ~ 24 mm with over 100 fibers.
The total length of the fiber is 20 km.
Two DAS interrogators: spatial resolution 3.5/3.75 m

[1] https://aamcar.com/lincoln-tunnel/
[2] https://atc.td.gov.hk/harbour
[3] Wikipedia:Kingsway Tunnel

Y. Yan, K Chandramouli, J. Zhang, C. Lu, A.P.T. Lau, "Multimodal Traffic Monitoring using Two Co-Routed Field Deployed Fibers in Metropolitan Environments, OFC 2024, M1K.4 , San Diego, USA, 2024

Conclusions

- Integration of sensing functionality will increase the value of deployed optical network. In addition, it may help to ensure reliable operation of high-capacity optical networks.
- Preliminary experiments have shown the possibilities. Further study is still necessary to choose the best approach.
- Many potential applications have been demonstrated with many future opportunities.

Thank you !