ICOP 2024 Italian Conference on Optics and Photonics

Invited paper

OVERVIEW ON OPTICAL SENSING TECHNIQUES OVER DEPLOYED TELECOM NETWORKS

Politecnico di Torino 1859

POLITECNICO MILANO 1863

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    - https://www.linkedin.com/company/surenet

Surveillance of the URban Environment exploiting deployed optical NETworks

PRIN2022 SURENET

- A. Rosa Brusin, G. Bosco, and P. Boffi are sponsored by the European Union under the Italian National Recovery and Resilience Plan (NRRP) of NextGenerationEU, partnership on 'Telecommunications of the Future' (PE00000001 - program 'RESTART').

PNRR RESTART

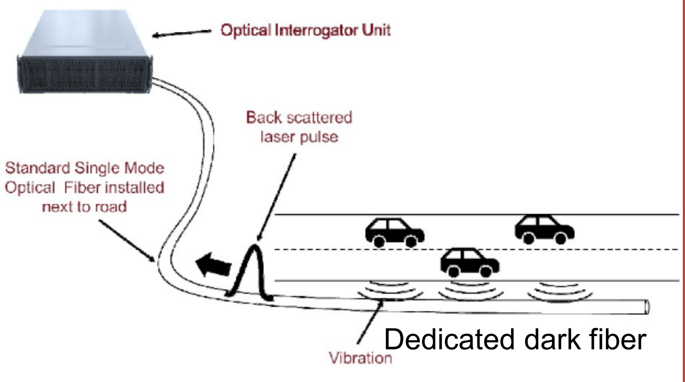
- Experiments were carried out in the PhotoNext Center laboratory at Politecnico di Torino www.photonext.polito.it

Focus of our work

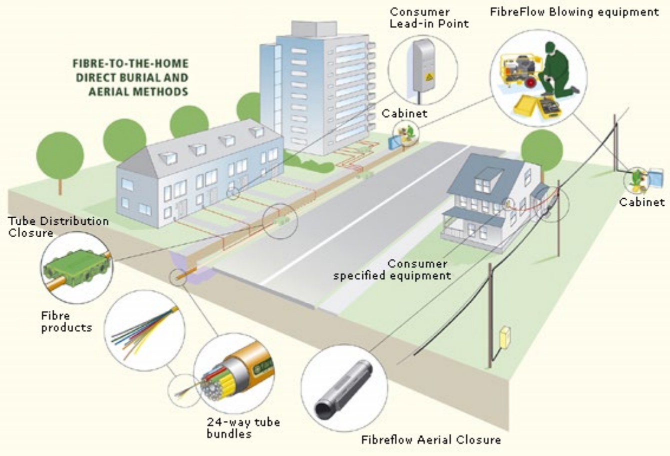
- An overview and taxonomy of **optical sensing over deployed telco fiber networks**

- Specific focus on
  - sensing techniques suitable for real time warning/alarm generation
    - fast processing (in the few seconds range)
  - physical layer compatibility and potential co-existence on the same fiber with standard DWDM telco

Traditional optical sensing



Deployed telecom fiber networks



Situation for today commercial solutions

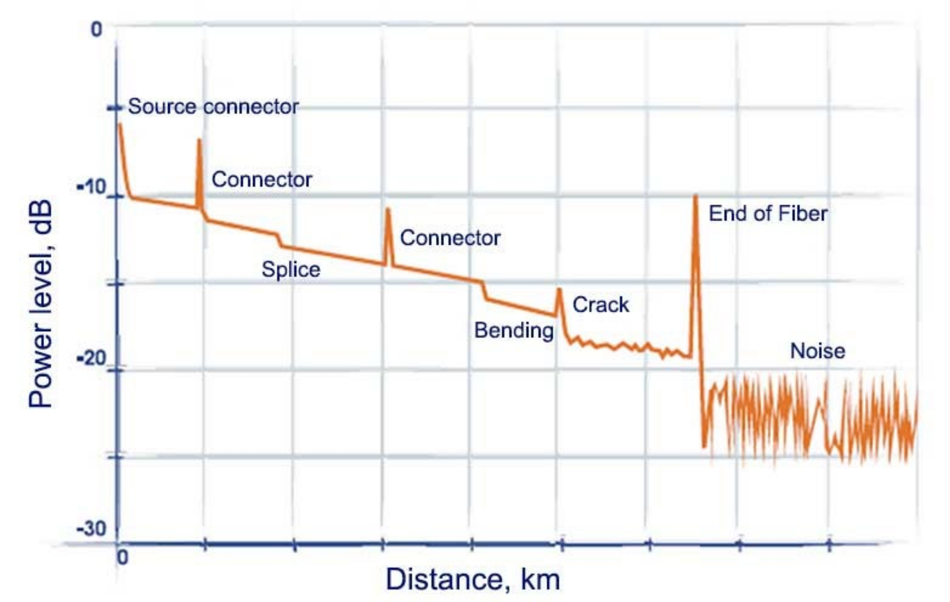
- Optical sensing over dedicated optical fibers for “special” applications
  - Oil and gas pipeline monitoring
  - Geotechnical and Structural Engineering
  - Power cable integrity and condition monitoring
  - Basic research experiments

- Different solutions available for distributed strain or temperature variations:
  1. Distributed acoustic sensing (DAS)
  2. Raman sensing
  3. Brillouin Sensing

What about sensing on telco fibers?

- So far, telecom network operators are using OTDR (optical time domain reflectometers) to monitor the physical status of their fibers
  - based on power-monitoring of Rayleigh backscatter

- Commercial OTDRs have acquisition time of the order of minutes
  - OTDRs give a “static picture” of the attenuation and reflections along the fiber link
  - Not suitable for mechanical vibrations monitoring



Quite cheap (200€ range)
Ubiquitously used by telco technicians

What's new in this field?

- Why telco fibers used ALSO as dynamic distributed sensors?
- Potential applications
  - Earthquake monitoring on undersea fiber cables
    - And more in general:
      - Tsunami early warning
      - Submarine surveillance (whales, large vessels, military submarines, etc etc)

OPTICAL SEISMOLOGY

Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables

Giuseppe Marra[1*], Cecilia Clivati[2], Richard Luckett[3], Anna Tampellini[2,4], Jochen Kronjäger[1], Louise Wright[1], Alberto Mura[2], Filippo Levi[2], Stephen Robinson[1], André Xuereb[5], Brian Baptie[3], Davide Calonico[2]

2018, DOI: 10.1126/science.aat4458

  - Mechanical vibration sensing for Smart Cities monitoring
    - Early warning of urban mechanical vibrations

One of the pioneers: Prof. Biondo Biondi, Stanford DAS project (started in 2016)
https://www.youtube.com/watch?v=cToYVUHKd0o

DOI: 10.1190/segam2021-3594539.1

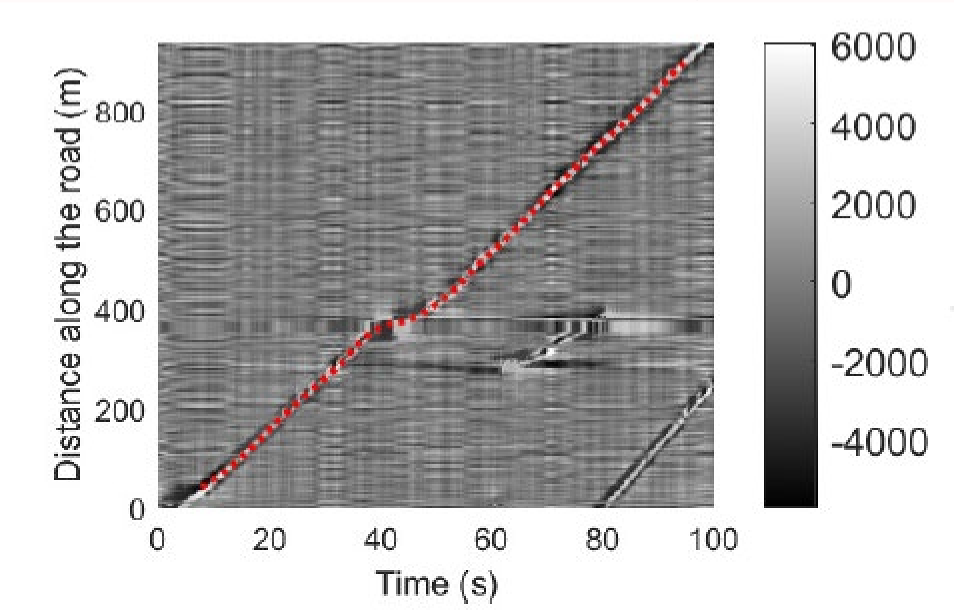
Scaling up to city-wide dark-fiber seismic arrays: lessons from five years of the Stanford DAS array project

Biondo Biondi, Robert G. Clapp, Siyuan Yuan, Fantine Huot, Stanford University*

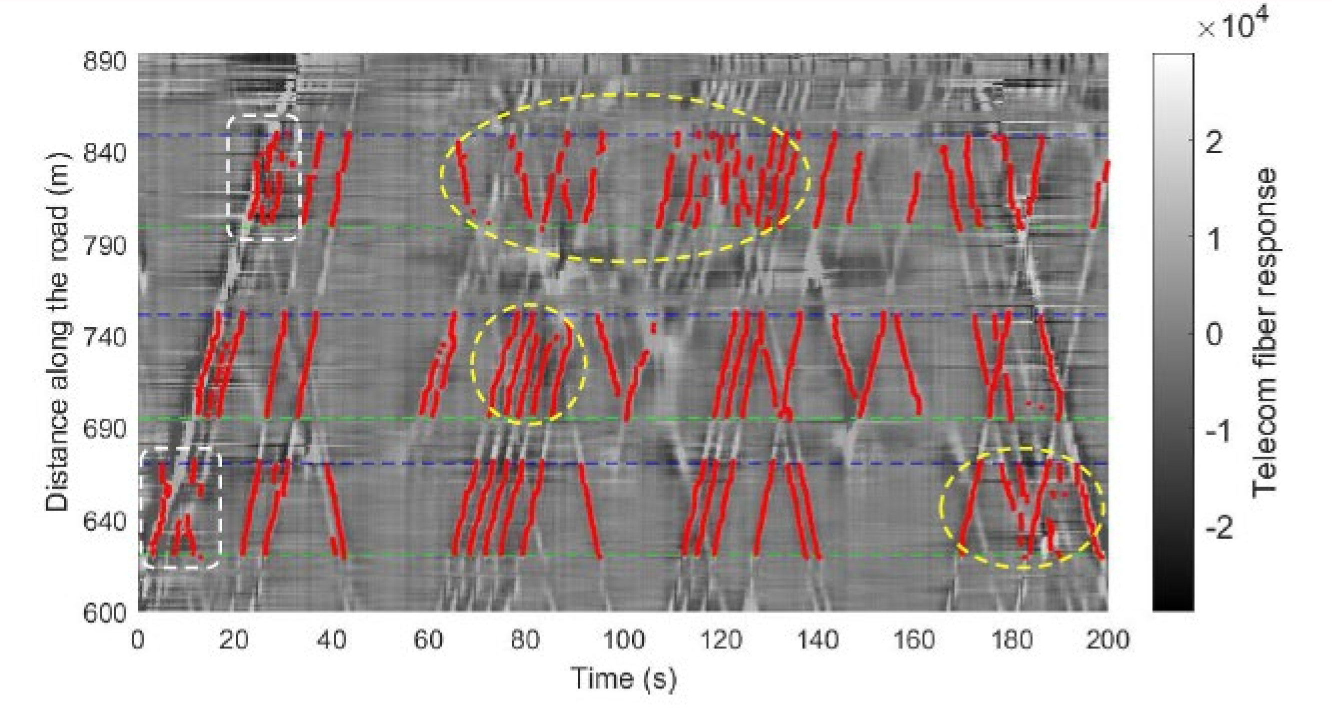
Published in 2021

Urban area applications

- From Stanford DAS project



Example of one car movement detection along a road in San Jose



Example of multiple cars movement detection along a road in San Jose

TelecomTM: A Fine-Grained and Ubiquitous Traffic Monitoring System Using Pre-Existing Telecommunication Fiber-Optic Cables as Sensors

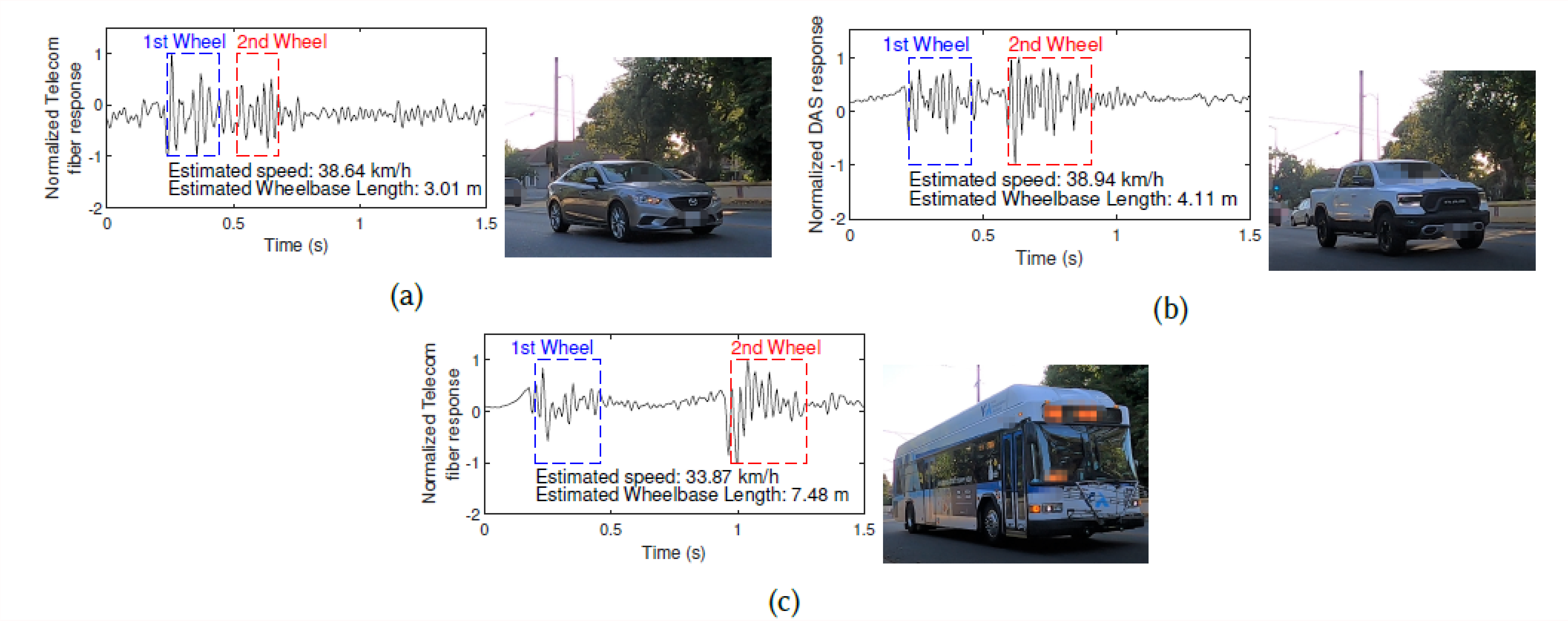
JINGXIAO LIU, Stanford University, USA
SIYUAN YUAN, Stanford University, USA
YIWEN DONG, Stanford University, USA
BIONDO BIONDI, Stanford University, USA
HAE YOUNG NOH, Stanford University, USA

https://doi.org/10.1145/3596262

Published in 2023

Urban area applications

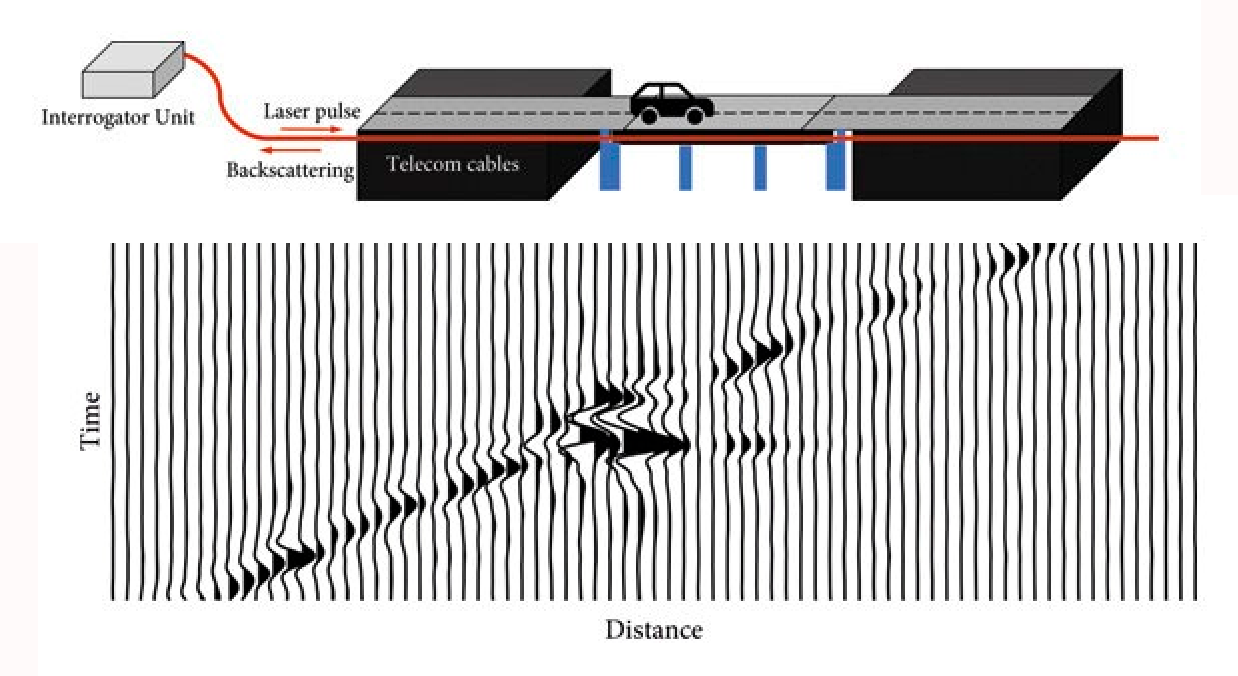
- From Stanford DAS project



Urban area applications

- From Stanford DAS project:

  structural integrity monitoring on bridges



- Telecom operators are also particularly interested in early-warning of potential fiber cuts

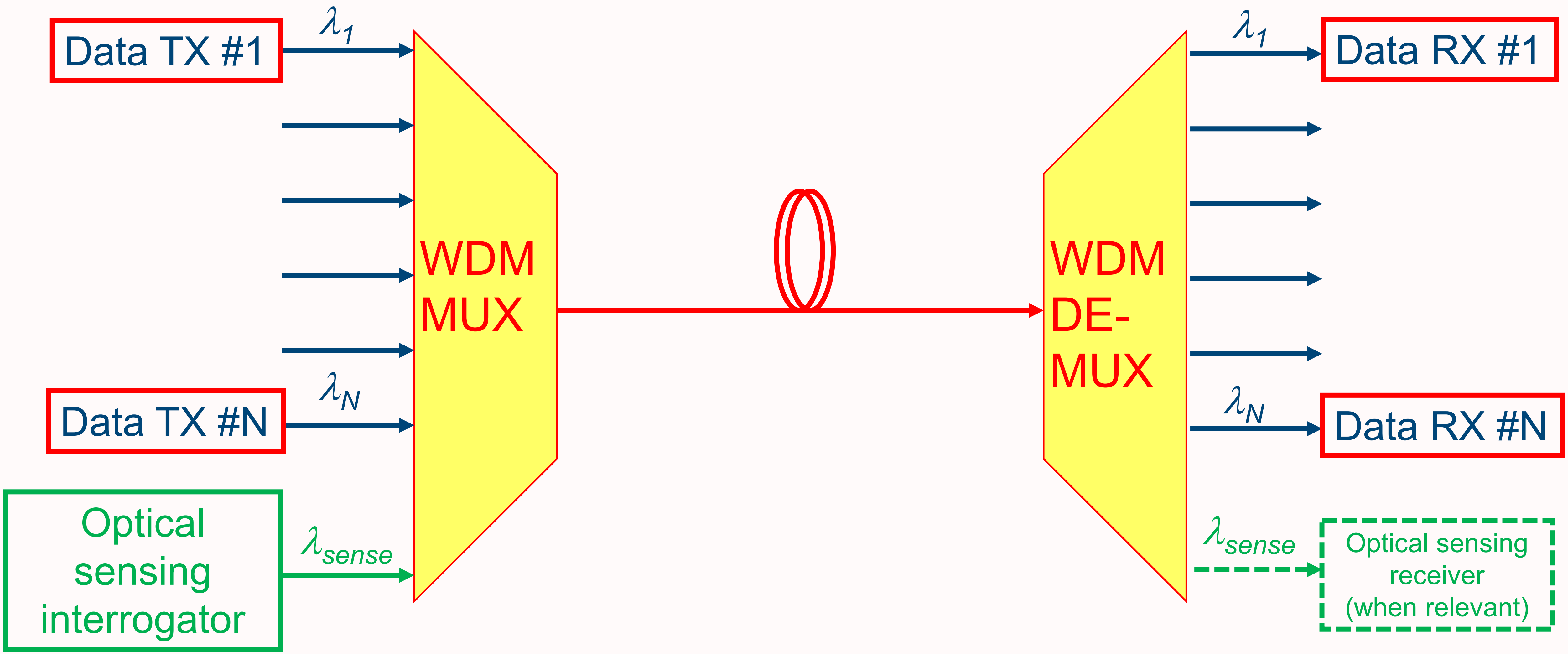
DAS is (by far) the most interesting sensing approach for distributed detection of “dynamic” events

Our work

- Ok… many interesting applications for optical distributed sensing in urban environment!

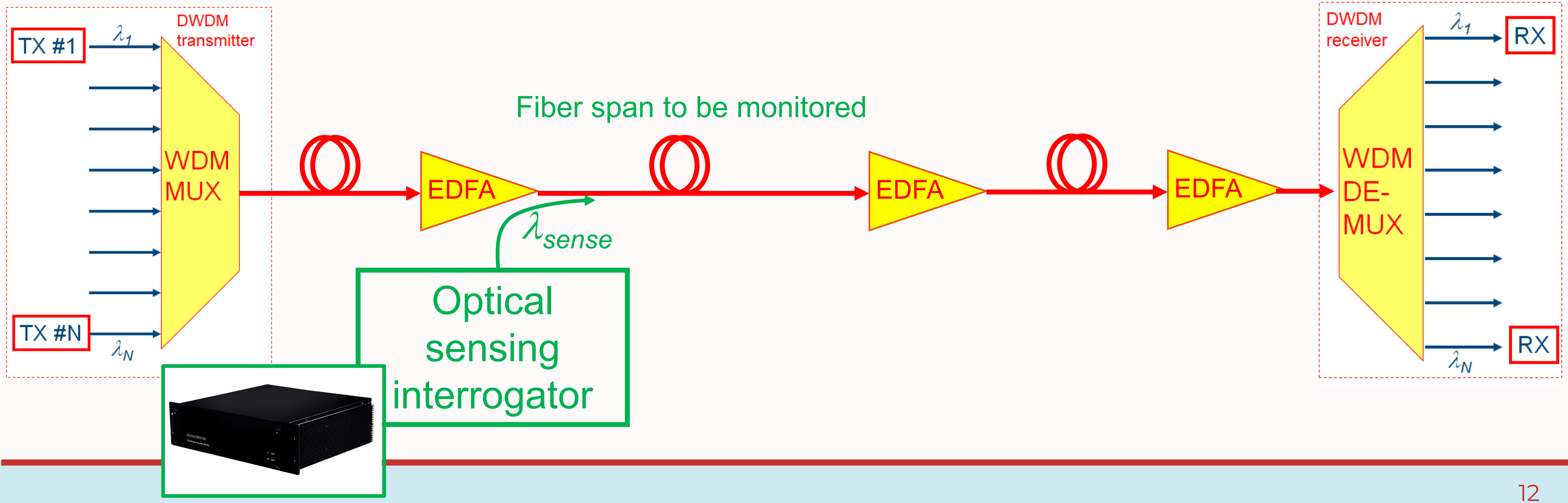
- **Our work**: analyze the compatibility of current optical sensing techniques AND data transmission on the SAME fiber
  - All examples presented in previous slides used dedicated dark fibers

The basic reference configuration



Distributed Acoustic Sensing (DAS)

- Let's start from **DAS… the "Queen" of distributed and time-resolved sensing**
- It works in back-reflection, so it will NOT pass through standard EDFAs
- <u>Single span distributed sensing is anyway possible</u>
  - Same as today "standard" OTDR monitoring,

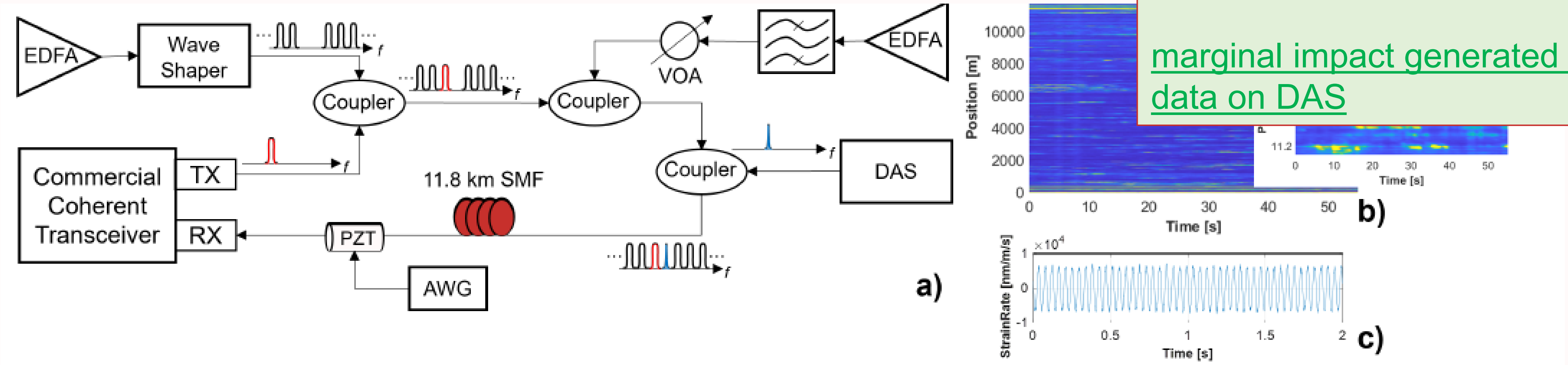


Distributed Acoustic Sensing (DAS)

- It requires only a narrow optical bandwidth, so it can be in principle be inserted on any available wavelength on ITU-T grid not used by data
- We performed some preliminary experiments on coexistence between a commercial DAS and DWDM coherent transmission (400G PM-QAM commercial transceivers)

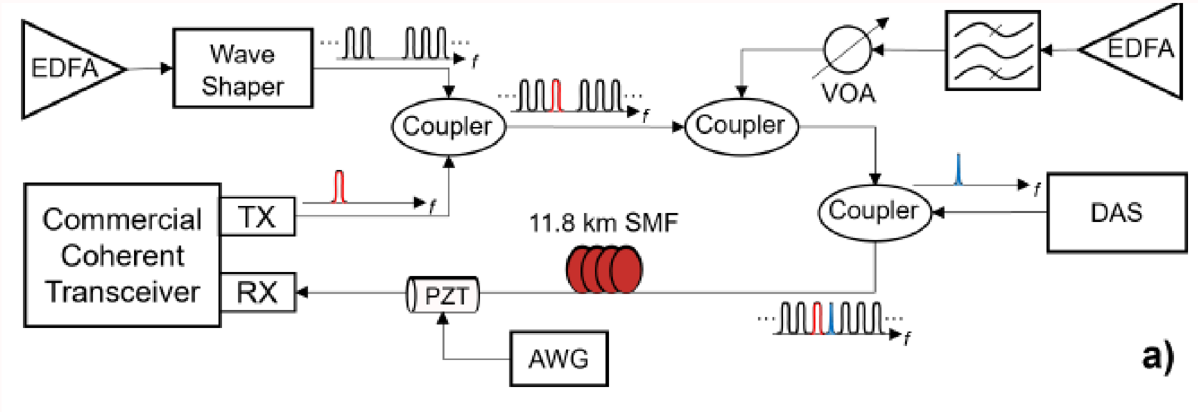
Main result of our experiment:

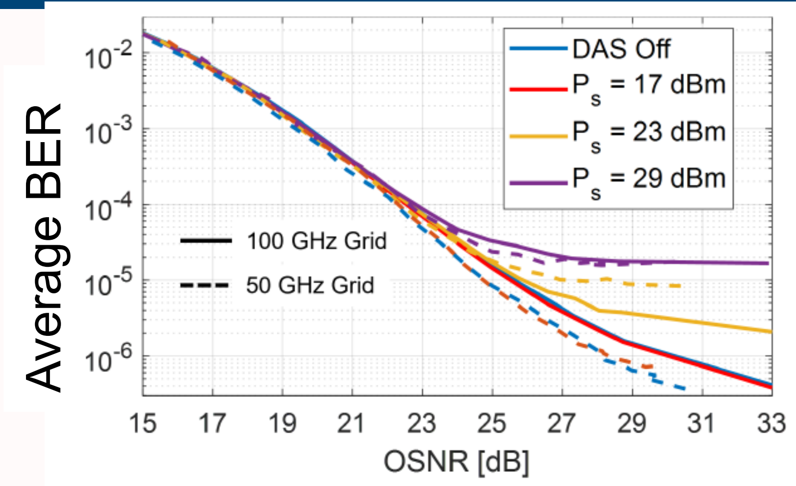
marginal impact generated by data on DAS



Experimental setup, b) waterfall plot of the DAS measurement, and c) strain rate evolution in time.

Distributed Acoustic Sensing (DAS)





- We saw some crosstalk generated by DAS on PM-16QAM, due to Kerr nonlinear effects in the fiber
  - The used commercial DAS is a pulsed one, with 20-30ns pulses and peak power up to 29 dBm (coupled at fiber input)
    - DAS pulses generate cross-phase modulation (XPM) on data signals
  - Lesson learned from our preliminary experiments
    - DAS peak power value is key for co-existence with data
    - Average BER measurement is NOT a good metric
      - Crosstalk is very bursty in pulsed DAS

Numerical Simulations: DAS XPM effect on data

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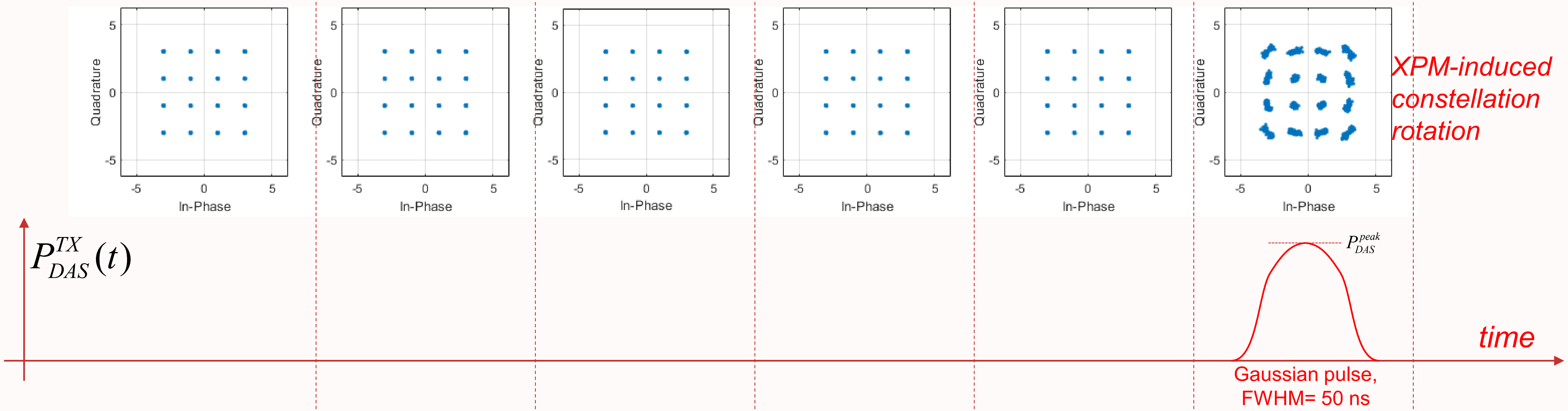
Numerical simulations using parameters similar to our experiment
(but intentionally without ASE noise)

Time-resolved 16-QAM scattering diagrams in receiver DSP, AFTER adaptive equalizer but before CPE

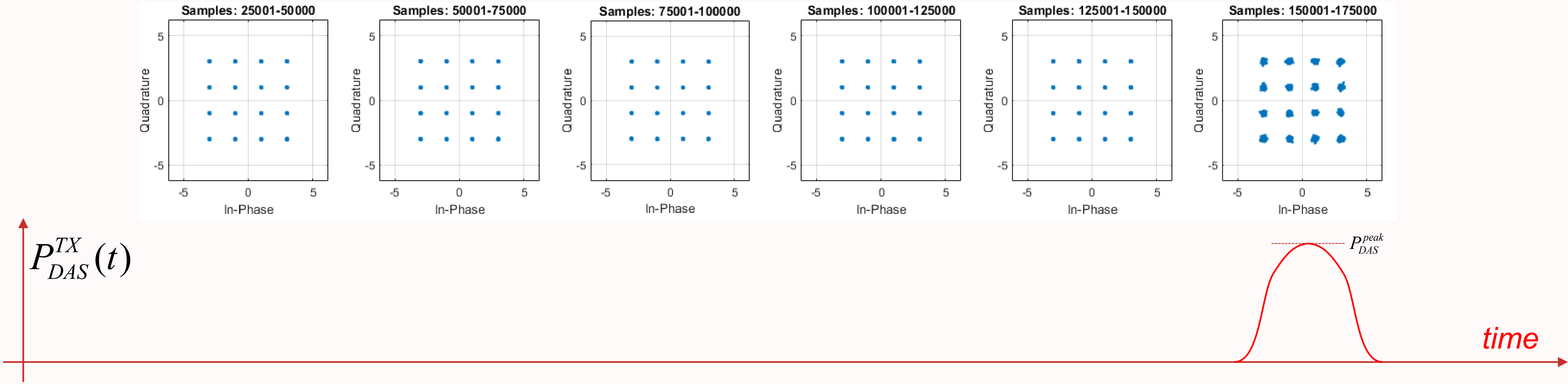


- **PM-16QAM, Δf =50 GHz, R_s=32 Gbaud, P_{ch}=-4 dBm, P_{DAS}=17 dBm, 11.8 km,**

  μ_{EQ}=[8e-4,5e-4], $Memory_{CPE}$=100 taps

Numerical Simulations: DAS XPM effect on data

Time-resolved 16-QAM scattering diagrams in receiver DSP, AFTER adaptive equalizer
AND Carrier Phase Estimation (CPE)



- XPM is the main effect, generating a constellation rotation on the received QAM constellation
- Exact penalty on data is thus strongly dependent on:
  - Details of the implemented CPE in the receiver DSP
  - Resilience of the implemented FEC code towards bursty error

More details in our ICTON2024 invited paper, July 2024 in Bari

Conclusion on DAS coexistence

- Ok for single span (between two EDFAs)

- Pulsed DAS peak power should be regulated on a case-by-case base for coexistance
  - Frequency-swept DAS would likely generate much lower XPM

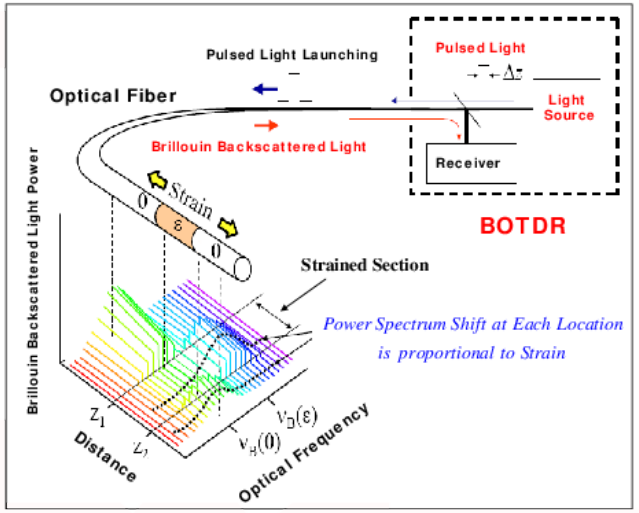
- The actual problem is the very high cost for current commercial DAS interrogators

- IF DAS become less expensive…
- … a very interesting research area will be on how to automatically post-process the enormous amount of generated data
  - Example: 1 meter resolution, frequency up to 5 kHz → 10 ksample/m/s
    - On a 50 km span: 500 ksample/s
    - Assuming 2 bytes per sample: 86 Gbyte per day

What about other optical sensing options? Brillouin

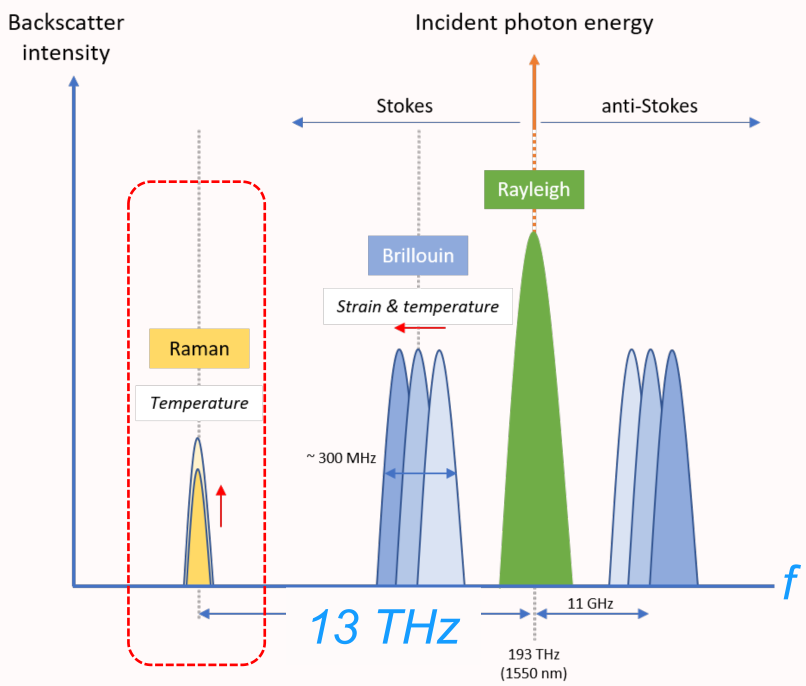
- Brillouin based sensing: it is used in special applications for temperature and strain sensing
  - B-OTDR: Brillouin OTDR

- In principle, coexistence is possible: same considerations as for DAS
  - Required optical band is $f_{laser}\pm 11\mathrm{GHz}$ so it fits inside an ITU-T frequency slot



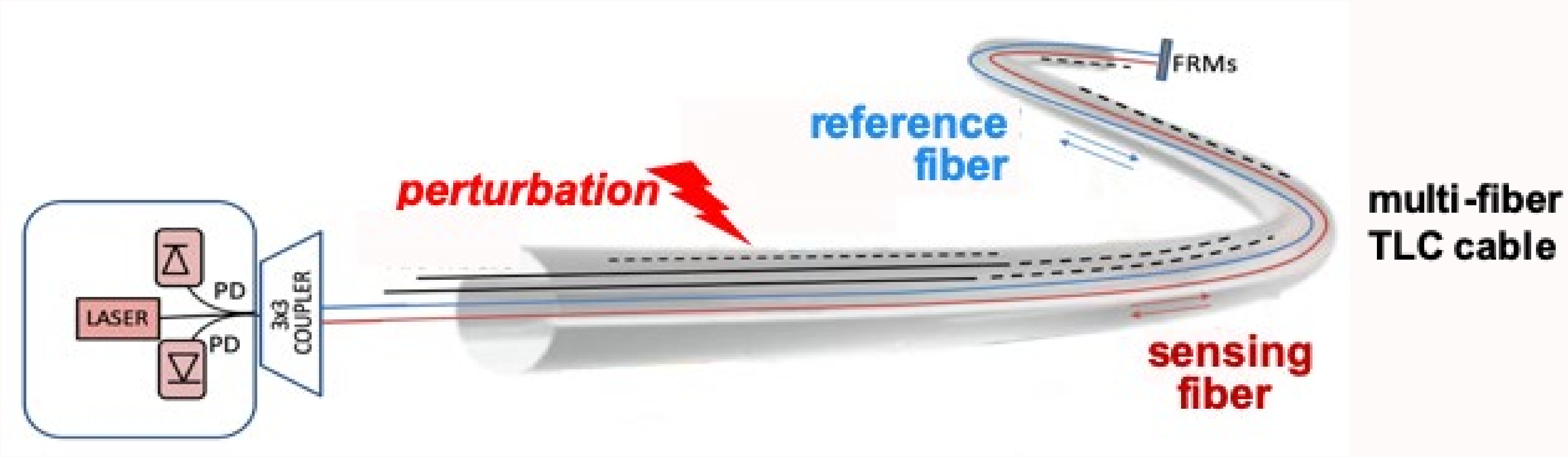
What about other optical sensing options? RAMAN

- Raman based sensing: it is used in special applications for temperature sensing
  - For instance: very good for oil/gas pipeline anomalous temperature monitoring
- It does NOT seem to be suitable for data coexistence on the same fiber since:
  - requires an enormous available optical bandwidth
    - The Raman generated signal is ±13 THz apart from the used laser
  - uses pulses with extremely high peak power
    - Even higher than for pulsed DAS



Interferometric solutions

- Interferometric schemes can be employed to monitor mechanical deformations (stress, vibration, pressure) and temperature variations affecting the fiber constituting the sensing arm of the interferometer.
  - POLIMI group developed innovative solutions based on Michelson interferometers, where the reference arm is not isolated, but is another fiber inside the same multi-fiber TLC cable of the sensing arm.



Interferometric solutions

- Sensing is not distributed, but integral over distance
  - ideal for elongation measurements and monitoring of structural vibration modes of buildings, bridges, etc.
- Positioning anyway possible thanks to dual interferometric schemes with the comparison of the different arrival times.
  - Low-cost, energy-efficient sustainable sensors, w/o the necessity of acquisition at high sampling rate, w/o complex DSP and w/o storage of huge quantity of data.
- Coexistence with data is surely possible:
  - just a dedicate wavelength is necessary;
    - high power pulses not required

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Vibration Sensing for Deployed Metropolitan Fiber Infrastructure

Ilaria Di Luch, Pierpaolo Boffi, *Senior Member, IEEE*, Maddalena Ferrario, Giuseppe Rizzelli, Roberto Gaudino, *Senior Member, IEEE*, and Mario Martinelli, *Member, IEEE*

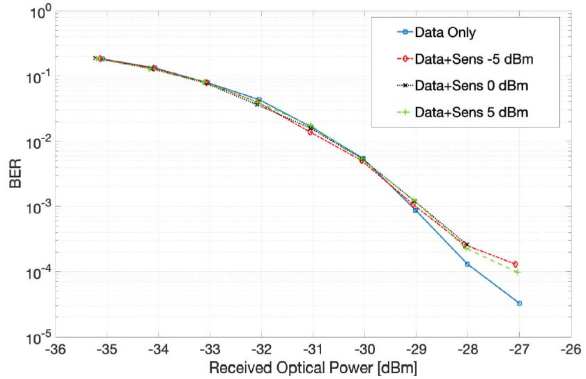


Fig. 7. BER vs. received signal power P_{RX}, after 32 km, for different power levels P_{IN} of the interfering sensing signal.

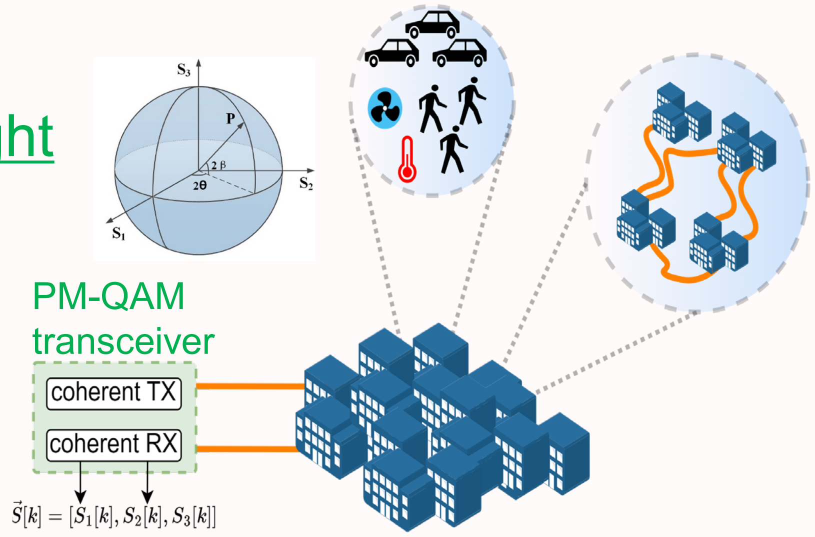
Interferometric solutions

- … a presentation in this same ICOP2024 session will be given on interferometric sensing based on two cores inside the same already deployed multi-core fiber!

15:00-15:30	**INV_04**	Overview on optical sensing techniques over deployed telecom networks *R. Gaudino, G. Rizzelli, A. M. Rosa Brusin, S. Pellegrini, V. Ferrero, G. Bosco, D. Pilori, P. Parolari, P. Boffi*
15:30-15:45	**O_09**	Polarization sensing in metropolitan areas *S. Pellegrini, G. Rizzelli, L. Andrenacci, L. Minelli, D. Pilori, G. Bosco, C. Crognale, S. Piciaccia, A. Tanzi, R. Gaudino*
15:45-16:00		Urban sensing by deployed uncoupled multicore fiber *M. Fasano, T. Hayashi, T. Nagashima, A. Mecozzi, C. Antonelli, P. Boffi*

Vibration detection without positioning: SOP sensing

- If positioning is not strictly needed, another option for vibration sensing is using State of Polarization (SOP) of the received light
- Regarding coexistence: it does not even require a dedicated wavelength, since SOP can be extracted:
  - From the receiver DSP in coherent PM-QAM links
  - Adding a polarimeter at the end of IM-DD link
- … a full presentation on SOP-based sensing in the next slot!



15:00-15:30	**INV_04**	Overview on optical sensing techniques over deployed telecom networks *<u>R. Gaudino</u>, G. Rizzelli, A. M. Rosa Brusin, S. Pellegrini, V. Ferrero, G. Bosco, D. Pilori, P. Parolari, P. Boffi*
15:30-15:45	**O_09**	Polarization sensing in metropolitan areas *<u>S. Pellegrini</u>, G. Rizzelli, L. Andrenacci, L. Minelli, D. Pilori, G. Bosco, C. Crognale, S. Piciaccia, A. Tanzi, R. Gaudino*

Our main papers on this topic:

Conclusion

- Optical sensing over deployed telco fiber is a “booming” research area
  - As demonstrated by the large number of papers submitted at recent conferences

- Co-existence on same fiber is not “easy”, but possible, and it should be studied more in details by simulation and experiments
  - This is the main focus of the PRIN2022 SURENET project

- Techno-economics is the key point
  - Distributed optical sensing is still a niche application with a small market
    - A great part of the cost is due to the very specific ultra-narrow linewidth lasers needed
  - Non-distributed sensing much less expensive (interferometric or SOP based)

Thank you for your attention!

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