State of polarization based sensing on optical fiber

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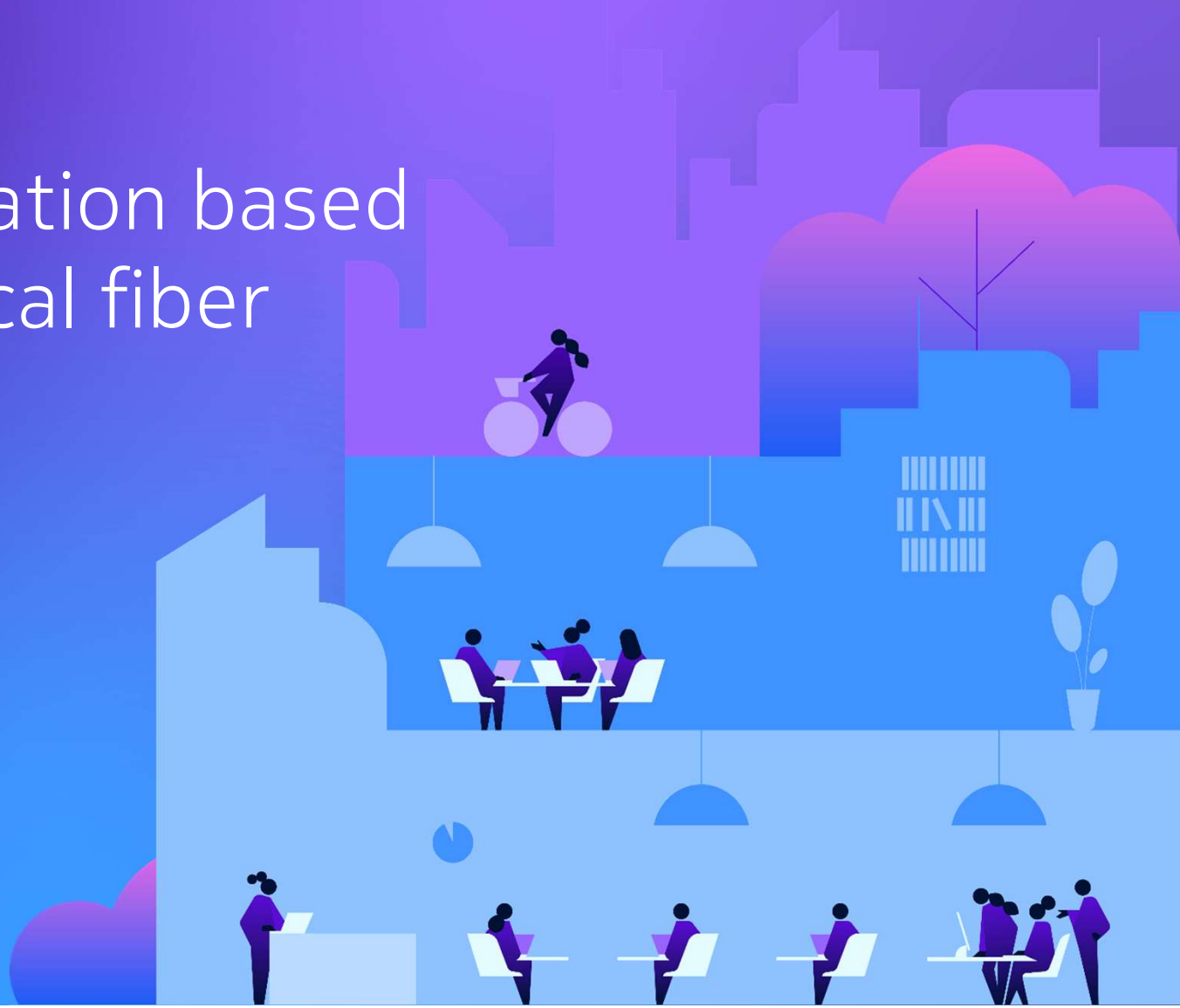
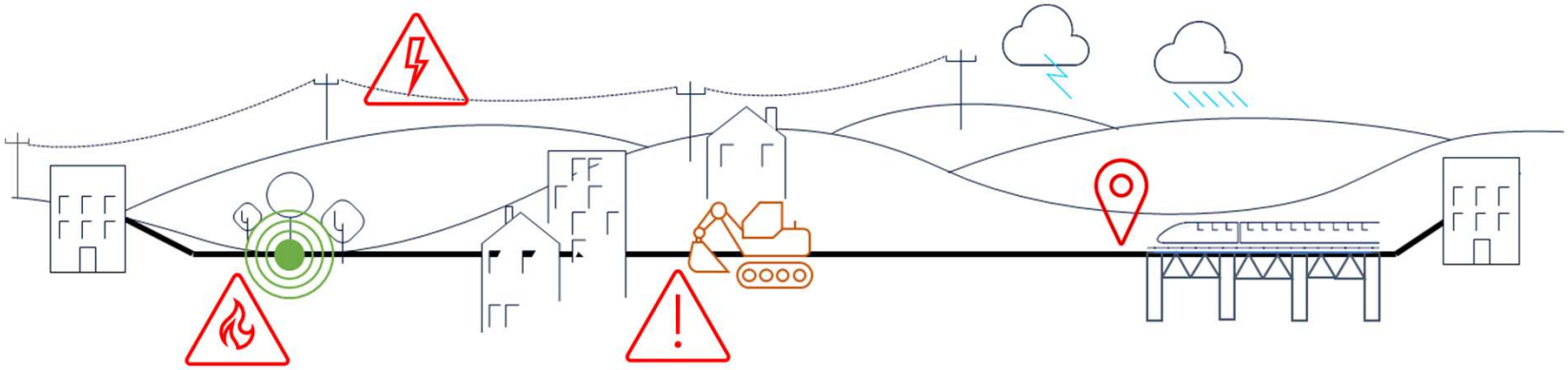
Nokia



Why Optical Network Is So Challenging?

Optical network complexity

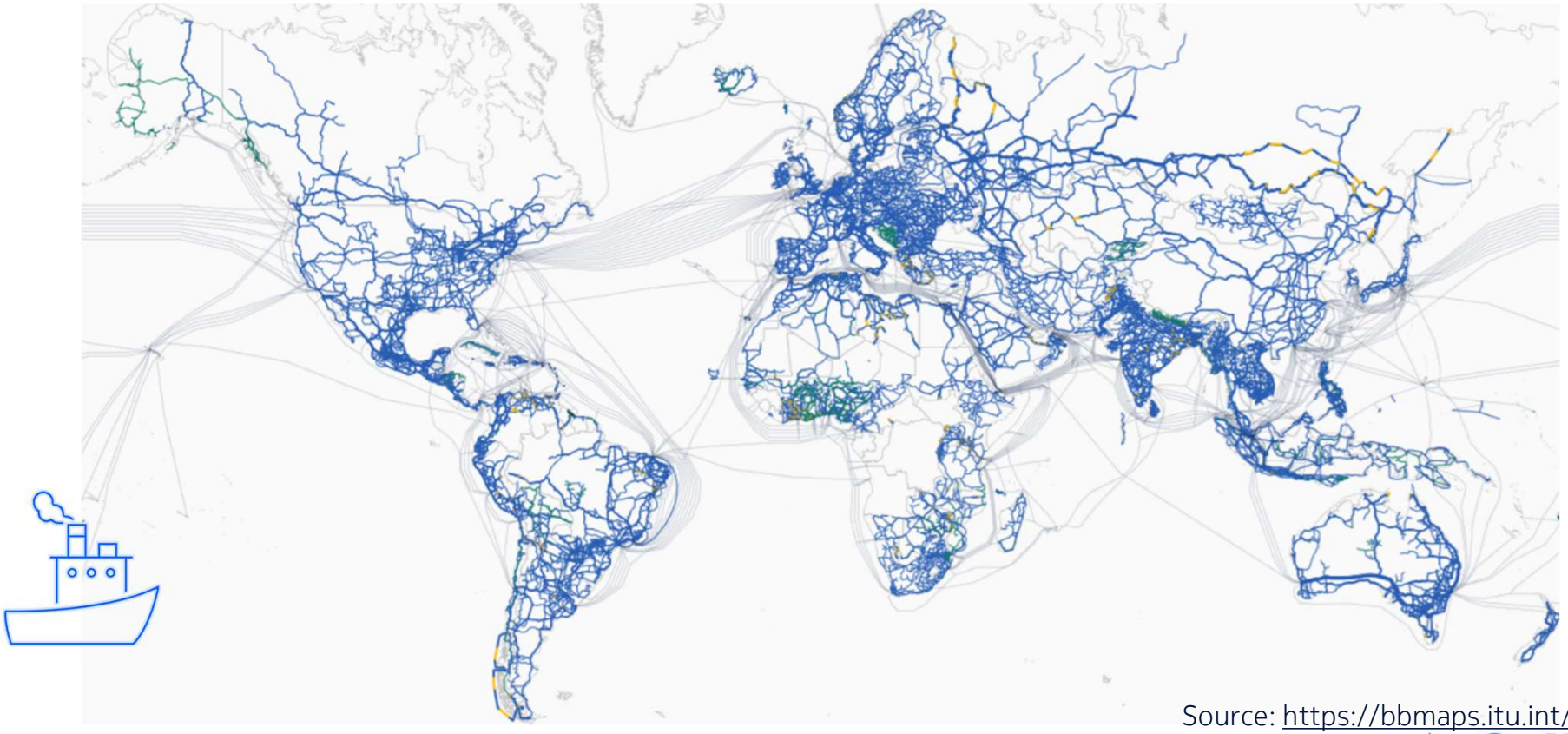


- The fiber network has many shapes and scales
- Pb/s are transported by optical fibers, many services concern bank transactions, AI-workloads, …
- Various threats exist:
  - Threats to the **network itself**
  - Threats to the **environment and people**

As the **value** of transiting **data** grows, the **cost** of **downtime** increases

Telemetry to protect our deployed networks

Fiber everywhere: Global map of fiber-optic deployed cables[1,2]



Source: https://bbmaps.itu.int/bbmaps/

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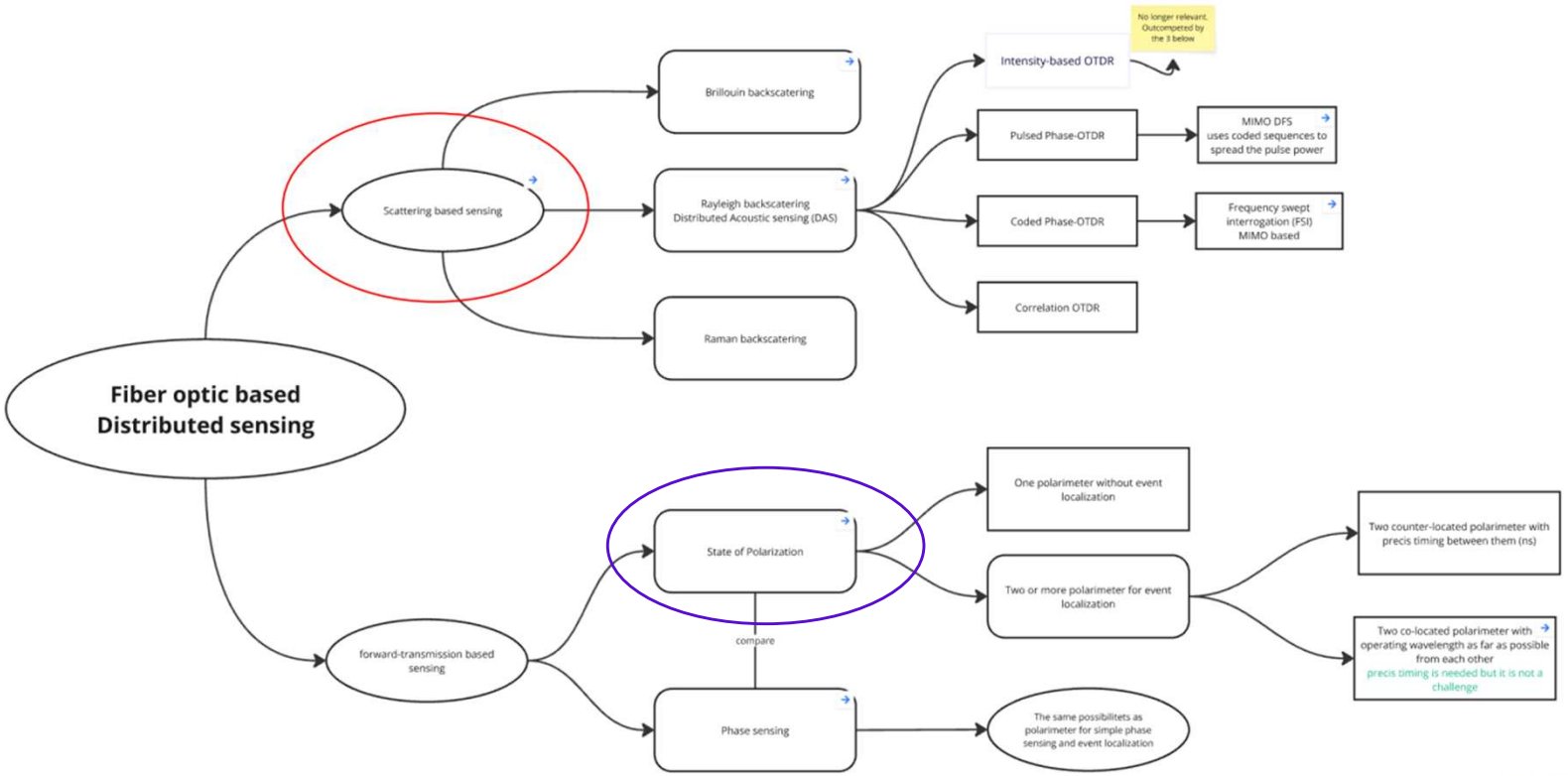
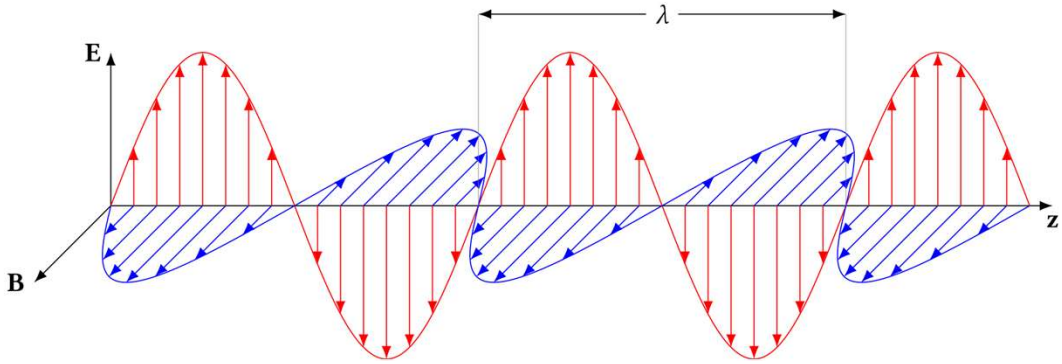


Why State of Polarization monitoring?

The light propagation

The light polarization



The light is an electromagnetic wave

This means that during its propagation there is a coupled oscillation between electric and magnetic field that are always perpendicular to each other

Different states of polarization correspond to different relationships between the directions of the fields and the direction of propagation

The polarization is the expression of the orientation of the lines of electric flux

In an optical fiber, the light is randomly polarized

Stokes parameters

The electrical field is received with a given energy, this is expressed by the S_0 Stokes parameter

Then we have the projection of the light on the (x, y) axes

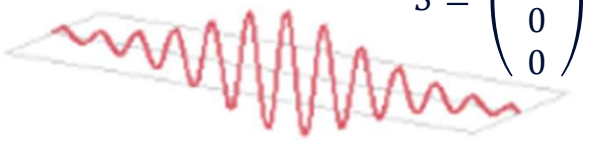
$$S = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{matrix} E_x^2 + E_y^2 \\ E_x^2 - E_y^2 \\ 2E_xE_y \cos\phi \\ 2E_xE_y \sin\phi \end{matrix}$$

Horizontal transmission

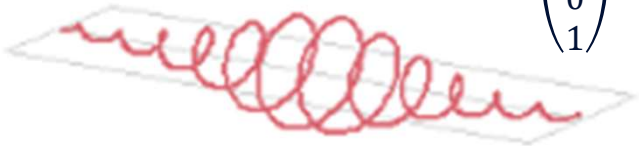
$$S = \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix}$$

Vertical transmission

$$S = \begin{pmatrix} 1 \\ -1 \\ 0 \\ 0 \end{pmatrix}$$



$$S = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$



Circular (right hand) transmission

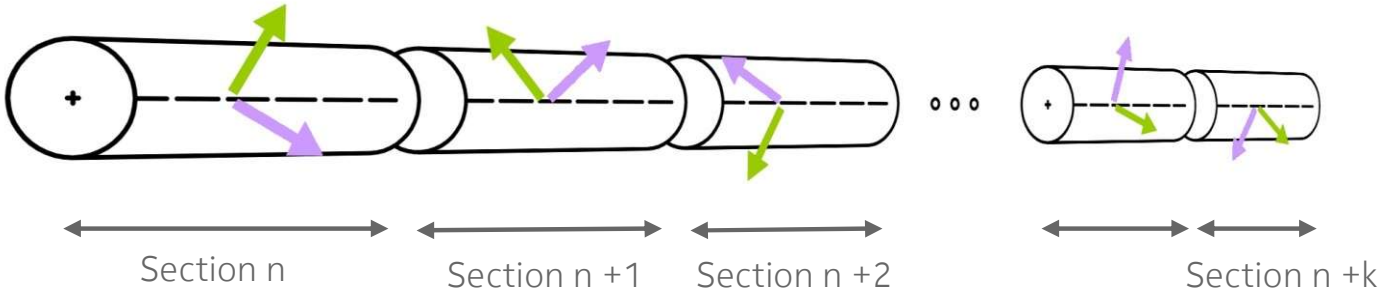
$$S = \begin{pmatrix} 1 \\ 0 \\ 0 \\ -1 \end{pmatrix}$$

Circular (left hand) transmission

Linear effects

Real optical fiber → infinitesimal succession of birefringent elements

Each birefringent element has its own particular axis, pulses are decomposed along principal de polarization axes

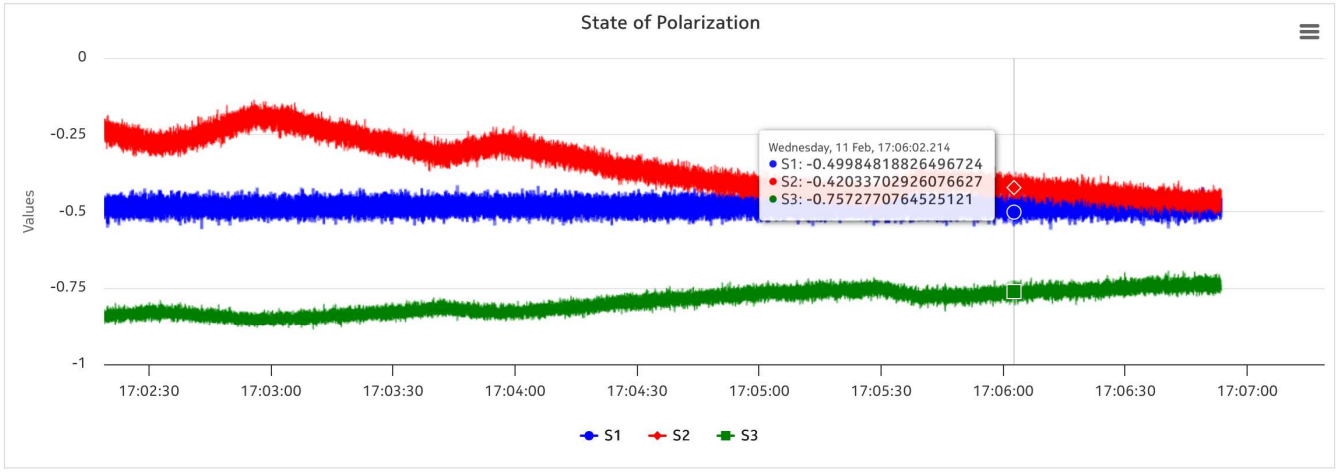


The received light is randomly polarized

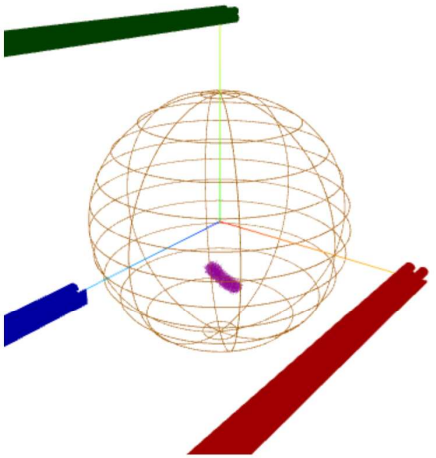
SoP graphical representation

Data - PSI-M-29 PORT-1-1-L1

Analysis - PSI-M-29 PORT-1-1-L1 - Interval [2026-02-11 17:02:19 2026-02-11 17:07:19]



Pointcarré spere



Linear effects

Real optical fiber → infinitesimal succession of birefringent elements

Each birefringent element has its own particular axis…

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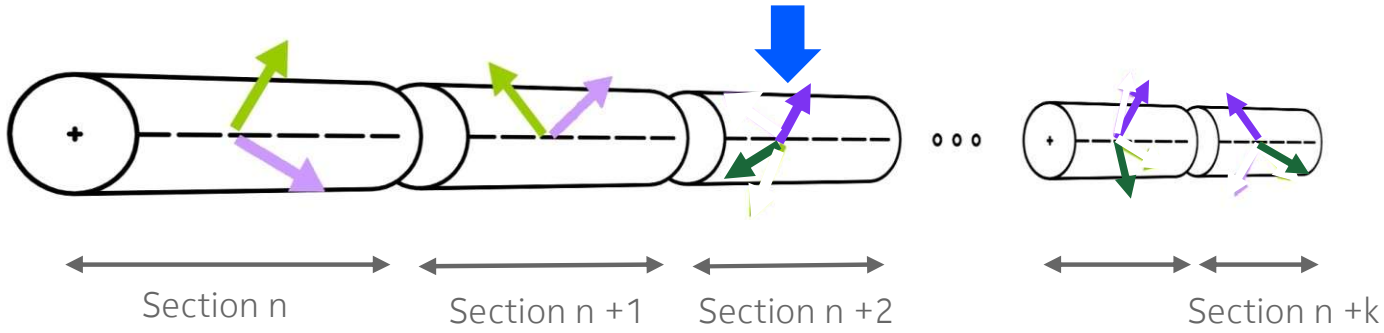
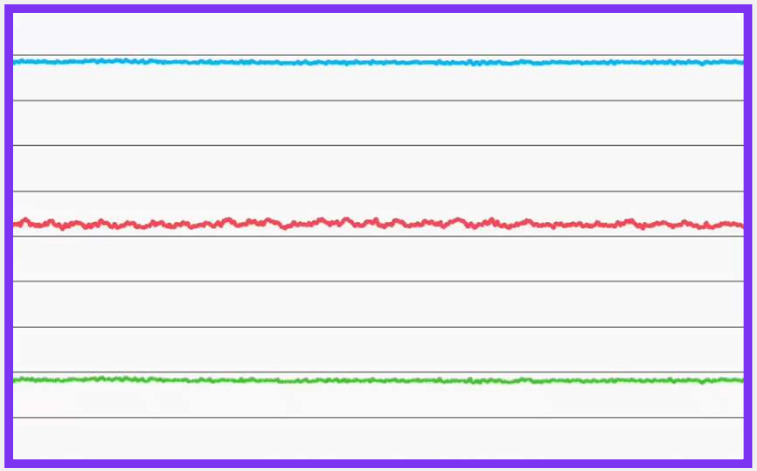


Polarization changes may be due to the imperfection faced during the propagation or medium deformations/stresses (static or dynamic)

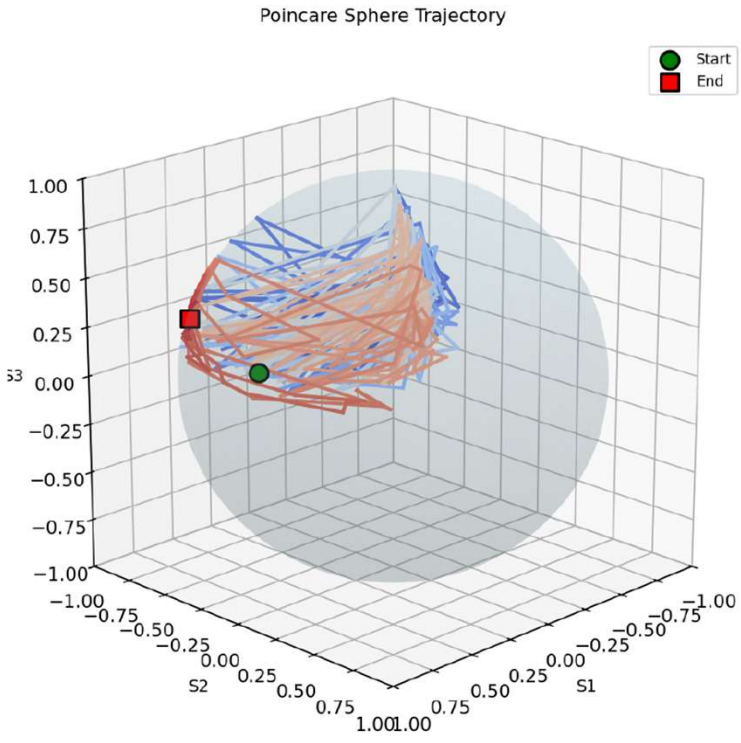
Polarization Unlocked: Stokes Vector variations

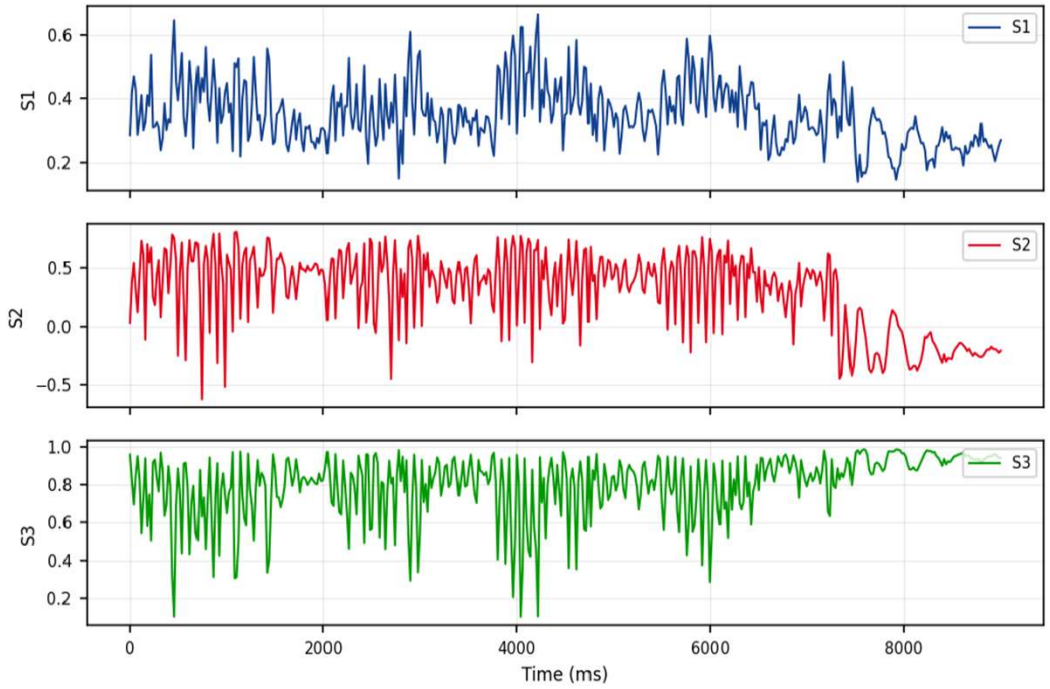
Sense

Generate and collect events from the fiber

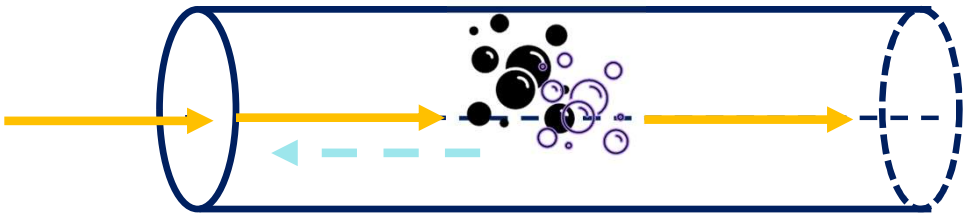


The 3 SoP and Point-carré sphere





The light propagation: forward and backscattering



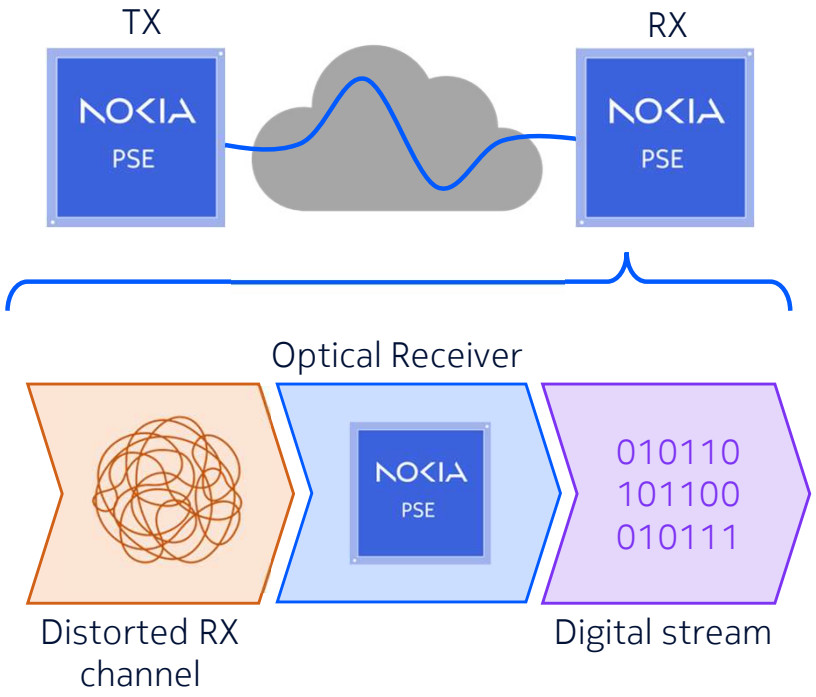
Backscattering waves
small percentage of the forwarding waves

SoP variations may be observed from both forwarding and backscattering waves

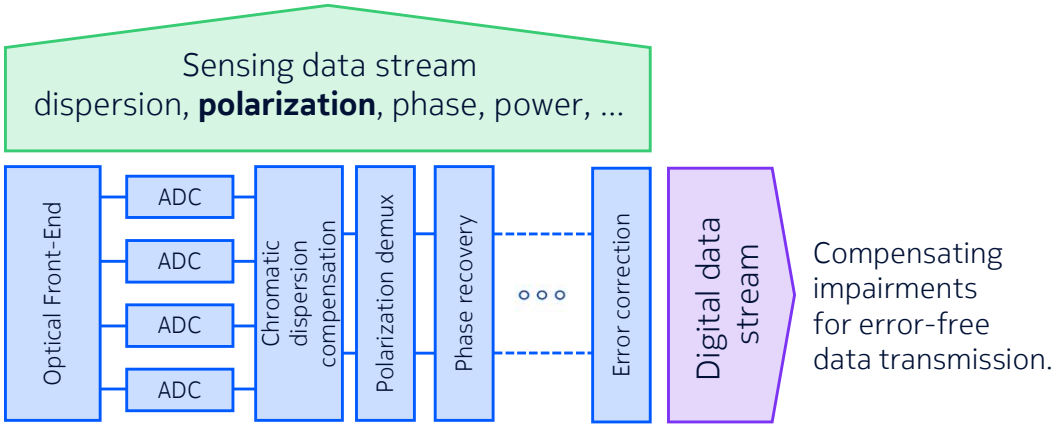
Forwarding SoP variation detection

Learning to see through the eyes of the transponder

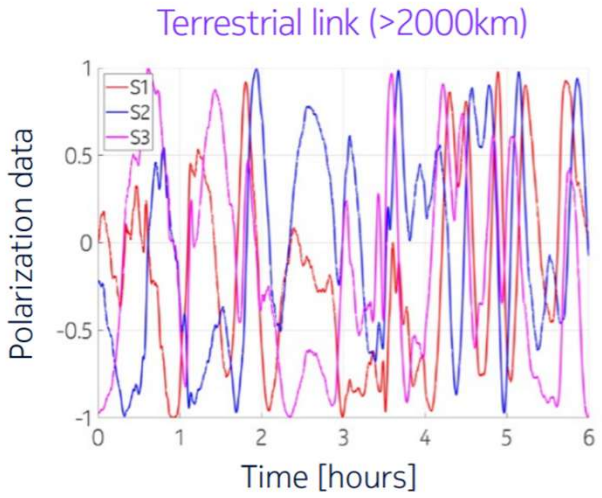
Coherent transponder sensing [3,4]

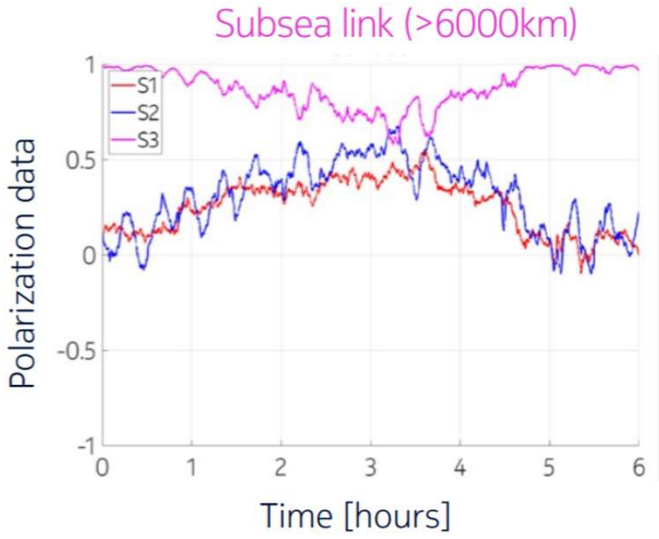


By leveraging recovery and compensation algorithms, we can **enable sensing capabilities**



Limits to DSP-based SoP sensing?





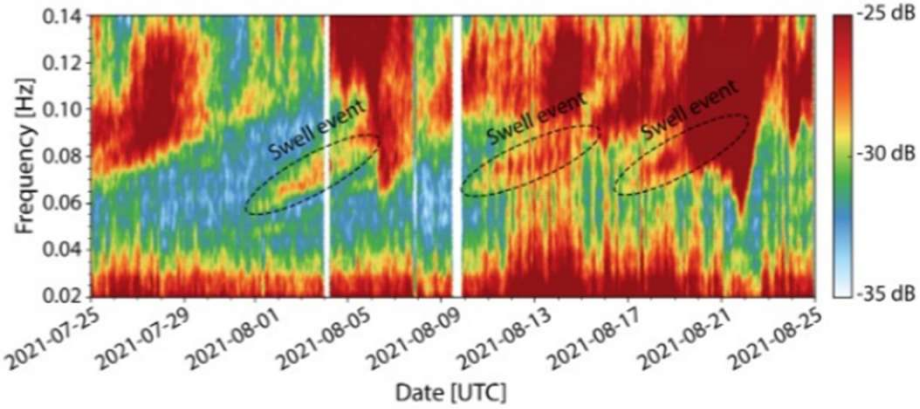
The only reach limitation is the optical coverage or the selected transmission profile of the transponder

Proof of Concept

Transoceanic SoP sensing to detects swells and waves[5]

Map showing the geometry of the Dunant fiber-optic cable. Prototype operates alongside regular DWDM channels

Spectrogram of average SOP rotation between S1 and S2 after rotation to S3 = 1 over 1 month of measurements on the Dunant cable.

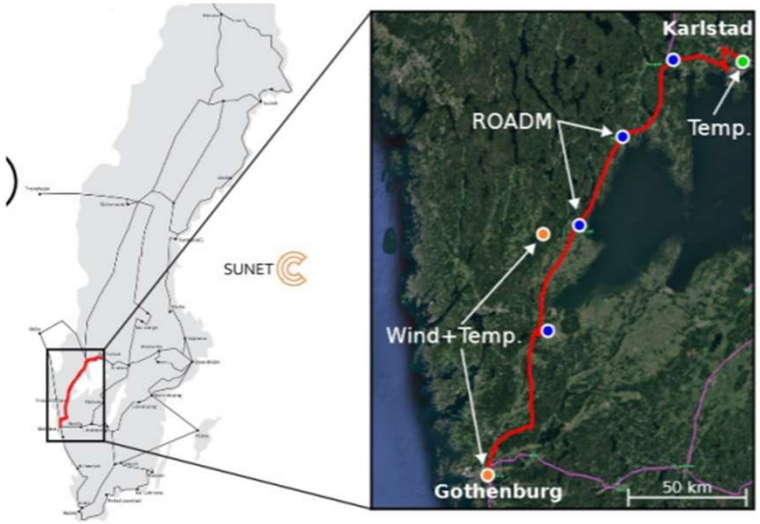


The packages of dispersive signals at 0.06-0.10 Hz - in the primary microseism band - are caused by the water wave pressure that is exerted by distant storms - swell events.

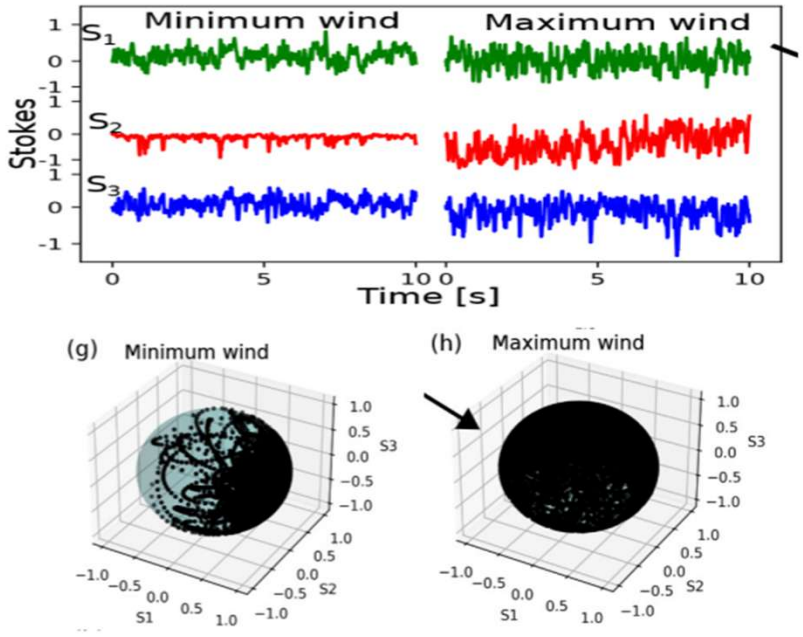
Proof of Concept

Terrestrial SoP sensing to detects aerial fiber stability

Map showing the approximate fiber route.
Aerial cables in Sweden.



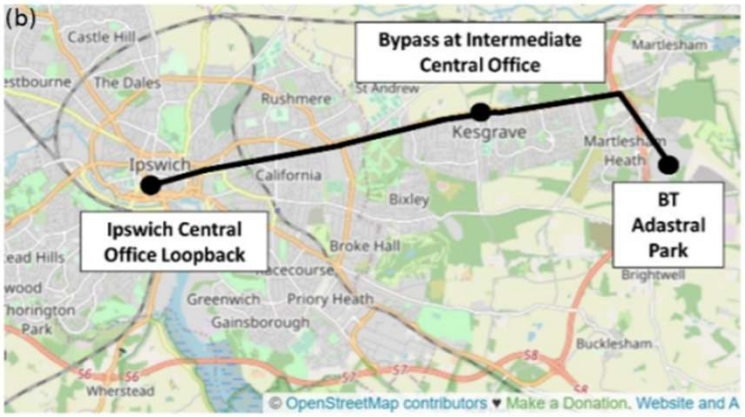
Stokes measurements and Poincare representation at different wind conditions. We observe a remarkable difference, indicating that the link is strongly susceptible to wind-induced polarization changes.



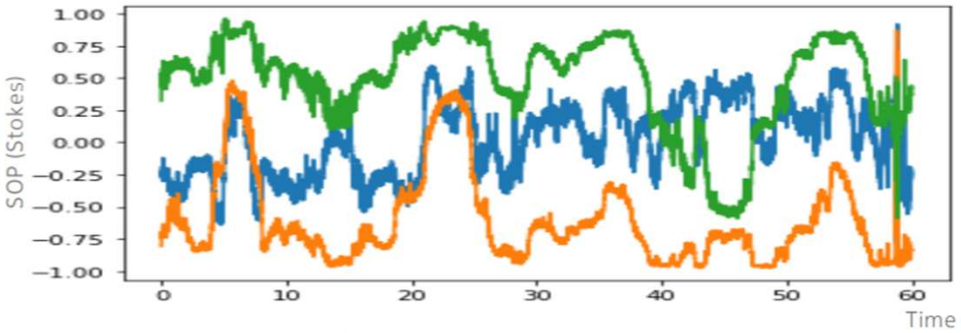
Proof of Concept

Metropolitan SoP sensing to detects aerial fiber stability

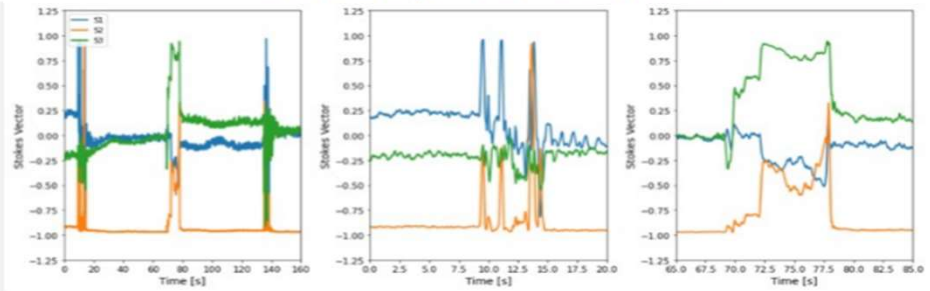
Map showing the approximate fiber route



Typical state of polarization traces (minutes) – background noise



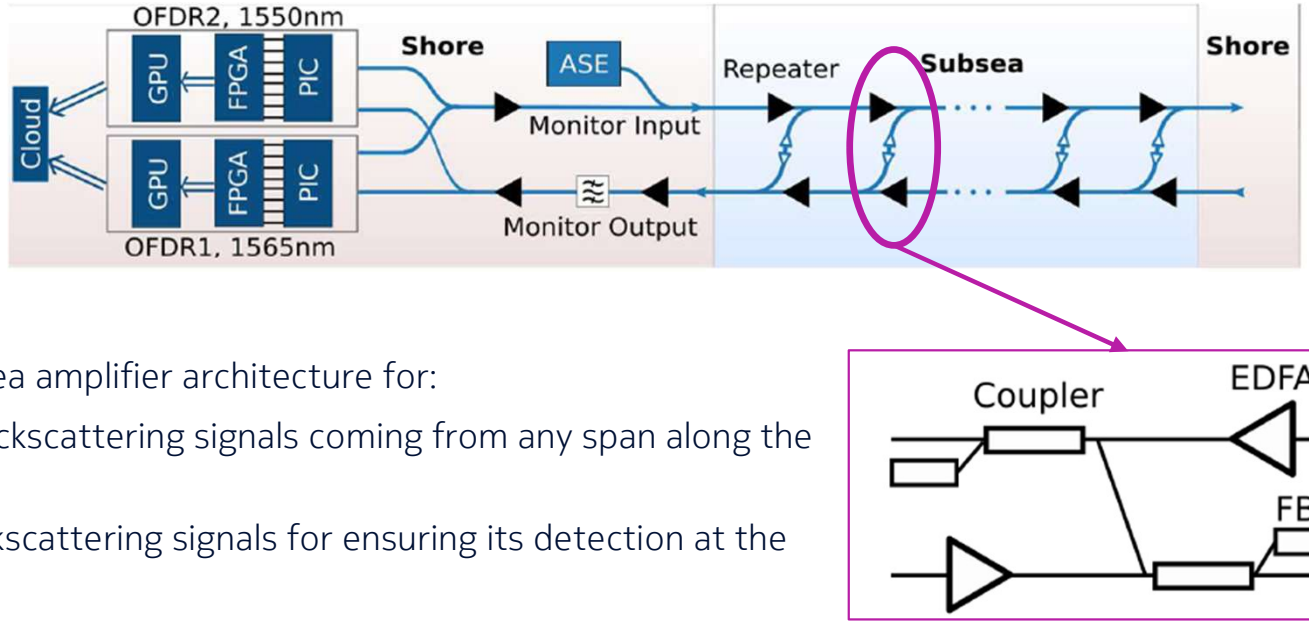
State of polarization traces containing three induced fiber perturbations (seconds).



Backscattering SoP variation detection

Coherent optical frequency domain reflectometer

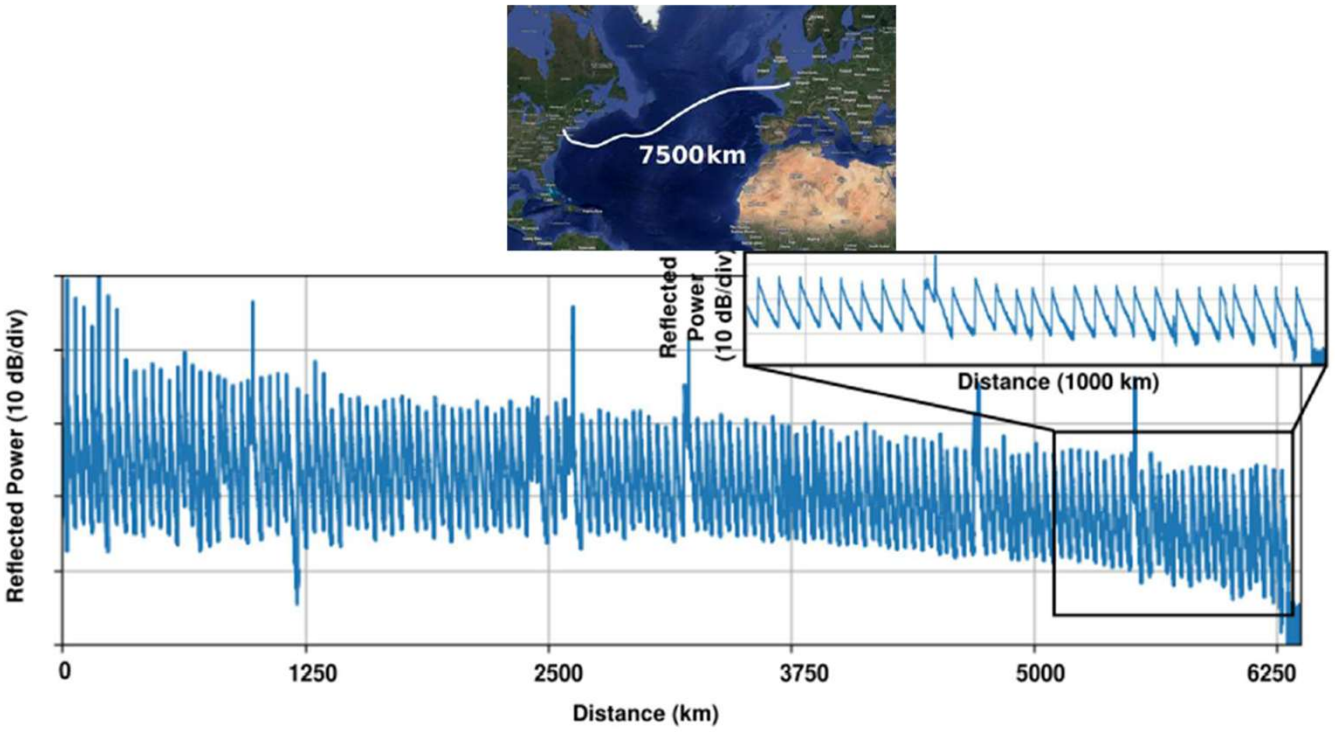
Backscattering in submarine networks[6]

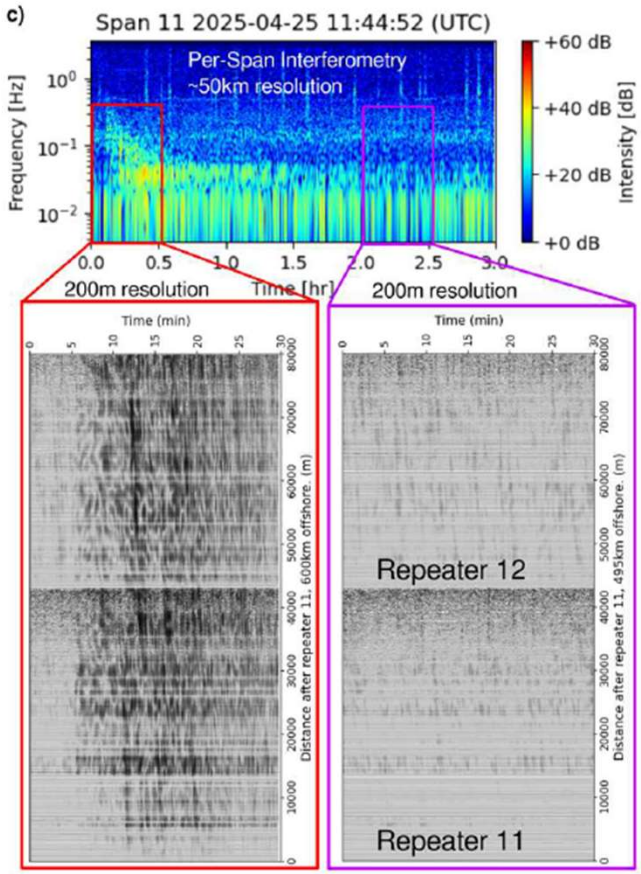


- Exploit the subsea amplifier architecture for:
  - Send-back backscattering signals coming from any span along the link
  - Amplifies backscattering signals for ensuring its detection at the receiver

Coherent optical frequency domain reflectometer

Backscattering in submarine networks[6]



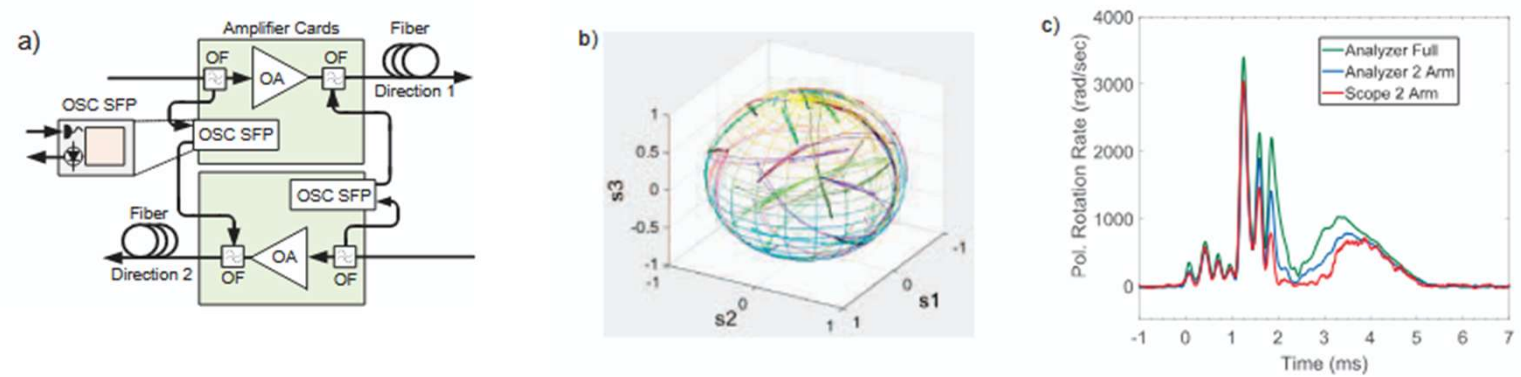


What about terrestrial solutions?

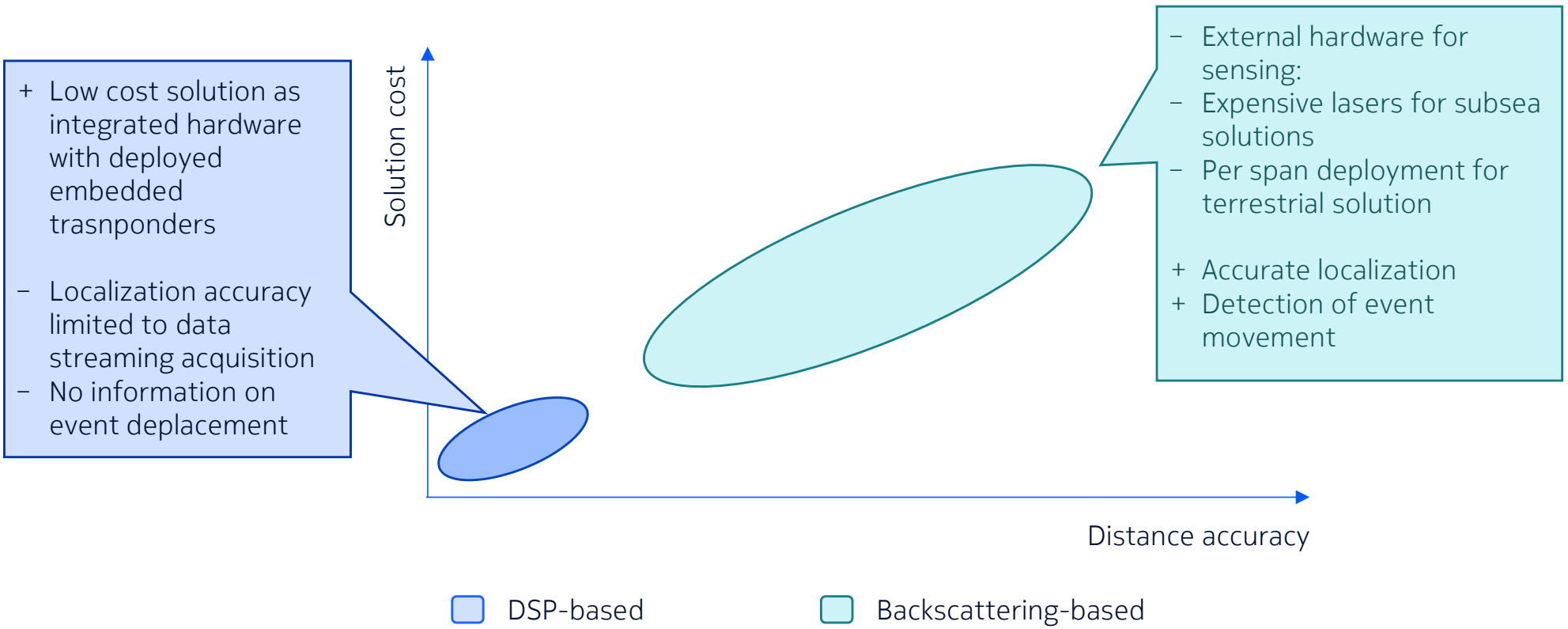
Distributed SoP sensing for terrestrial networks

What about terrestrial networks?[4]

Per span SoP variation detector have been proposed on a span-by-span basis between amplifiers



Which technology, which advantage

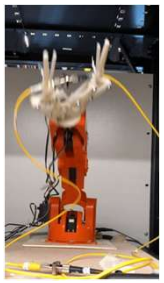


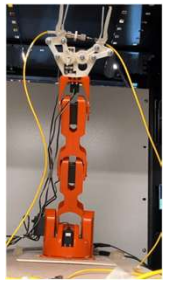
Machine Learning and event classification

Detection of external events

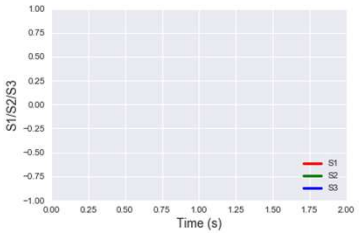
Based on State of Polarization (SoP)[3]

SoP events have a specific signature… how to recognize it?

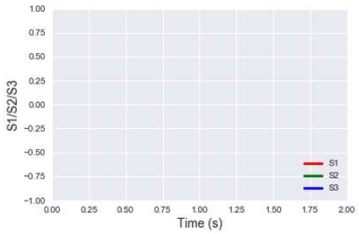




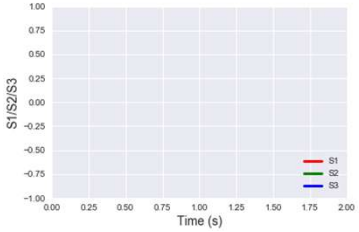
"digging"



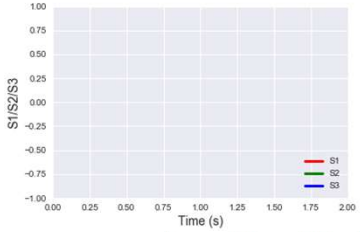
"rotating"



"swinging"

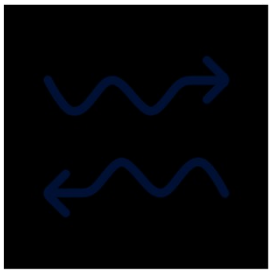


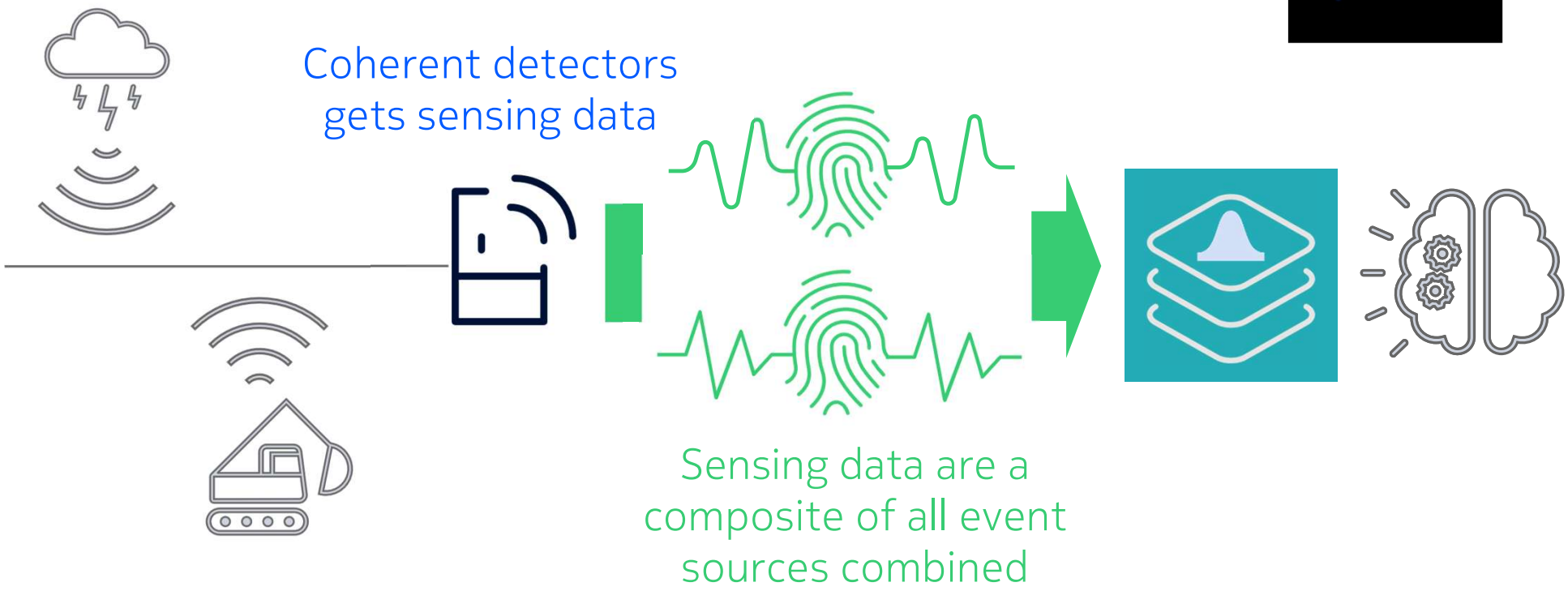
"stretching"



Understanding what we see

Harnessing AI-powered pattern recognition to decode event traces[7,8]





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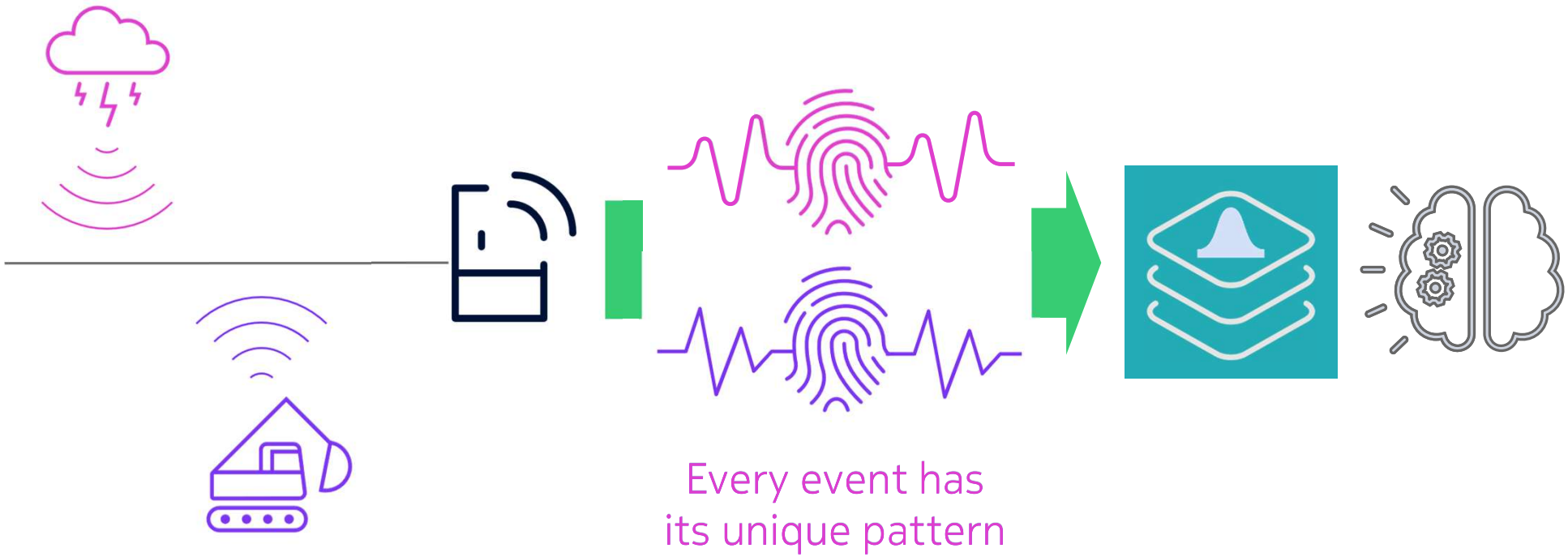

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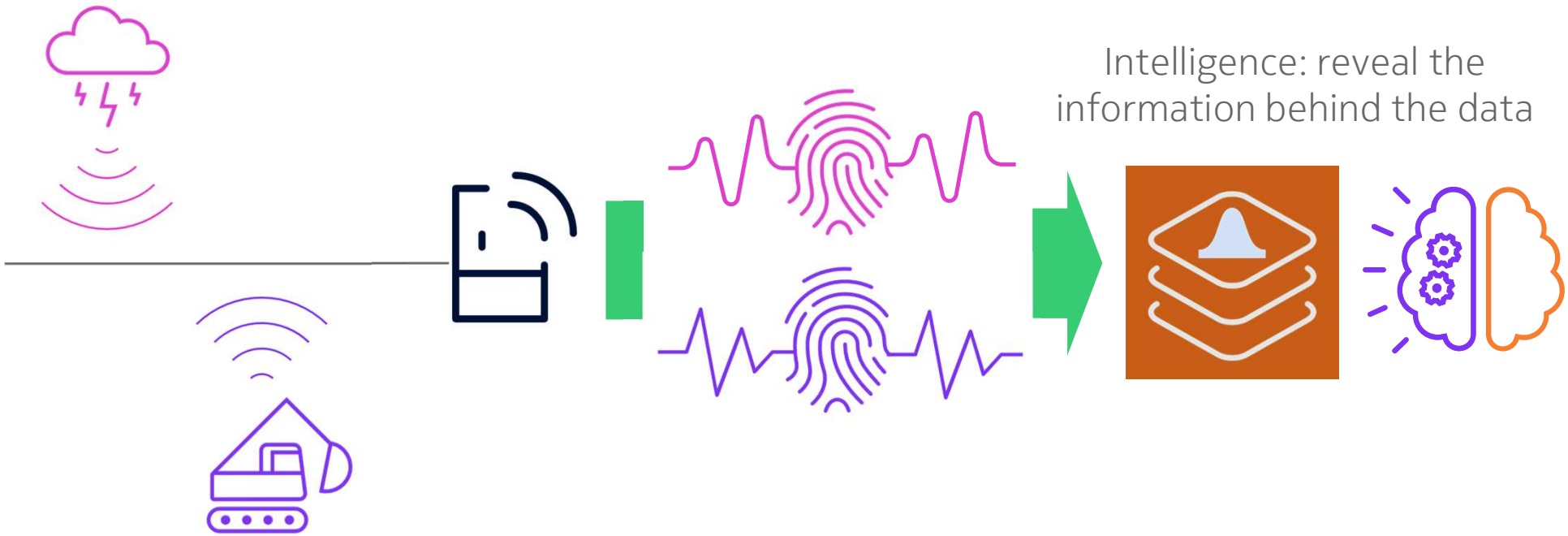
Harnessing AI-powered pattern recognition to decode event traces[7,8]



Use-Cases

SoP-based fiber sensing of use-cases

Streamlining operations → reduce Opex by automating manual tasks like risk-group management

- Fiber characterization: at turn-up and after repairs
- Ongoing fiber monitoring

Network integrity and service assurance → Prevent outages proactively and enable premium services with guaranteed reliability

- SLA breach analysis with outage root-cause reporting
- Fault localization for repairs and liability assignment
- Route premium services via low-risk fibers
- Real-time sensing to early detect fiber breaks and avoid service disruption
- Advance threat warning: construction, anchors, fishing nets, sabotage
- Intrusion detection for network security
- Environmental monitoring: storms, earthquakes, tides, etc


NOKIA

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