Sven-Christian Ebenhag

Development of a Coherent Time and Frequency Transfer Transceiver

Outline

- Why?
- National Distribution
- Background and introduction
- Specification
- System so far
- Questions

Why a national distribution system for Time and Frequency?

- Citizens and critical public services depends on the availability of electronic communications
- Electronic communications depend on accurate time and sync/frequency
- Time and frequency distributed with GNSS can be easily disrupted and is a factor of uncertainty

A national distribution system for Time and Frequency

- A system independent of GNSS that, from a national perspective, can guarantee robust and secure time.
- The system must be robust and available throughout the country on equal terms.
- Services provided through the system must be affordable for operators so that price is not a stopping factor.
- Regulatory authorities must be given transparency and direct access to the infrastructure, which means that it must be based in and operated in Sweden.


MEASUREMENT- AND WEB SERVERS
NTP SERVERS
IP NETWORK MANAGEMENT
PTP AND GNSS
FREQUENCY DISTRIBUTION
FREQUENCY MEASUREMENT
FREQUENCY AMPLIFIER
FREQUENCY AND PHASE ADJUSTMENT
FREQUENCY GENERATOR (CS)

The Swedish Model

- Distributed by Netnod, traceable to UTC(SP)@RISE and is funded by PTS
- 6 time nodes located in secure rock caverns at 5 different locations around Sweden (Stratum-1 time servers)
- Time scales are steered towards UTC(SP)
- Both free and commercial services with SLA

Clocknodes @ Netnod
Traceable to UTC(SP) @ RISE

- Redundant timescale-nodes based on Microchip 5071 standard performance Cesium clocks

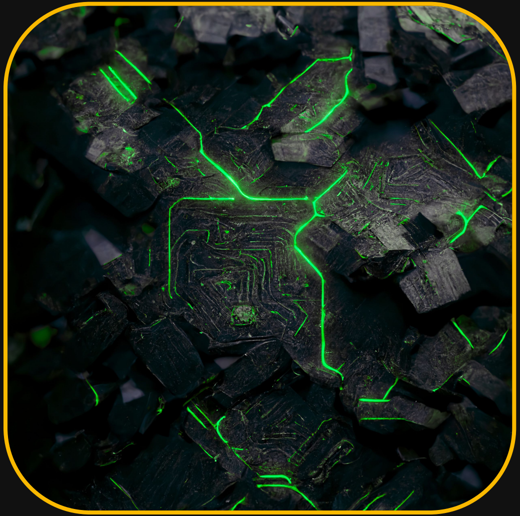
- NTP/NTS servers are equipped with a custom-built FPGA-based hardware implementation

Netnod PTP

Ensure your network nanosecond level accuracy with the most robust, reliable and accurate source of time available without running your own atomic clock.

Netnod Time Direct

Get the most accurate and reliable time available over an IX port with a fully-managed, secure time service that guarantees 30μs accuracy from UTC.



Netnod Time Remote

Get accurate and reliable time securely delivered wherever you are located in Sweden with a guaranteed accuracy of 1ms from UTC.

NTP service

Connect for free to one of the most advanced and secure NTP services available which also includes…

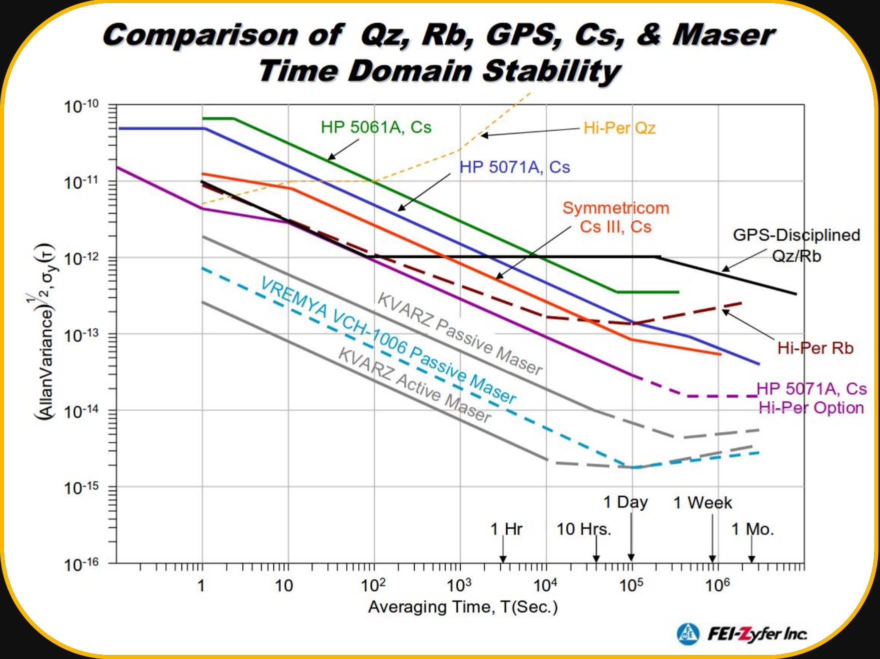
NTS service

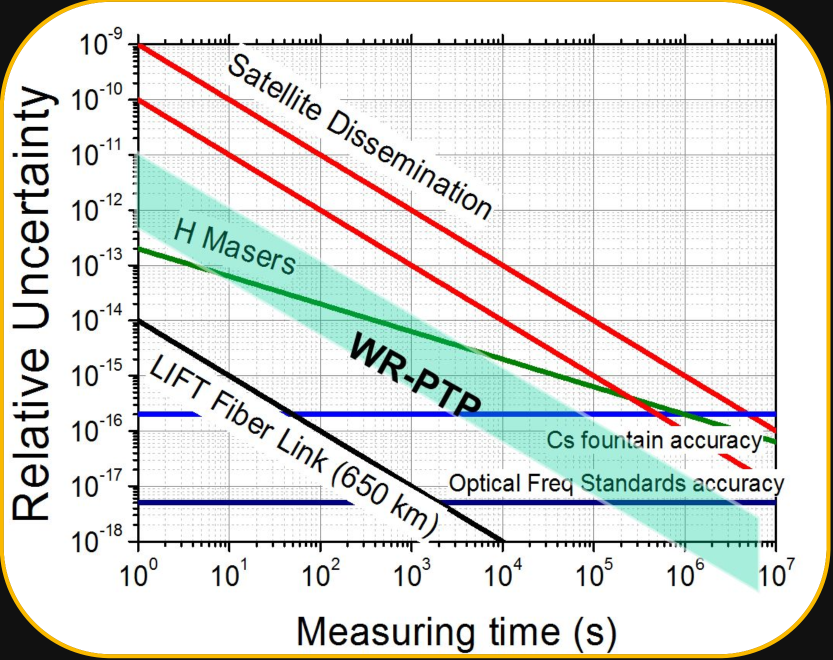
Connect for free to ensure you are receiving secure and accurate time from a trusted source

Where to access NTS?

- Netnode hosts six nodes in five locations around Sweden with Stratum-1 NTS servers
  - Stockholm x 2
  - Göteborg
  - Malmö
  - Sundsvall
  - Luleå

Different types of clocks



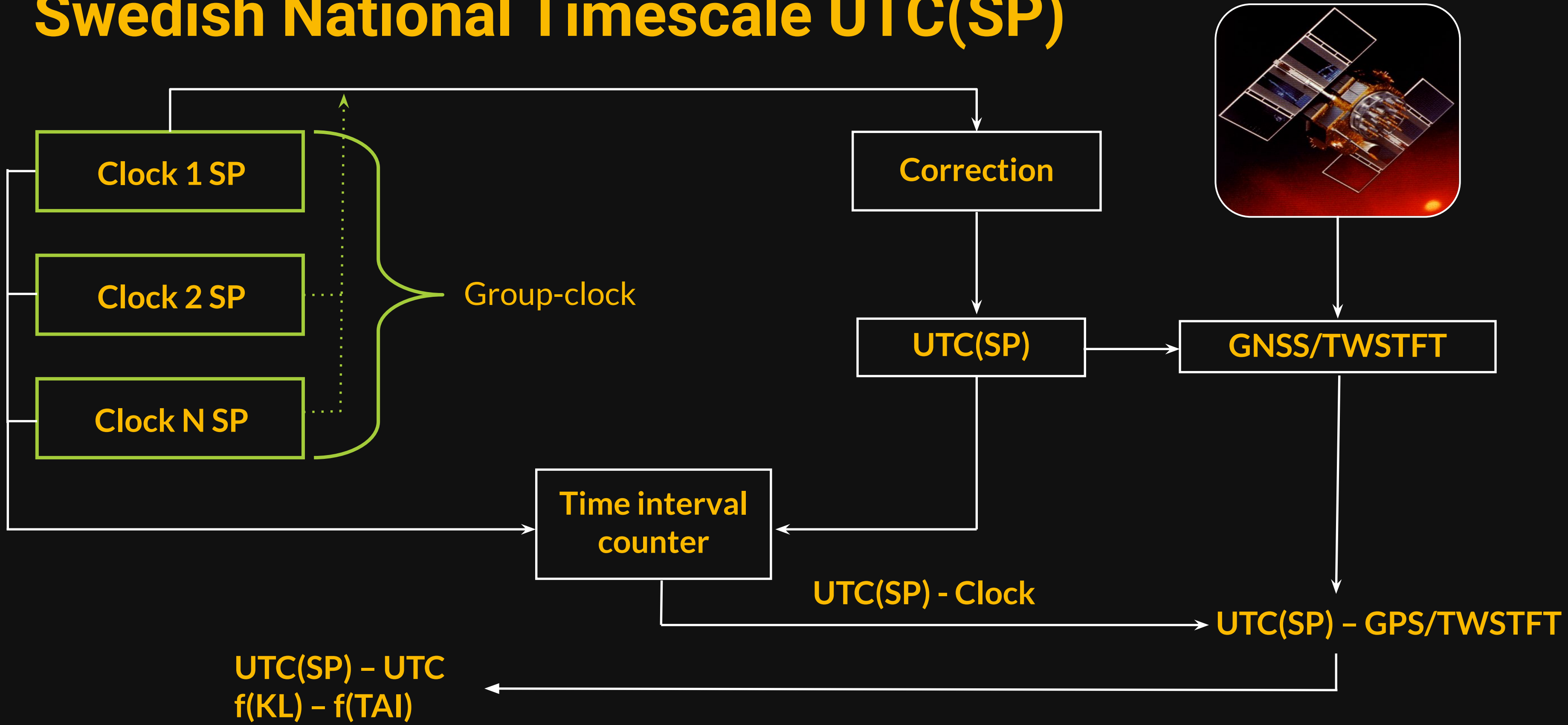


JRP 17IND14 http://empir.npl.co.uk/write/

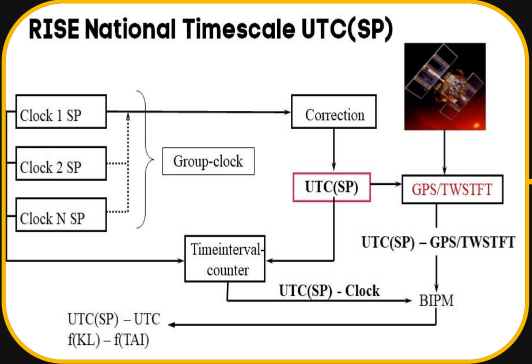
WRITE - White Rabbit Industrial Timing Enhancement

EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Swedish National Timescale UTC(SP)



Netnod Time and Frequency Distribution



Autonomy/ positioning

Aviation

Defense

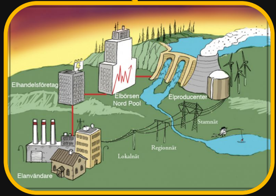
Economy

EU-projects Research

HPC/Storage

Research

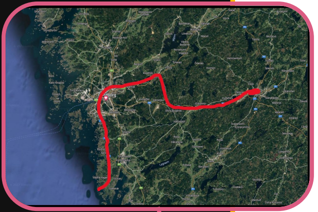
Authorities

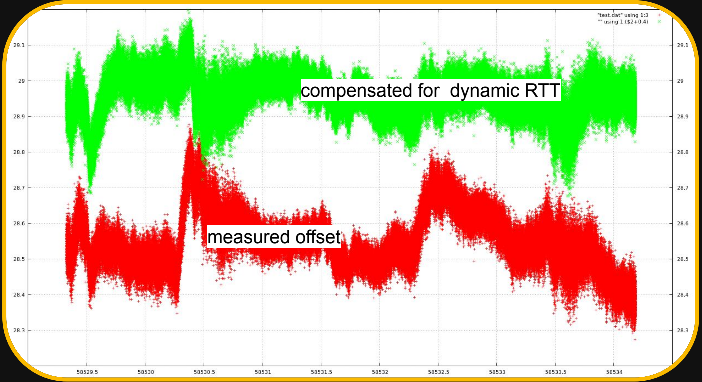


The energy sector

White Rabbit and Coherent Communications

- Run AM light beside coherent 100G slots in SUNET-C
    - ROADM based, no dispersion compensation
    - Unidirectional, two fiber, same wavelength
- 80 km (**8 ms** RTT) in southern Sweden 7SOL LEN GM/SL @RISE , 13 hops
- C36, with several empty slots space to next carrier
- Initial DCM+AMP, but expect less than 100 ps broadening,
- works without DMC,
  need about zero dBm input
- High jitter, both on 1pps and the LEN reported clock offset
- Uncorrected alpha,
  change in offset correlates with RTT changes of several hundred nanoseconds





What are we planning to do now?

Field Trial of FPGA-Based Real-Time Sensing Transceiver over 524km of Live Aerial Fiber

Mikael Mazur[1], Dennis Wallberg[2], Lauren Dallachiesa[1], Erik Borjesson[3], Roland Ryf[1], Magnus Bergroth[2], Borje Josefsson[2], Nicolas K. Fontaine[1], Haoshuo Chen[1], David T. Neilson[1], Jochen Schroeder[4], Per Larsson-Edefors[3] and Magnus Karlsson[4]

(1) Nokia Bell Labs, Murray Hill, USA
(2) Sunet, Tulegatan 11, Stockholm, Sweden
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(4) Department of Microtechnology and Nanoscience, Chalmers University, Sweden

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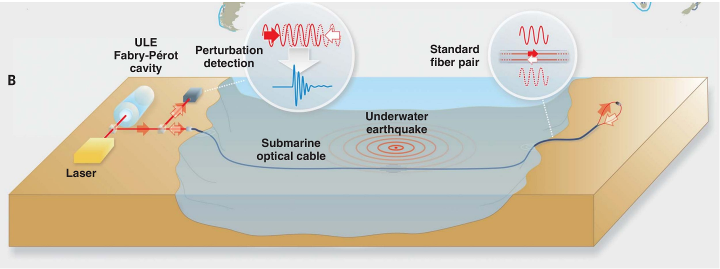
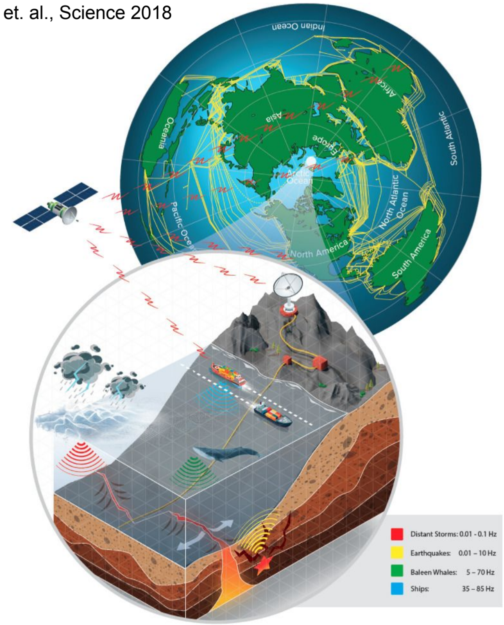
Fiber Sensing
Bridging the community gap

- Fiber sensing
  - Tones of single-mode fibers deployed for sensing purposes
  - Fiber is very sensitive: Strain, temperature, mechanical perturbations,…
  - The fiber sensitvity enables the fiber sensing field…
    but is also the reason we need dynamic DSP tracking!
- Example of sensing effects/techniques
  - Phase interferometry, polarization interferometry
  - Rayleigh, Brillouin and Raman scattering
- Why use telecom networks for sensing?
  - Improve the network reliability and protect against outages
  - Deployed fibers can expand coverage to new areas
  - Overall improve the role of fiber infrastucture in our society



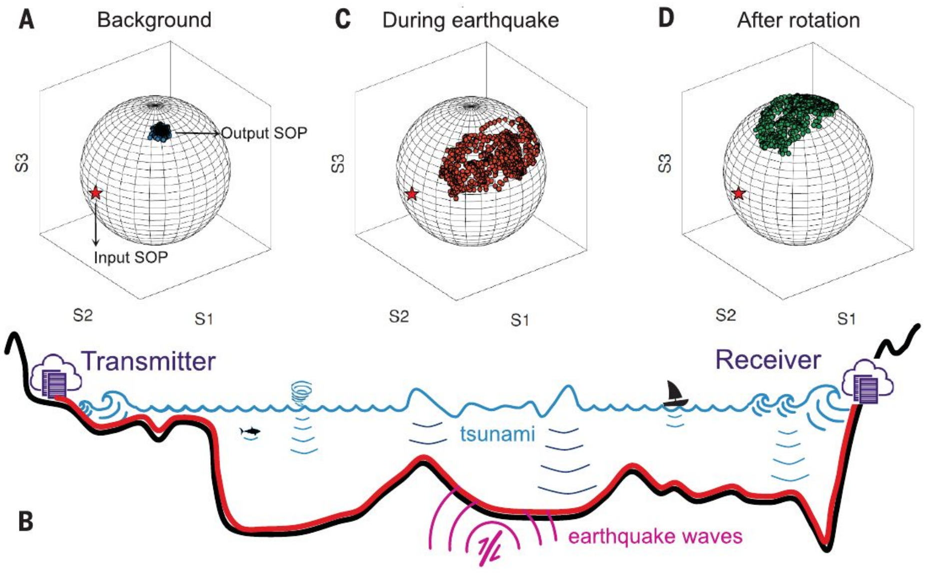
Marra et. al., Science 2018



M. Landro et. al., Sci. Rep. 2022

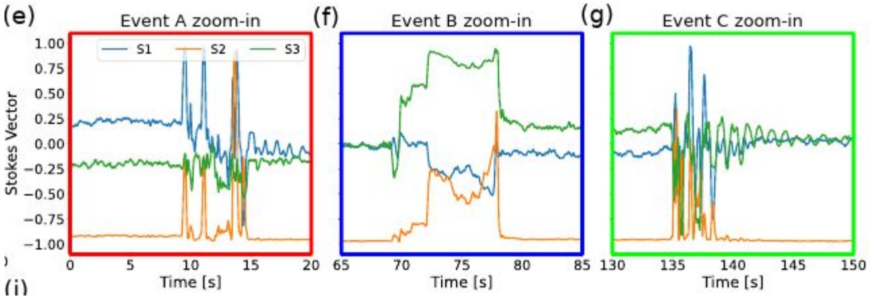
Examples of Transceiver-based Sensing

Earthquake detection using commercial transceivers



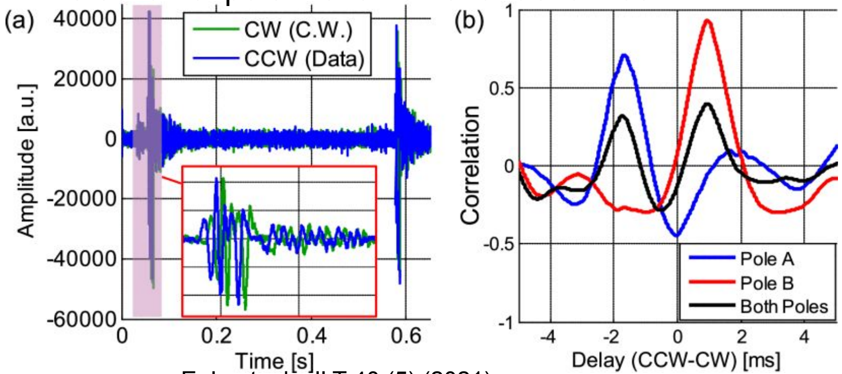
Zhan et. al., Science (2021)

Detection of fiber patch panel tampering over field link



M. Mazur et. al., Proc. ECOC (2022)

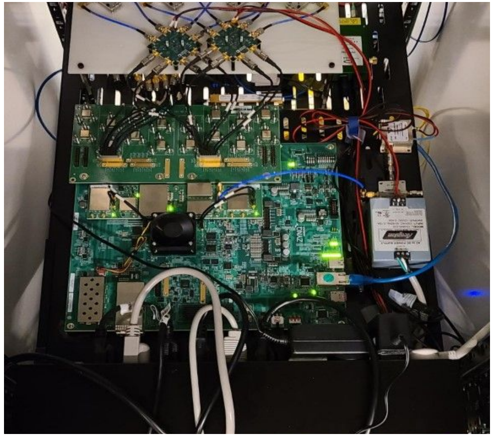
Detection of pole movements for aerial fiber



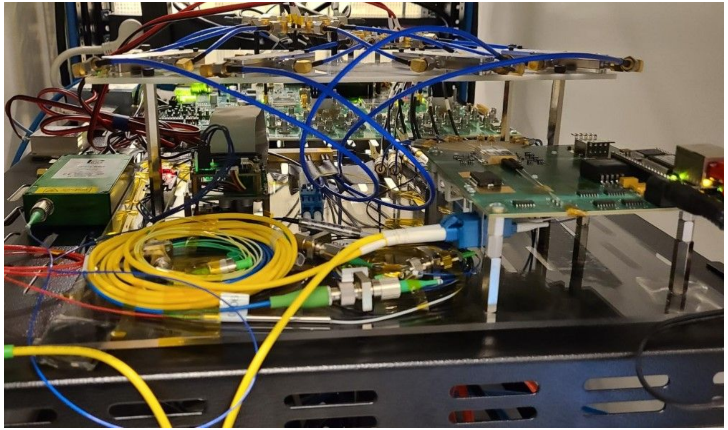
E. Ip et. al., JLT 40 (5) (2021)

NOKIA Bell Labs

Coherent Transceiver Prototype



- FPGA-based coherent DSP Engine
  - 1GBd transmission
  - 125MHz DSP clock rate, 8 parallel lanes
  - Complete pilot-based coherent DSP written in VHDL
  - All DSP blocks updated every clock cycle

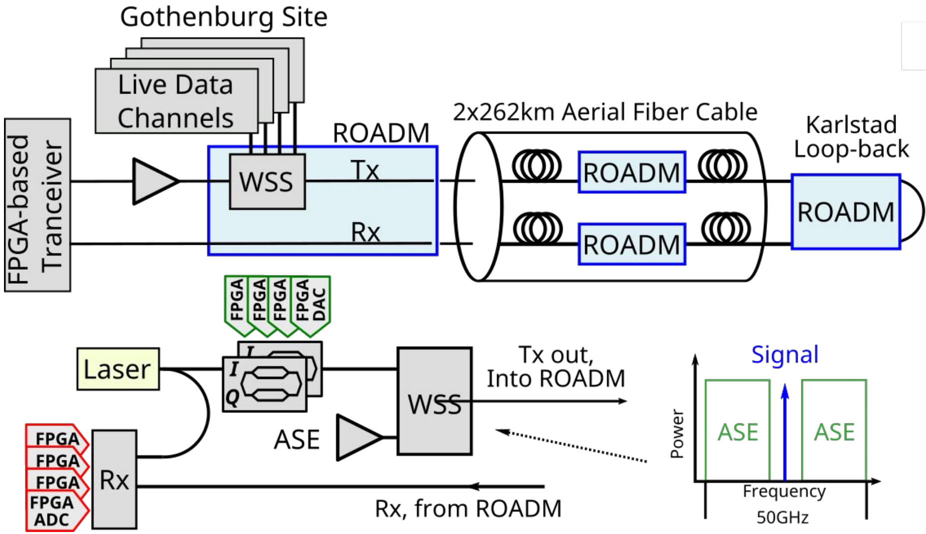


- Sensing capabilities
  - Polarization and phase sensing
  - This work focus on equalizer-based sensing
  - Complete streaming of equalizer state at MHz rate
  - Both hardware and software-level filtering implemented

NOKIA Bell Labs

Live Network Trial

- Connected to ROADM node in Gothenburg
  - 50GHz channel emulated by combining with ASE
  - Combined with multiple live coherent transceivers
  - Launch power equalized using ROADM WSS
- Loopback in Karlstad
  - Channel extracted using ROADM node
  - Physical loopback to transmit signal back to Gothenburg
- Receiver implementation
  - Full band drop-node, passive splitter
  - No optical filter present due to equipment limitations
  - Coherent Rx in homodyne configuration



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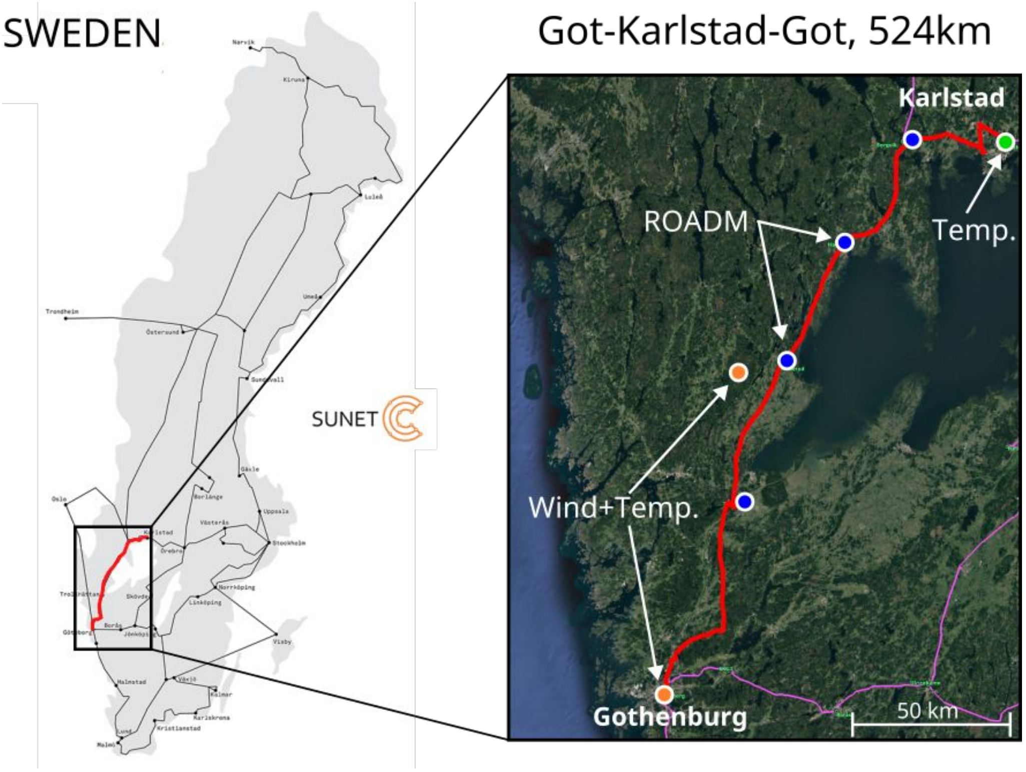
Field Trial – 524km of Aerial Fiber

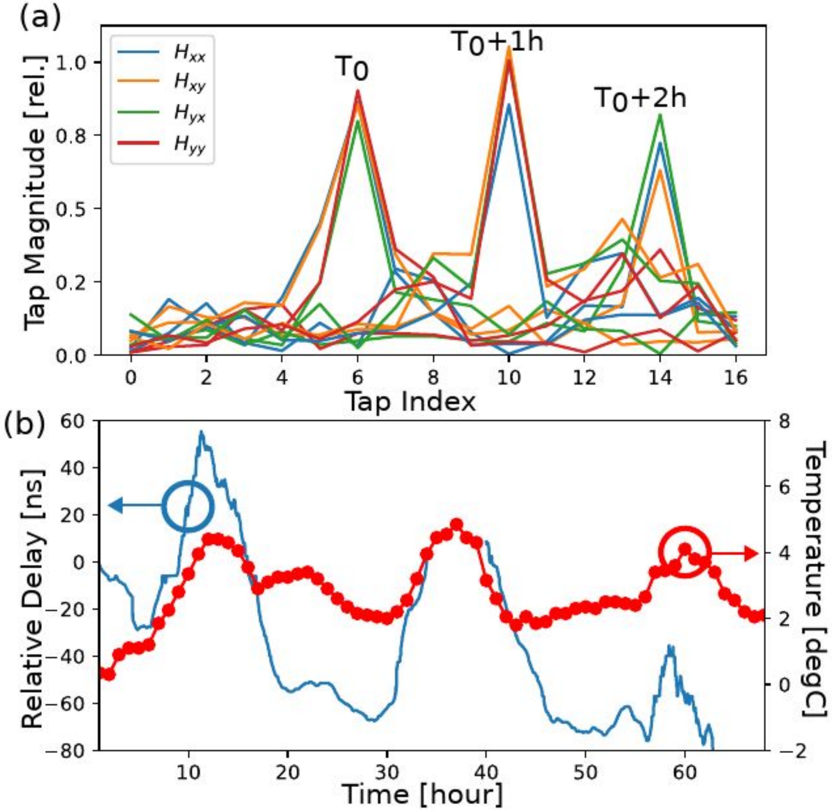
- Sunet Network
  - Provides connectivity to universities
  - Part of Nordnet, connects Scandinavia
  - Different links with a high degree of redundancy
- Specific test link
  - Gothenburg-Karlstad
  - 262km one way
  - Passes 5 live ROADMs
- Aerial fiber link
  - Fiber wound around high power lines
  - Very exposed to the environment



Results – Time-of-flight measurements

What can be learned from

- Dynamic equalizer for timing recovery
  - Stochastic gradient descent to optimize sampling position
  - Fiber stretch is an example of link-induced delay
- Time-of-flight measurements
  - Typically done using time-domain pulses
  - Transmitted signal is a continuous pulse train
  - Monitoring sampling position and phase → time-of-flight (ToF) measurements
- Correlation with weather stations along the link
  - Good qualitative agreement
  - Very dynamic link, lot of length change!
  - Requires clock tracking/referencing for non-loopback configs



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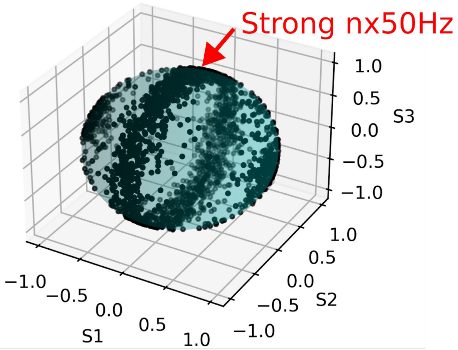
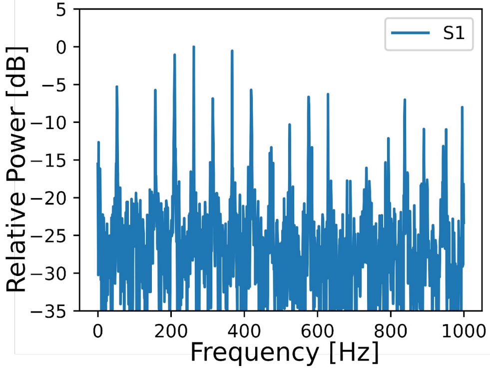
Results – State of Polarization

Aerial fiber wound around high voltage cables

- Measured polarization
  - Stokes vector extracted from received X-polarization
  - Strong 50Hz and overtones
  - Tones present for all Stokes parameters
- Strong tones dominates the polarization response
  - Similar to system noise
  - Must be filtered out to enable environmental sensing
- Correlation with weather stations along the link
  - Good qualitative agreement
  - Very dynamic link, lot of length change!
  - Requires clock tracking/referencing for non-loopback configs

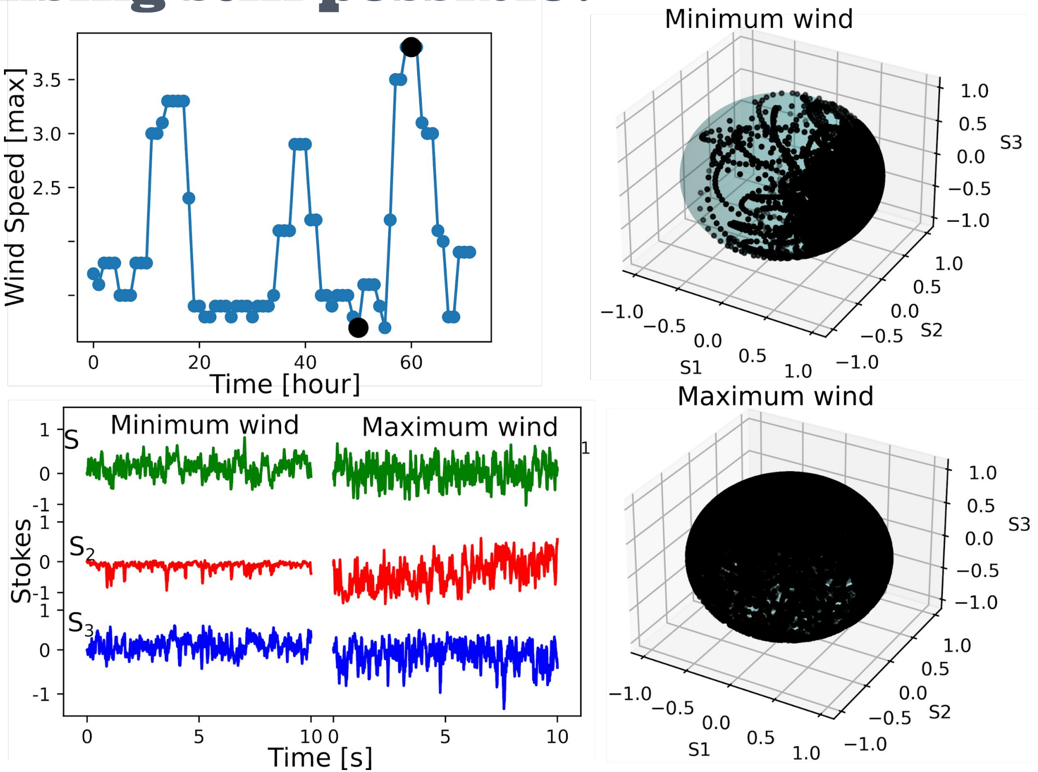




Results – State of Polarization

Is environmental sensing still possible?

- Nature is typically well behaved
  - No distinct frequency tones
  - Broadband, low-frequency response
  - Ranges of interest can be filtered out
- Extracting wind contributions
  - Focusing on frequencies below 45Hz
  - High sampling rate avoids aliasing
  - Filtering and decimation can be done in HW
- Difference in wind conditions observed
  - Amount of SOPR clearly correlates
  - Aerial fiber, highly affected
  - Frequencies of interest very different



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Collaboration partners

Erik Börjeson

Postdoc, Fotonik, Mikroteknologi och nanovetenskap

RI. SE Research Institutes of Sweden

NETNOD

Funding partner

PTS

Time transfer in coherent networks

- Limitations from network
  - No, or small, variation in amplitude on optical signal
  - Optical dispersion compensation for 100 GB transmission – any other data-rate must be handled by channel.
  - Duplex transmission
  - 50 Hz polarization variation

- Limitations from TT
  - Combination of 1PPS and timing data on same channel
  - Two way transfer. Mimize influence of optical pathlength asymmetrical variation
  - Tx and Rx must experience constant delay
  - Any DSP operations must be adjusted for constant total delay

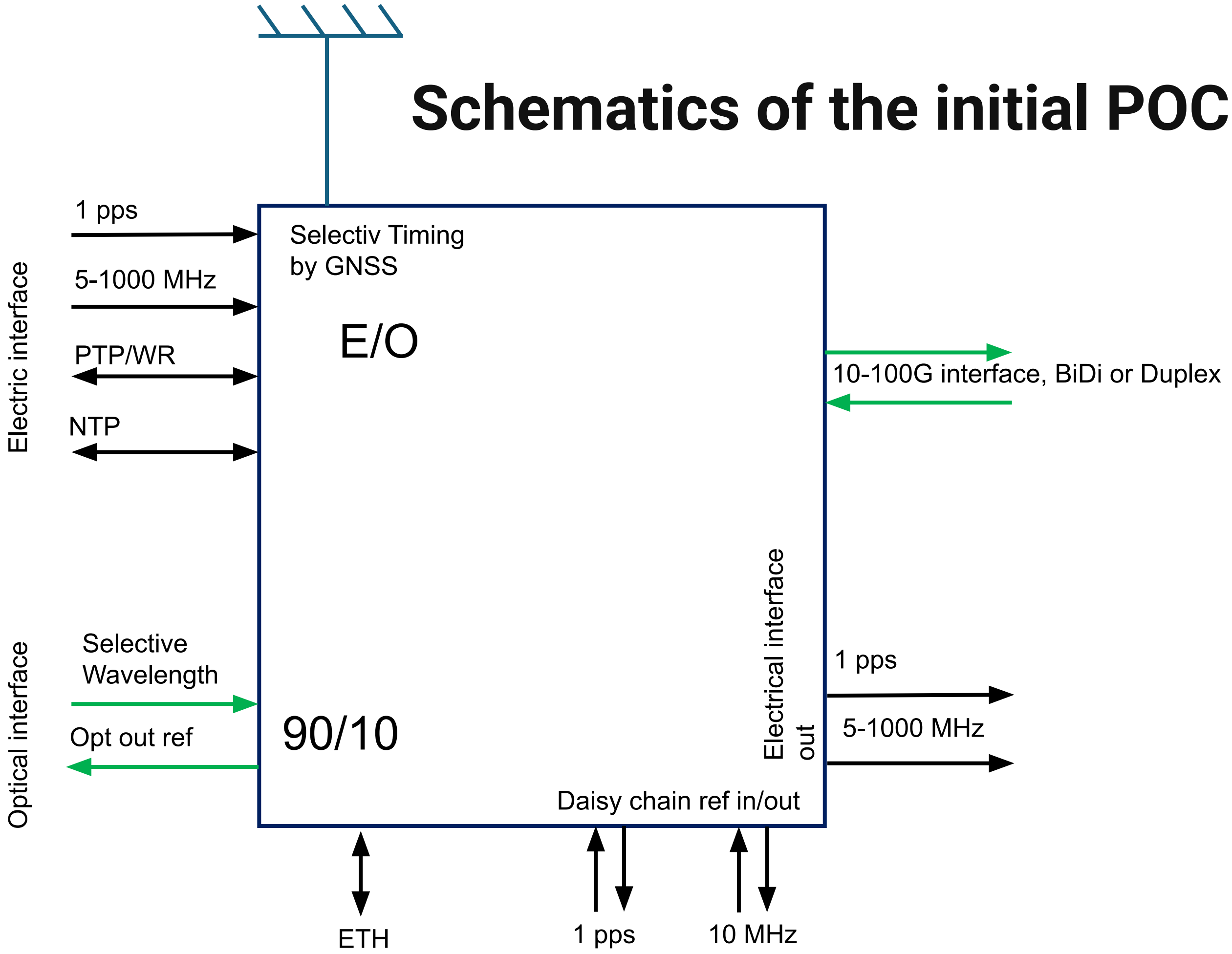
Specification for TiFKON (Tid och frekvensöverföring I koherenta nät)

- A TiFKON link consists of two identical transceiver modules for electrical and optical time and frequency transfer
- Electrical 5-1000 MHz signals and ADEV with target better than 1x10-13 at 1 s average, below 1x10-17 for 1000 s average
- Electrical 1 pps signal with possibility for 100 pps, coherent with frequency signal, TDEV better than 3 ps for 10 s average and better than 1 ps for 1000 s average
- TiFKON shall be actively stabilized against fiber induced fixed fluctuations and phase correction interval is 2us
- Outgoing 1 PPS flank shall be adjustable with 1 ps resolution, negative delay is possible,
- Maximum optical loss 25 dB. Optionally, the system can be enriched with optical amplifiers.

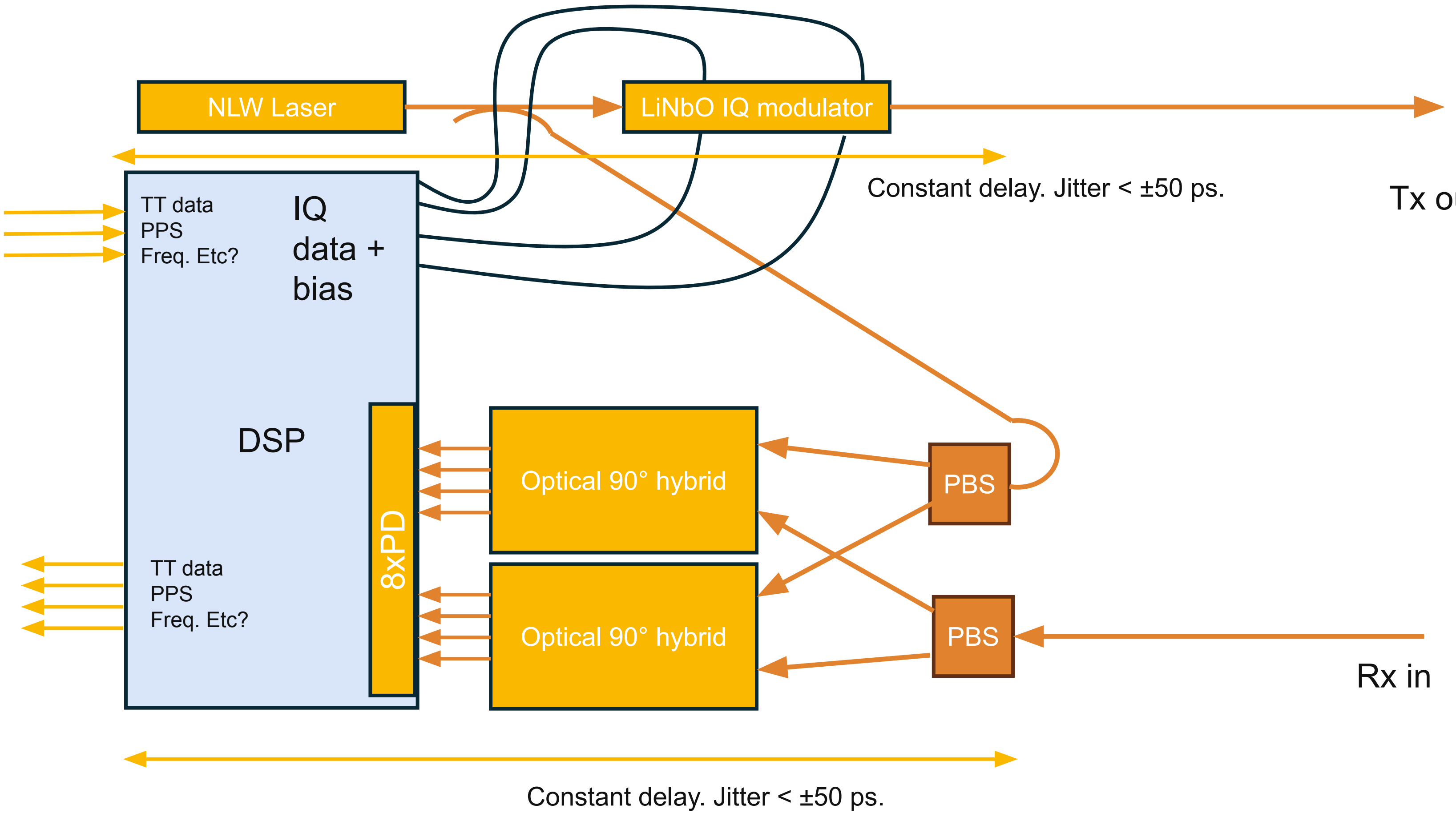
Specification for TiFKON (Tid och frekvensöverföring I koherenta nät)

- **Active delay stabilization**
  - The unique features of the system are based on the concept of active compensation of fiber delay variations. The signal that reaches the receiver is sent back to the transmitter module and is used to compensate for fluctuations in the path delay.
- **Autocalibration**
  - The automatic calibration of the time transfer is based on round-trip delay measurements, which are performed at the transmitter side. After installation and initial calibration, the input-to-output delay that gives an offset is continuously measured to compensate for longer variations
- **PPS adjustment**
  - 1 PPS output signal shall be adjustable with 1 ps resolution to compensate for the delay introduced by the fiber link. If desired, the link shall be adjustable so that link delay is compensated.
- **Dispersion options**
  - The system is based on coherent phase modeled signals and is affected by polarization dispersion which must be compensated for and the part of chromatic dispersion that is present may be calibrated away initially.

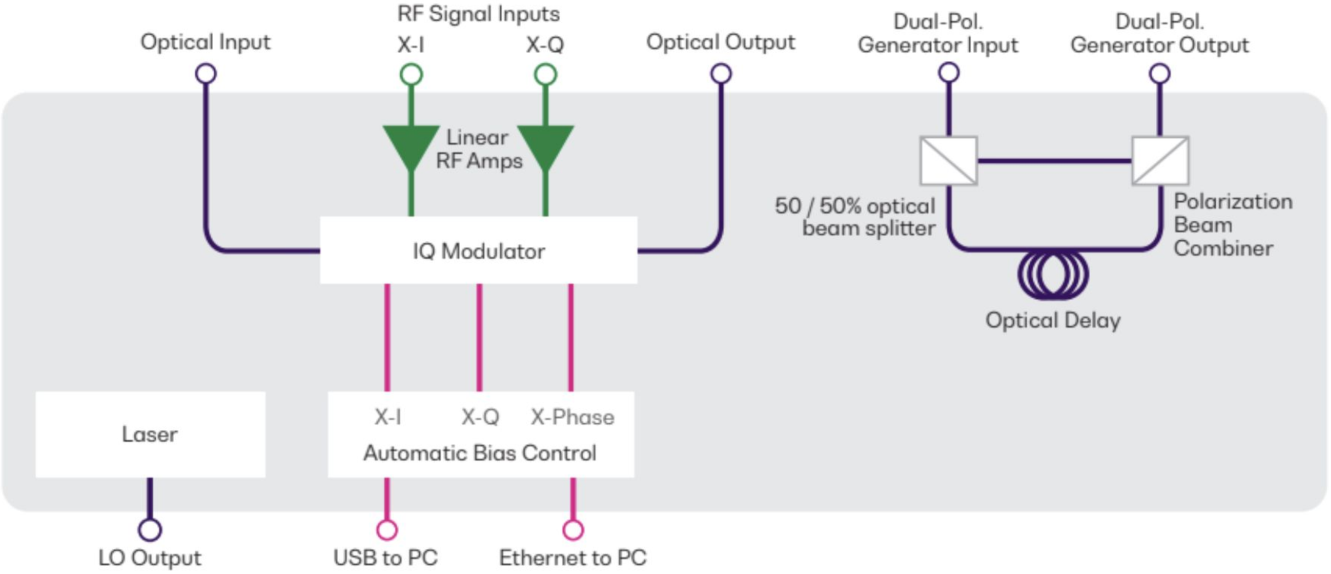
Schematics of the initial POC module



TxRx for TT in coherent transmission networks



Schematics of the initial POC optical transmitter



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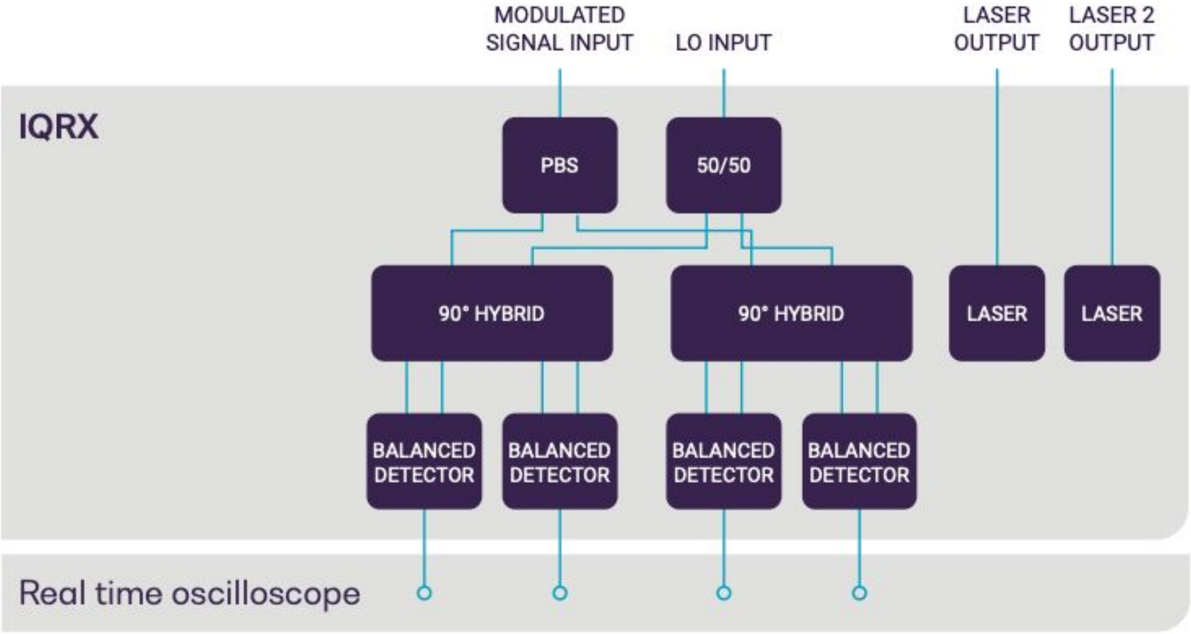
Schematics of the initial POC optical receiver



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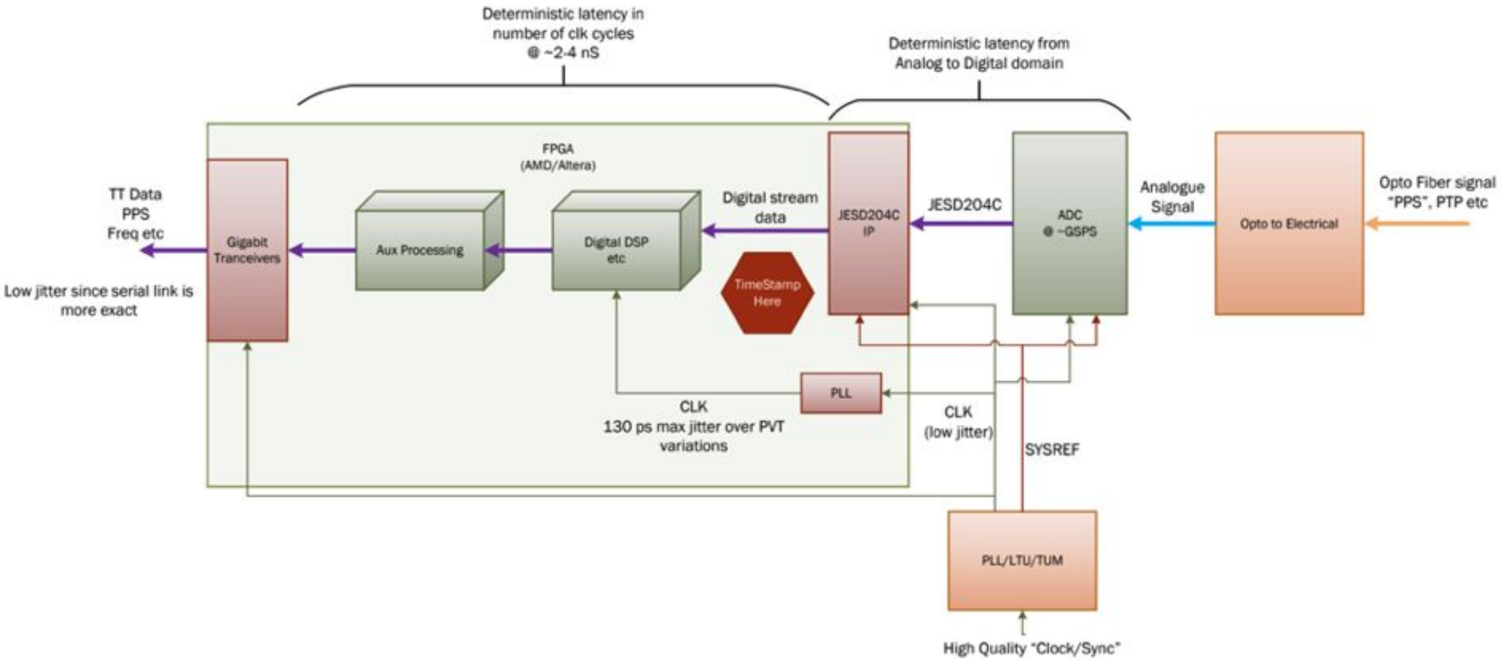
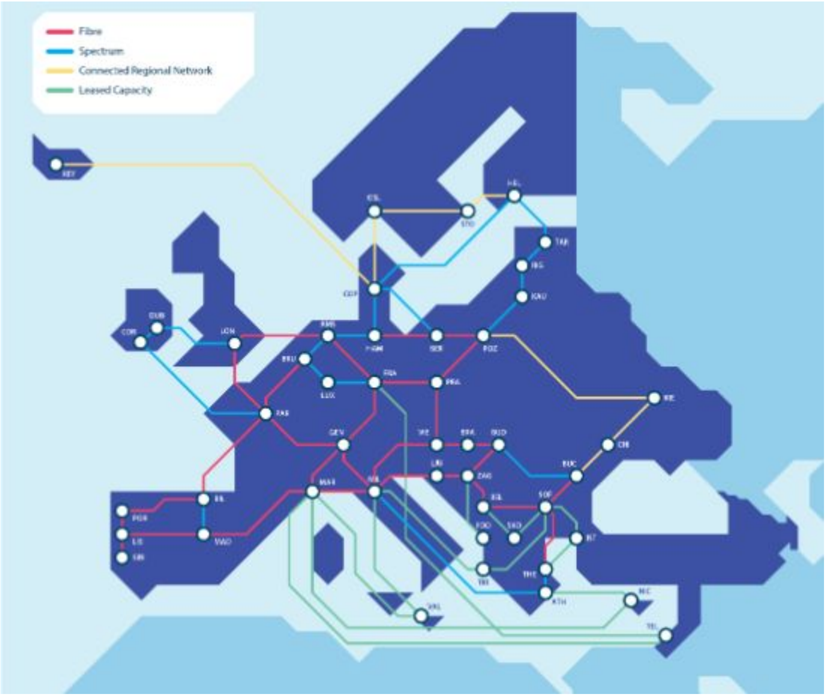
Initial receiver FPGA schematics



So far

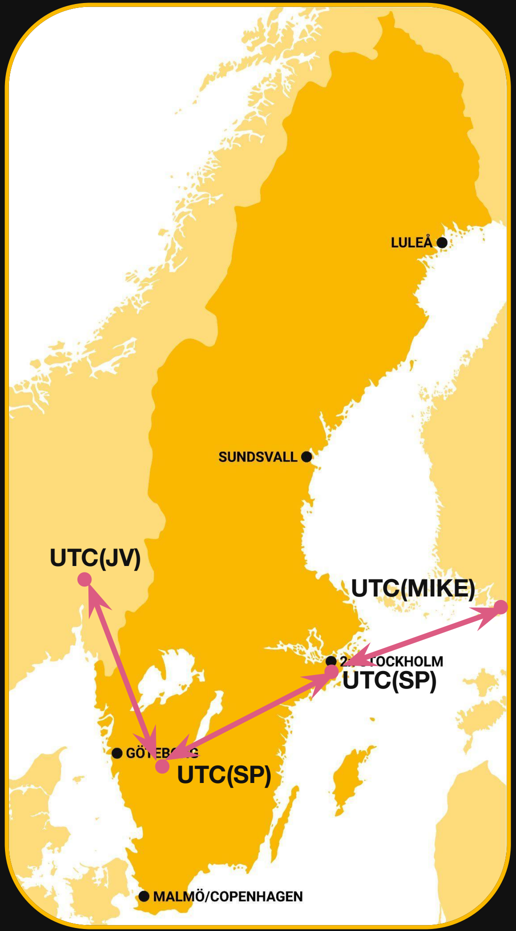
Aim specifications

- 10-100GBit compatible (QPSK,16QAM)
- 1pps
- Frequency 5 to 100 MHz
- 19 inch rack
- Bi-direct and duplex
- Sub ns
- PTP, WR or custom format
- Redundant power
- FPGA
- Daisy Chain
- Selective wavelength
- Optical ref output



Initial Start of a Nordic Timing Network

- Distributed by Netnod, traceable to UTC(SP) @RISE financed by Swedish Post and Telecom Authority
- In black 6 time nodes placed in secure locations across Sweden steered to UTC(SP)
- Work in progress of connecting UTC(k) in nordic countries



Questions?