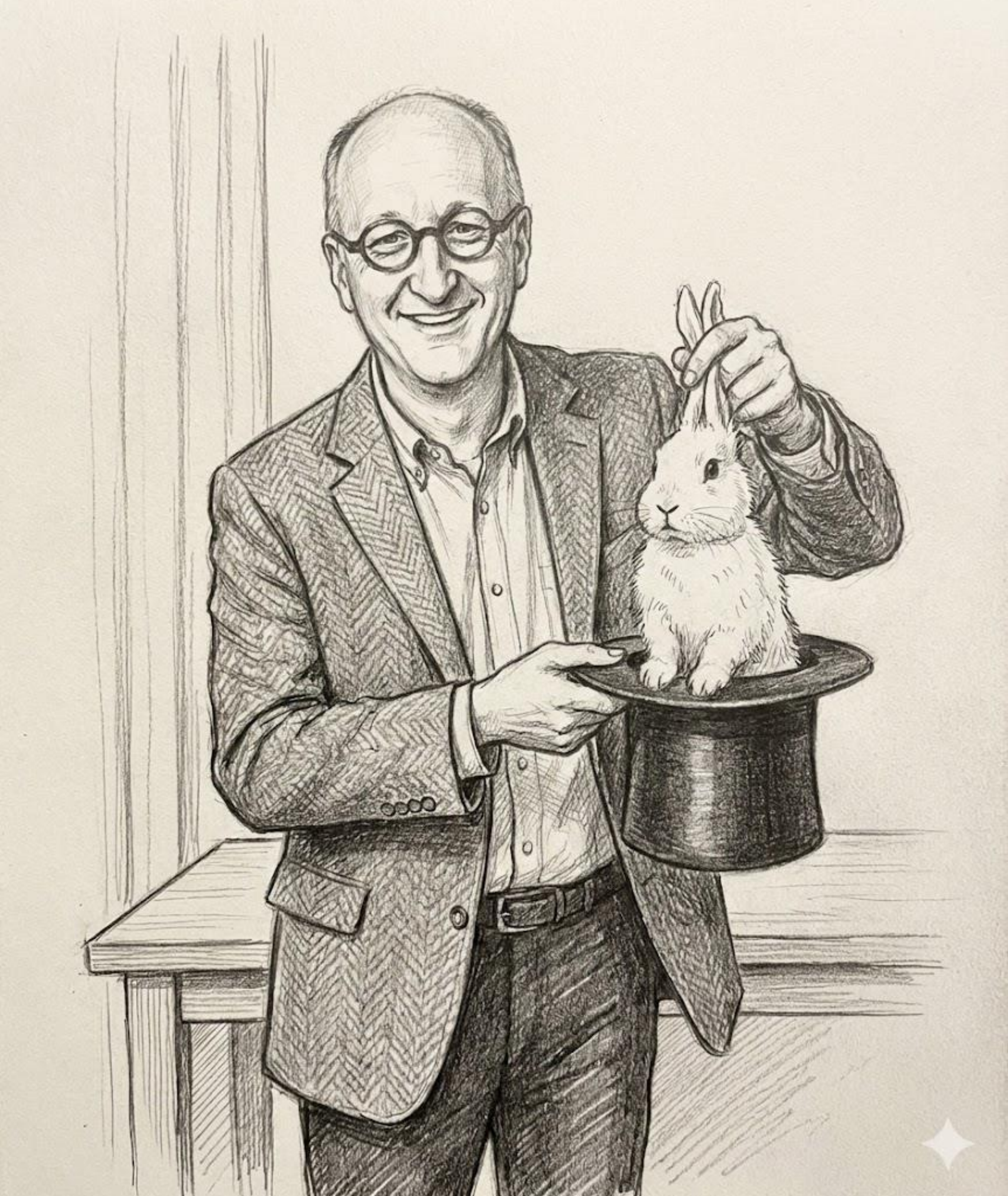
Long-haul White Rabbit Time Distribution:

Recommendations for NRENs from the GN5-2 Incubator Project

Guy Roberts
NETWORK ARCHITECT

WR InfoShare

13 May 2026

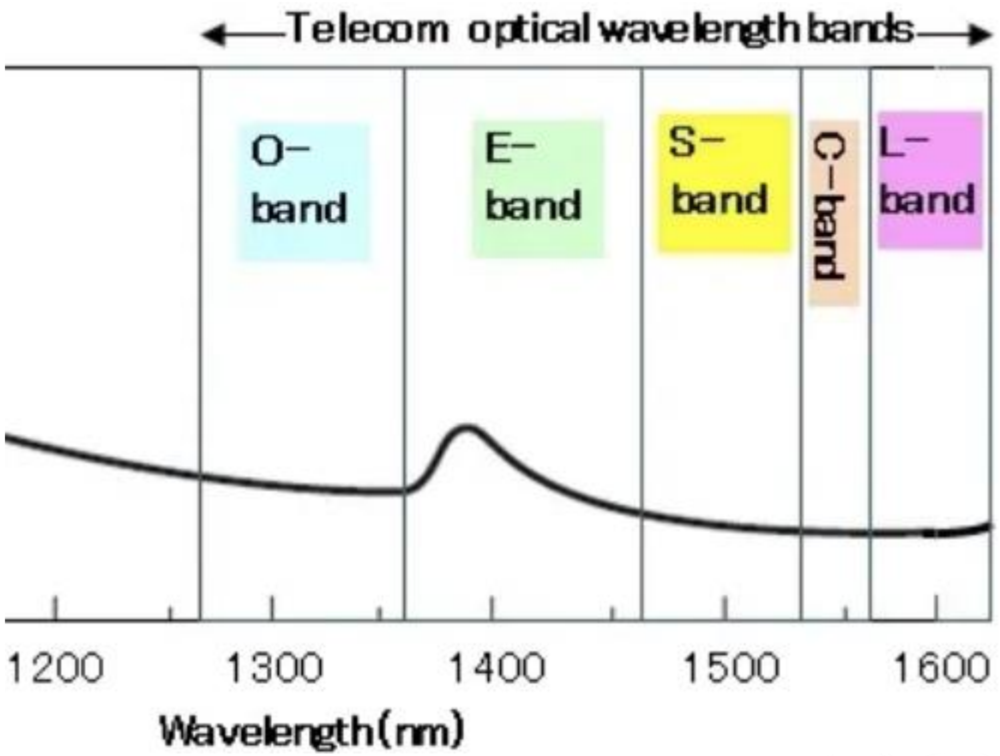


Sharing the long-haul fibre — safely

- Lab and field trial both confirm that WR can share a long-haul fibre with internet traffic without risking the integrity of that traffic
- Coexistence is conditional, not automatic — the optical-layer needs careful design
- The two big decisions for an NREN at this layer:
  - Where to place the WR wavelength (C-band vs. L-band, edge vs. middle)
  - How to regenerate the WR signal between amplifier sites (1R / 2R / 3R)
- Suitable guard-bands must be used to ensure no degradation of internet traffic
- These decisions all have cost implications

Where should the WR wavelength live?

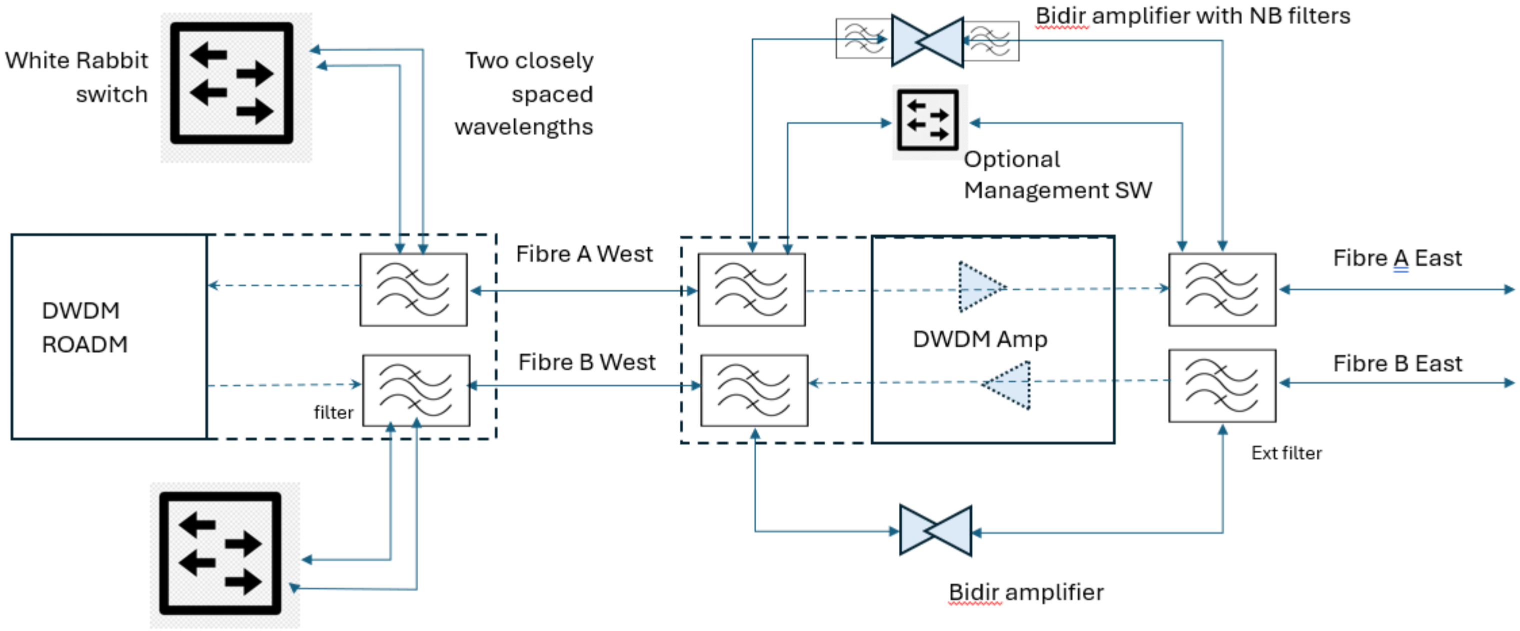
- Reserving WR channels in the C-band reduces the spectrum available for revenue-generating data channels
- The L-band is still amplifiable by EDFA but is typically unused for data — making it an attractive home for WR
- Choose the band based on:
  - New-build vs. retrofit — new builds can readily add L-band filters and save C-band spectrum
  - Whether the DWDM platform already includes built-in L-band filters
  - Whether the C-band is running short of available spectrum
- Guard-band tip: placing WR at the edge of the C-band halves the guard-band cost vs. placing it in the middle



1R — Bidirectional amplifiers: best performance, with caveats

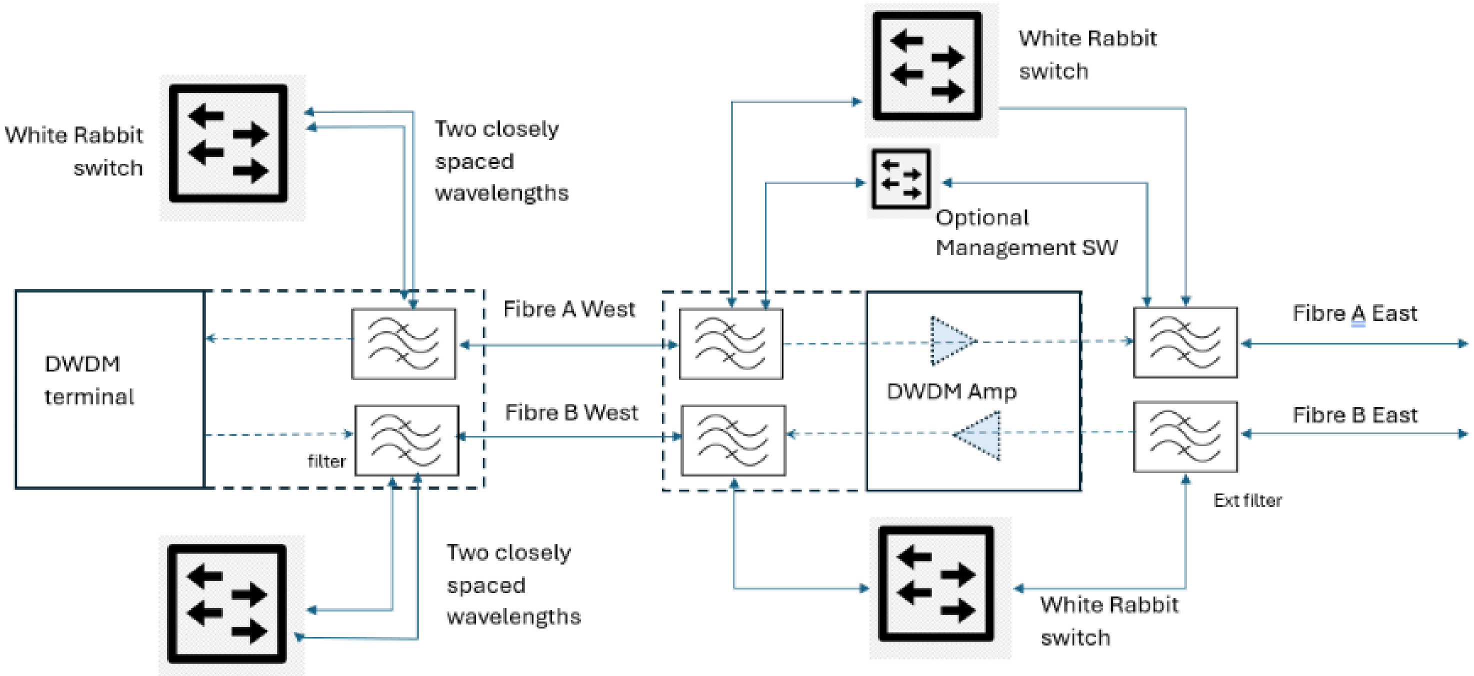
- Testing shows bidir amps give the best time-distribution performance of the 3 options
- Considerations to keep in mind for design and cost:
  - Higher cost on longer systems
  - 3R regeneration still required after every 5–8 bidir amps
  - Interaction with Raman pumps can cause asymmetric gain — must be evaluated up front
  - Susceptible to gain oscillations if reflections are present on the fibre

- Mitigation: keep amplifier-to-amplifier fibre spans below 80 km / 20 dB, and use APC connectors throughout to suppress reflections



2R and 3R — cost-effective and flexible alternatives

- OEO regenerators (2R)
  - Readily available at low cost; performance close to bidir amps
  - 2R allows the wavelength to change between regens (calibration becomes more complex)
  - Cheaper OEO regen variants often lack carrier-grade OAM (dual PSUs, SNMP, remote management) — choose carefully
  - Cooling of cheap chassis has been a problem with long-haul tunable lasers



- WR switches (3R)
  - Can be used in place of OEO regens, with more flexibility but lower performance — accuracy degrades faster than other options
  - Higher cost to chain; clock stability of the switch matters greatly on long systems
  - Insist on carrier-grade features; open-HW versions may have limited vendor support and warranty

costing tool

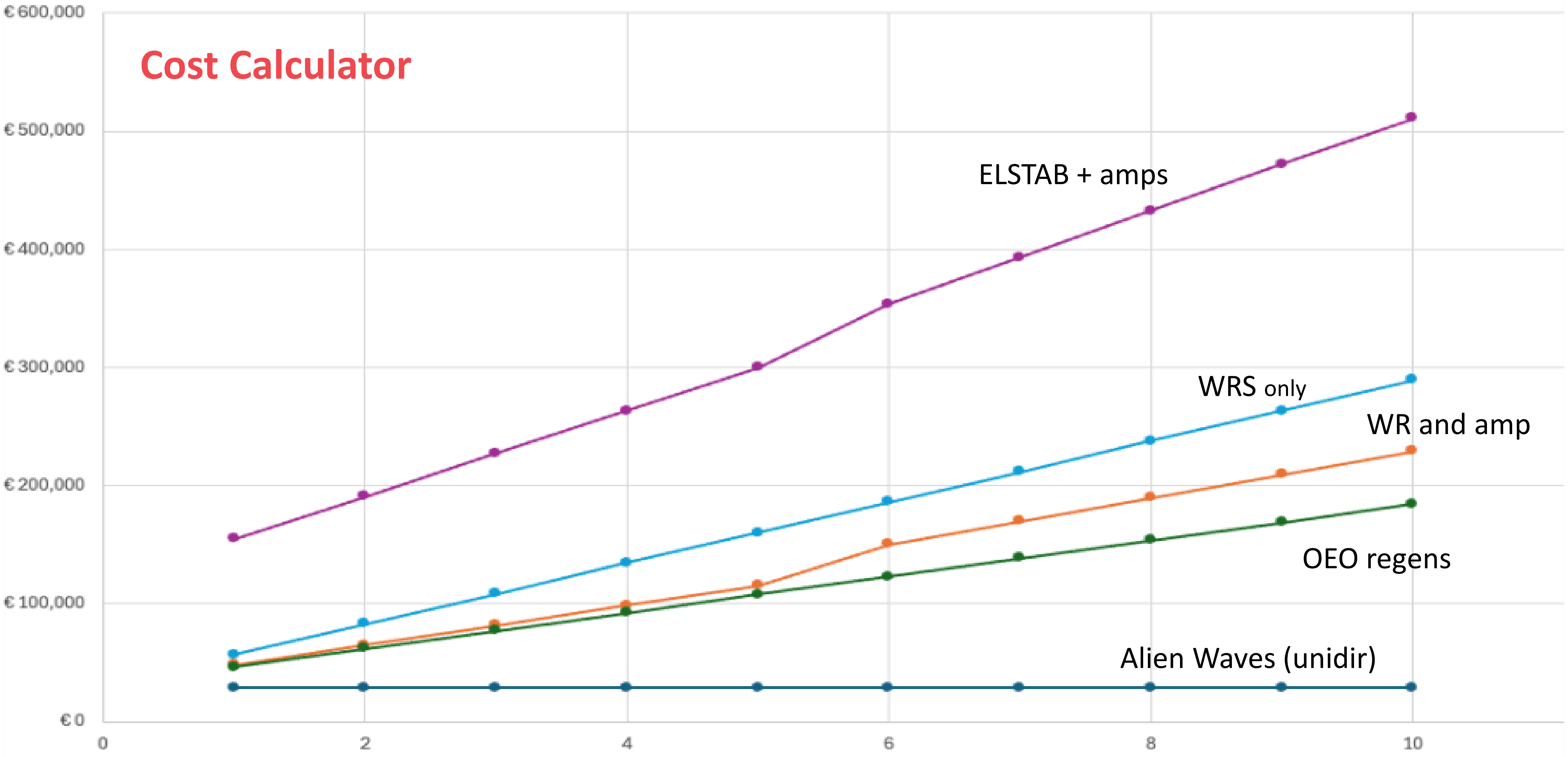
White Rabbit - cost calculator

term (yrs)	5
number of ILAs	10
number of 50GHz guard bands required	2
Carrier Grade WR terminal required?	no
Terminal filter cost	€ 850
Amplifier manufacturer: CZL or PTS	CZL (Bi-dir option only)
Equipment Annual Maintenence % of CAPEX	10%

include connectivity costs	no

	one off	annual
AW cost per 50Ghz		
AW licence cost		(one per AW)
50GHz channels per DF		
DF Lease cost		

		Equipment		Connecitivity		Total		
Scenario name	**description**	**CAPEX**	**Maintenance/annum**	**NRC**	**ARC**	**one off / Capex**	**ARC**	**TCO**
Alien wave	WR signal is carried over a DWDM alienwave. Each direction is on a separate fibre	€ 19,000	€ 1,900	€ -	€ -	€ 19,000	€ 1,900	€ 28,500
Bi-dir amp C/L-band	The WR signal bypasses the telecoms amplifier and is sent to a specialist T/F bidir amp	€ 132,700	€ 19,270	€ -	€ -	€ 132,700	€ 19,270	€ 229,050
OEO C/L band	The WR signal bypasses the telecoms amplifier and is sent to an OEO regen	€ 122,700	€ 12,270	€ -	€ -	€ 122,700	€ 12,270	€ 184,050
WRS at amp sites C/L	The WR signal bypasses the telecoms amplifier and is sent to a White Rabbit Switch	€ 192,700	€ 19,270	€ -	€ -	€ 192,700	€ 19,270	€ 289,050
ELSTAB	The ELSTAB signal bypasses the telecoms amplifier and is sent to a specialist WR amp	€ 320,700	€ 38,070	€ -	€ -	€ 320,700	€ 38,070	€ 511,050


Cost Calculator
€ 600,000
€ 500,000
€ 400,000
€ 300,000
€ 200,000
€ 100,000
€ 0
0
2
4
6
8
10
ELSTAB + amps
WRS only
WR and amp
OEO regens
Alien Waves (unidir)

What does the WR wavelength really cost you?

The whitepaper provides a cost calculator covering a wide range of technical solutions — actual cost varies widely between NRENs

The biggest variable: how each NREN values DWDM spectrum

- Some NRENs treat the WR channel as zero cost — the DWDM build is already a sunk cost
- Where C-band spectrum is scarce, could treat WR spectrum as a cost

Spectrum cost is increased when the WR channel sits in the middle of the C-band, requiring guard-bands on both sides

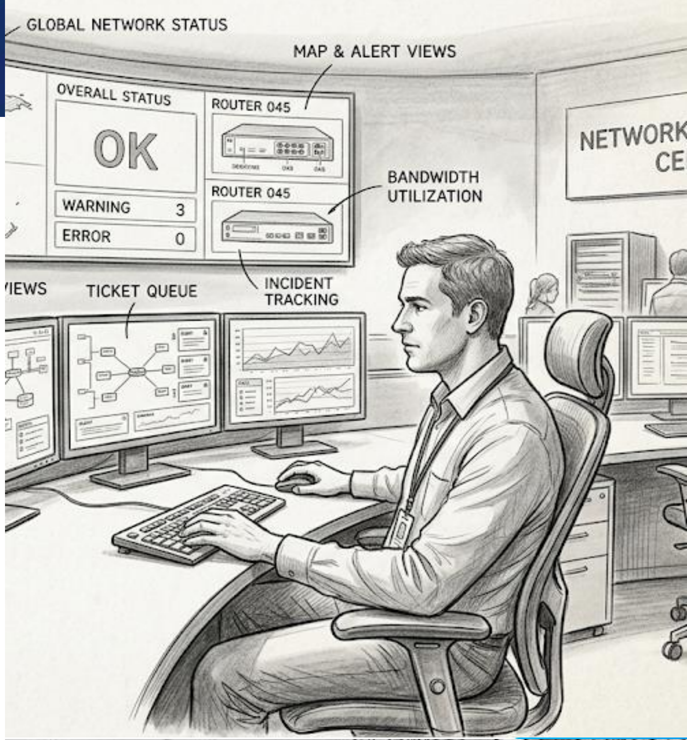
Operators can plug their own assumed values for WR-channel cost and number of guard-band channels into the calculator

Regeneration and supervisory-channel costs

- **Regeneration cost**: strongly dependent on the total link length
  - Shorter systems are better suited to bidirectional amplifiers
  - Use the costing tool to make the trade-off concrete for your topology
- **Optical Supervisory Channel**: amplifier sites usually lack local internet access
  - Build an OSC into the solution
  - WR switches can sometimes double as the management path
  - Many DWDM amplifiers expose an Ethernet port that can carry the OSC
  - If using bidir amps or OEO regens with no on-site network, budget for a dedicated OSC — this is not included in the provided cost calculator

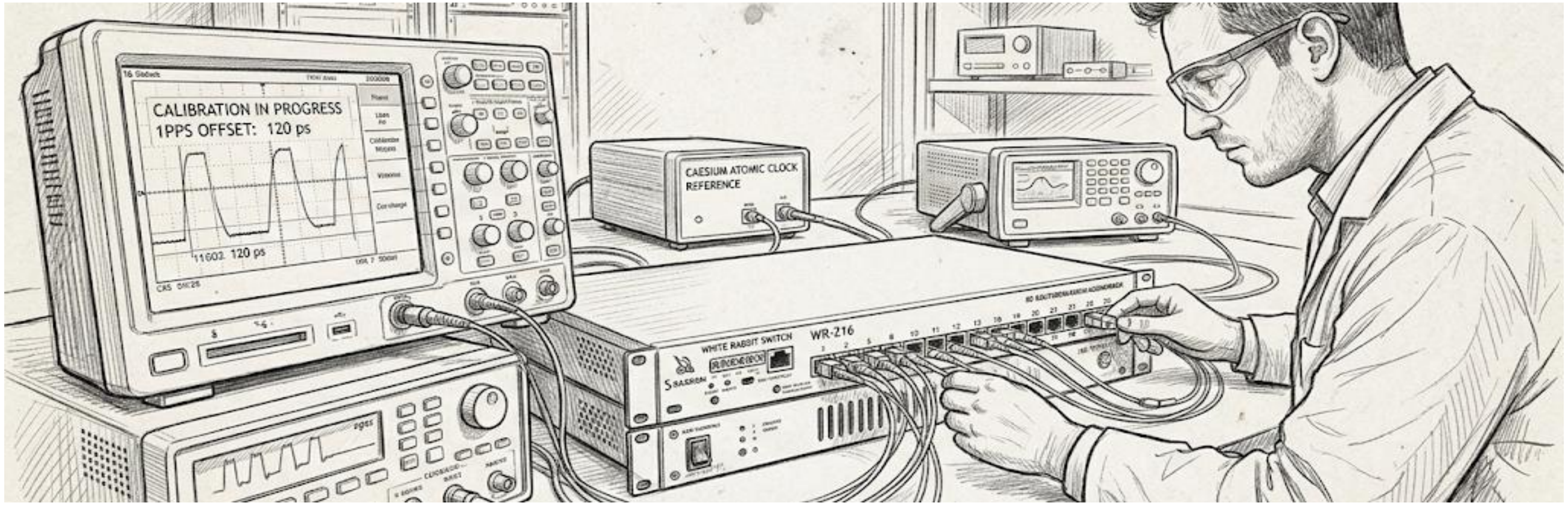
Designing for operations from day one

- A long-haul WR network must be operable and maintainable — design these features in from the start:
  - Dual power supplies for reliability
  - CLI or API for monitoring and configuration
  - SNMP traps for alerting
  - OSC channel for management (a WR switch is one option)
  - Local management Ethernet switch where needed
  - Temperature monitoring and fan-failure alarms; fan-speed monitoring
- In-band management of open-source WR switches via SNMP is under discussion in the WR consortium but not yet defined
- Support model matters: GÉANT uses an integrator with a central European spare-parts depot for on-site swap-outs — some NRENs will use in-house staff, others will outsource



Calibration is essential — plan for it

- Calibration is an inevitable requirement of deploying WR - see section 2.4 of the whitepaper
- Excellent documentation on methodology is available from the WR collaboration:
  - https://gitlab.com/ohwr/project/white-rabbit/-/wikis/Documents/White-Rabbit-calibration-procedure
- Any Tx/Rx asymmetries need to be measured and accounted for - ideally before the equipment is installed
- Practical NREN guidance: start with manual calibration but plan to migrate to automated calibration rigs as your time network scales
- Beware of Tx/Rx on different fibres - calibration will be needed after every fibre repair

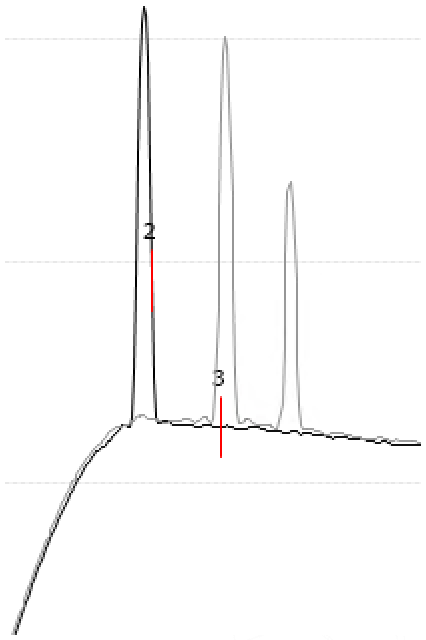


If you choose to use bidirectional amplifiers (1R regen) then parasitic reflections are a risk

- Keep bidirectional gain as low as possible and strictly below the lasing threshold
- Suppress reflections with the use of splicing rather than optical connectors
- If connectors are need use high-grade angled polished connectors (APC) rather than standard polished connectors (PC)

Additional techniques:

- Narrow-band optical filtering before each amplifier can help
- Use distributed amplification instead of lumped gain (Raman gain helps!)
- Break up very long runs of amplifiers with regeneration.

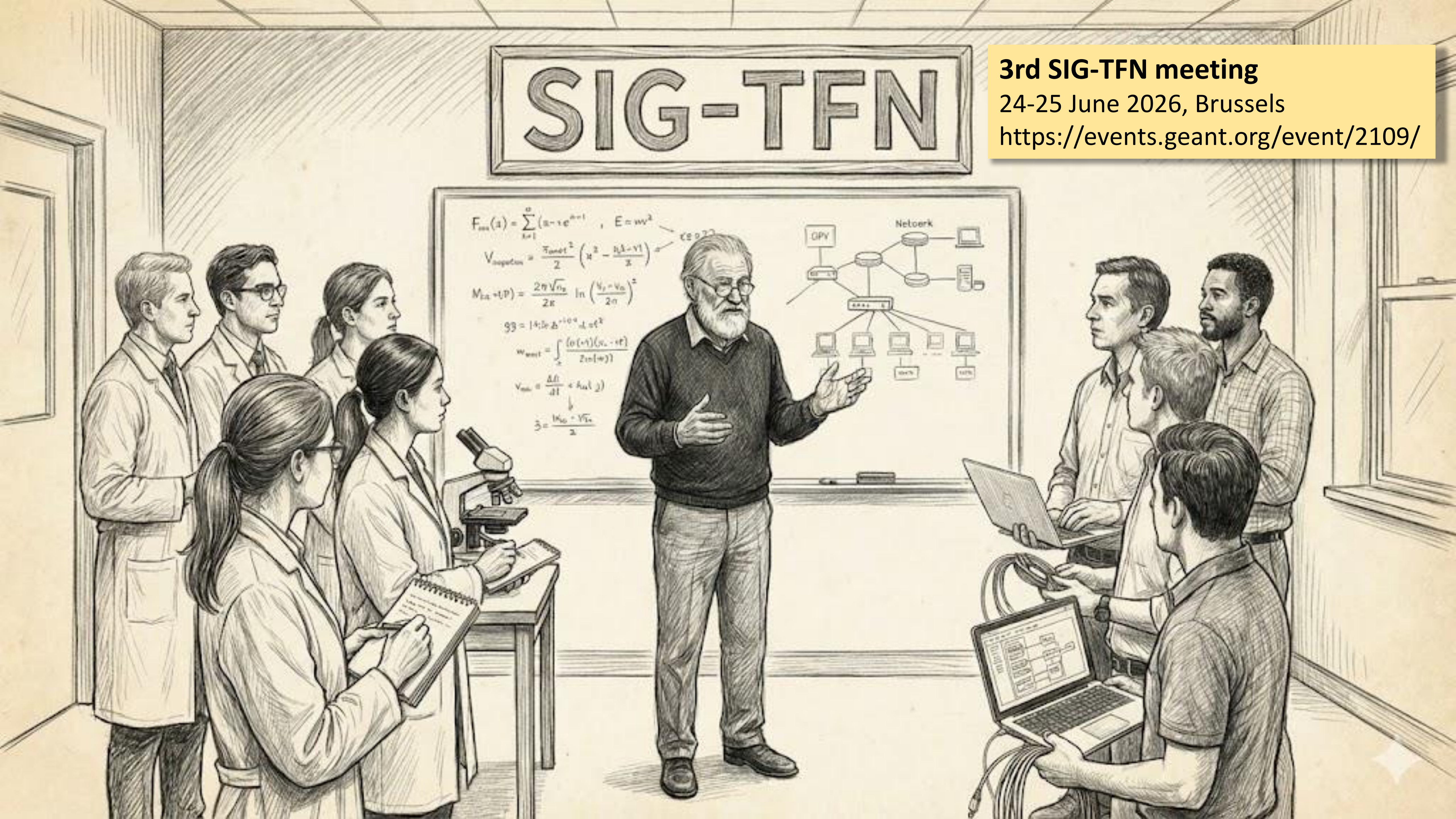


Don’t forget cooling — it bit us in the lab

- DWDM transceivers actively temperature-stabilise their DFB laser chip, so they consume more power than conventional SFPs and need better cooling
- In the lab, DWDM SFPs in simple CTC 2R SFP-SFP media-converter chassis overheated within hours, "retuning" to a different wavelength and dropping the link
- The fix: a higher-grade chassis with better heat dissipation and active fan cooling — after which transmission was stable for the long term
- Recommendation: when ordering transceivers, explicitly check the heat-dissipation and cooling capability of the host OEO regenerator chassis

Conclusion

- Coexistence works: 1 Gbps WR signals can share fibre with 400G coherent channels with no measurable BER impact, given a standard 100 GHz guard-band
- Stability achieved: ±100 ps time transfer stability over a 498 km field-installed loop using five bidirectional amplifiers — well inside the 1 ns target
- Three regeneration options compared:
  - Bidirectional optical amps (1R) — best performance
  - OEO media converters (2R) — strong cost-performance trade-off
  - WR switches (3R) — flexible, but more jitter in cascade
- Optimal solution will be a trade-off between budget and performance



3rd SIG-TFN meeting

24-25 June 2026, Brussels

https://events.geant.org/event/2109/

Thank You

www.geant.org

Co-funded by
the European Union

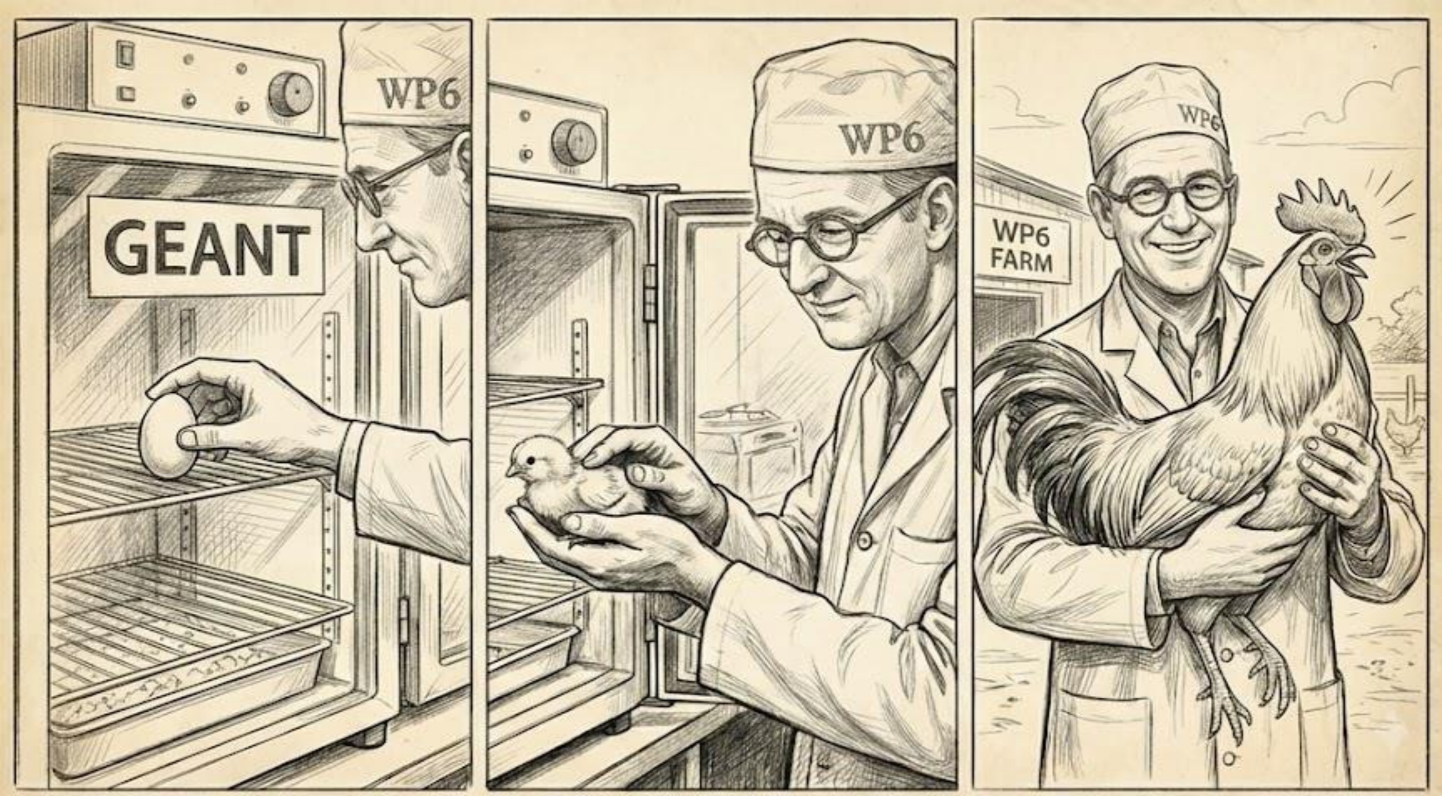
White Rabbit incubator in WP6

- **Challenges**: current WR deployments are based on 1Gbps and 10Gbps NRZ modulation. NRZ is not ideal on DWDM systems designed for only coherent optics

- **Objectives**: learn from existing deployments of WR over long-haul DWDM systems and carry out experiments and a field trial.

- Competing solutions are available at amplifier sites: bidirectional amplifiers, WR switches for regeneration, and Optical-Electrical-Optical regens have been proposed.

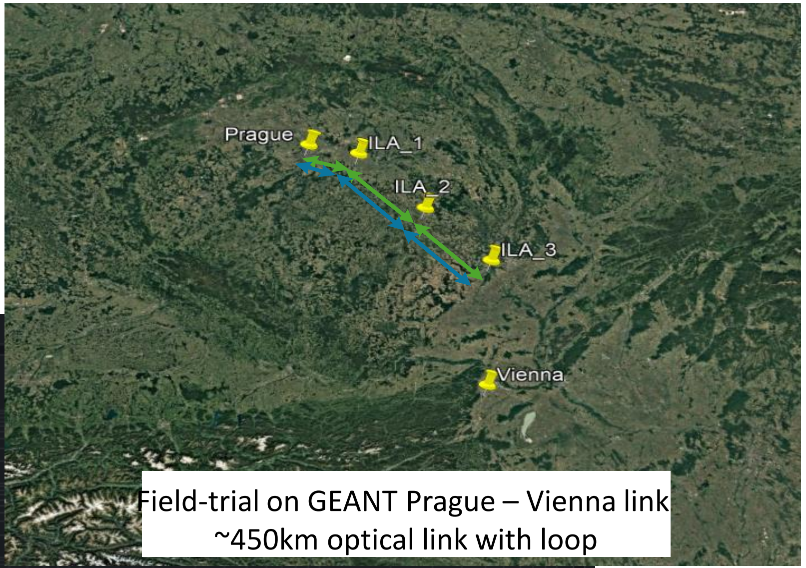
- How can NRENs get the best out of WR in their networks?



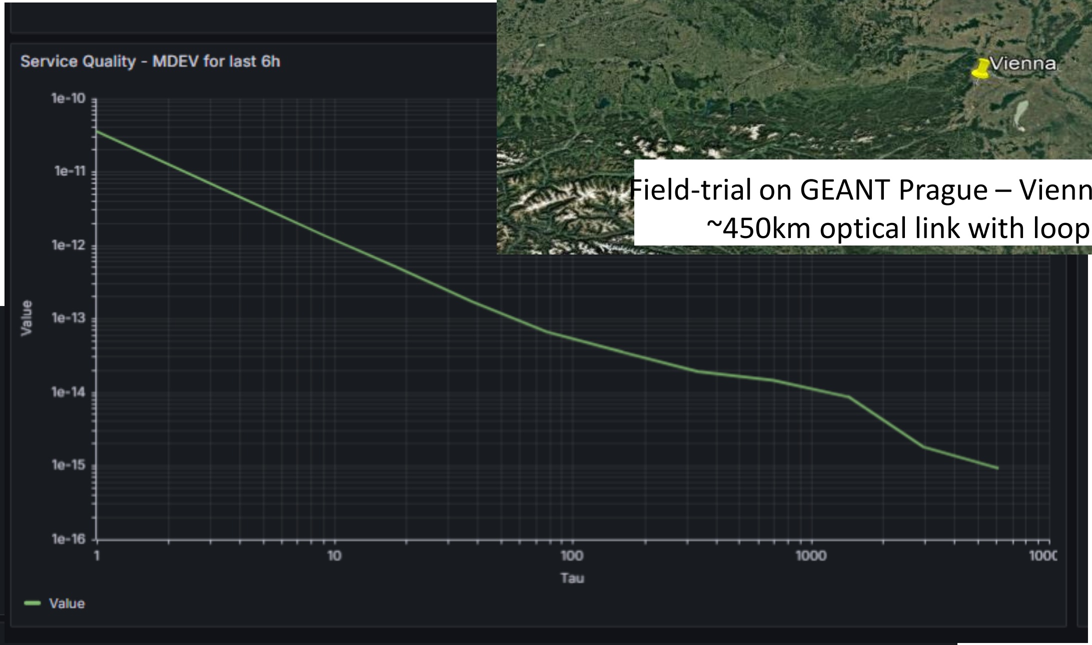
Long-haul White Rabbit Trial

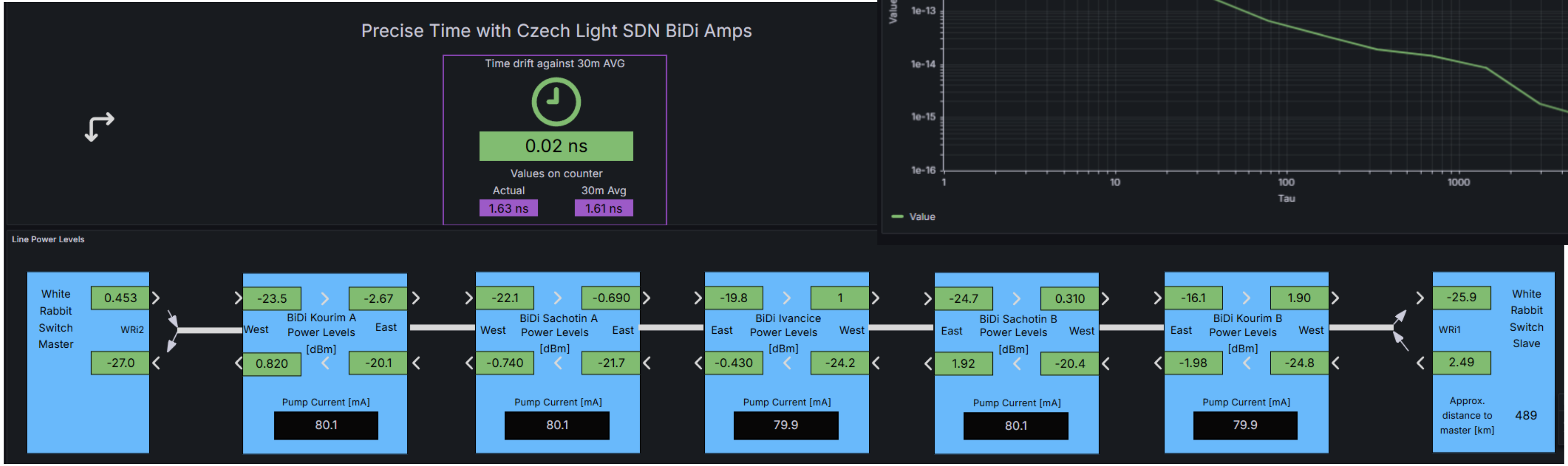
- Trial to demonstrate the high precision WR time distribution over the L-band in GEANT network
- Link built over 450km and 6 hops from Prague towards Vienna
- Typical time drift of 0.02ns compared to reference

With integration period of 10,000 s can achieve accuracy of one part in 1e15



Field-trial on GEANT Prague – Vienna link
~450km optical link with loop



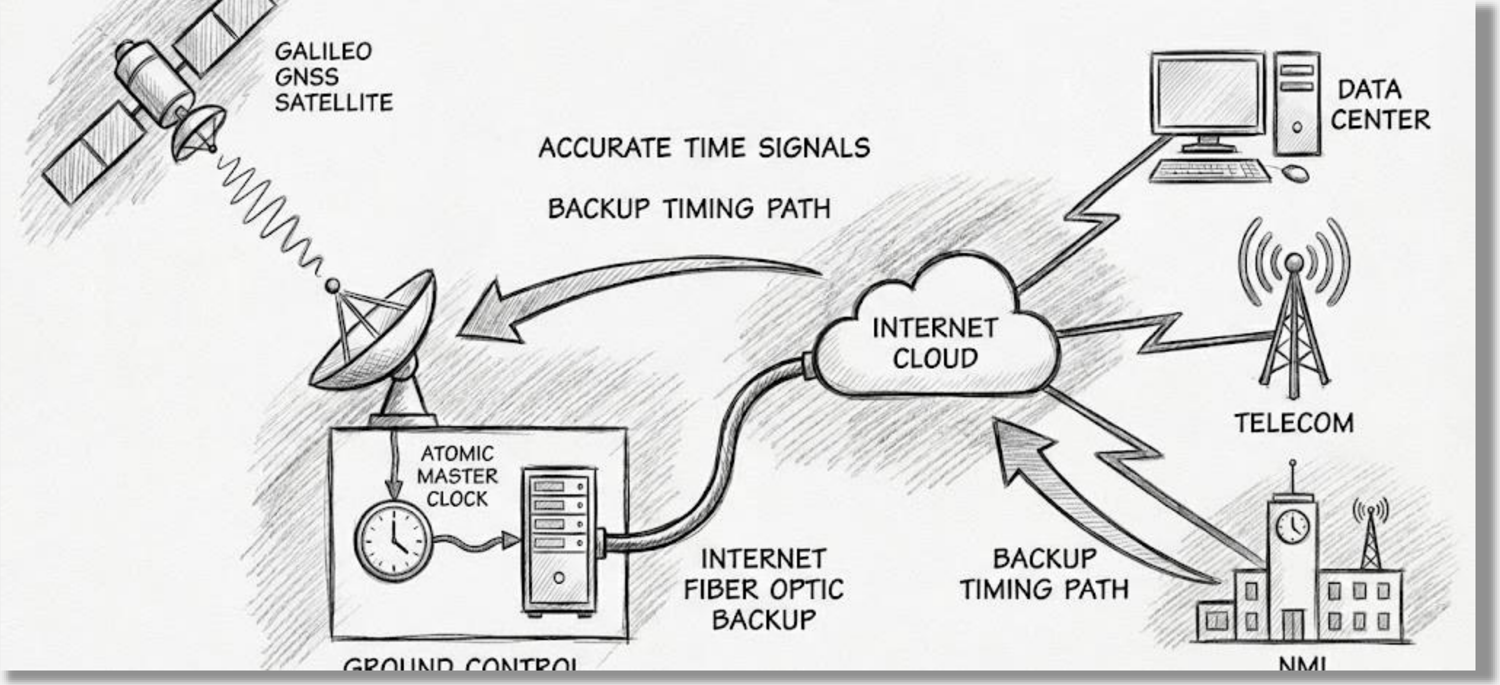


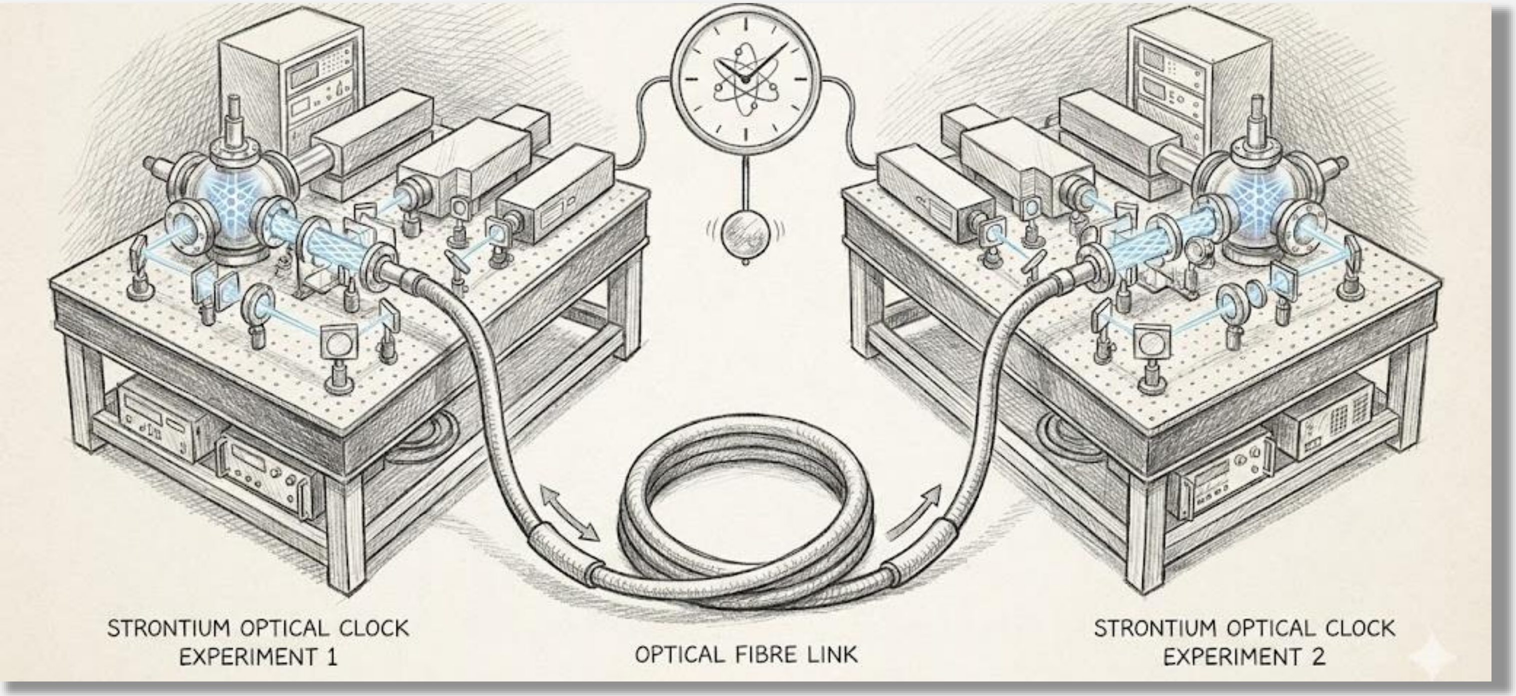
Time

- UTC comparable across the world
- GNSS or NTP/PTP
- Needed for many commercial applications

Frequency

- Ultra precise local comparisons
- Uses RF or carrier waves
- Used for science experiments

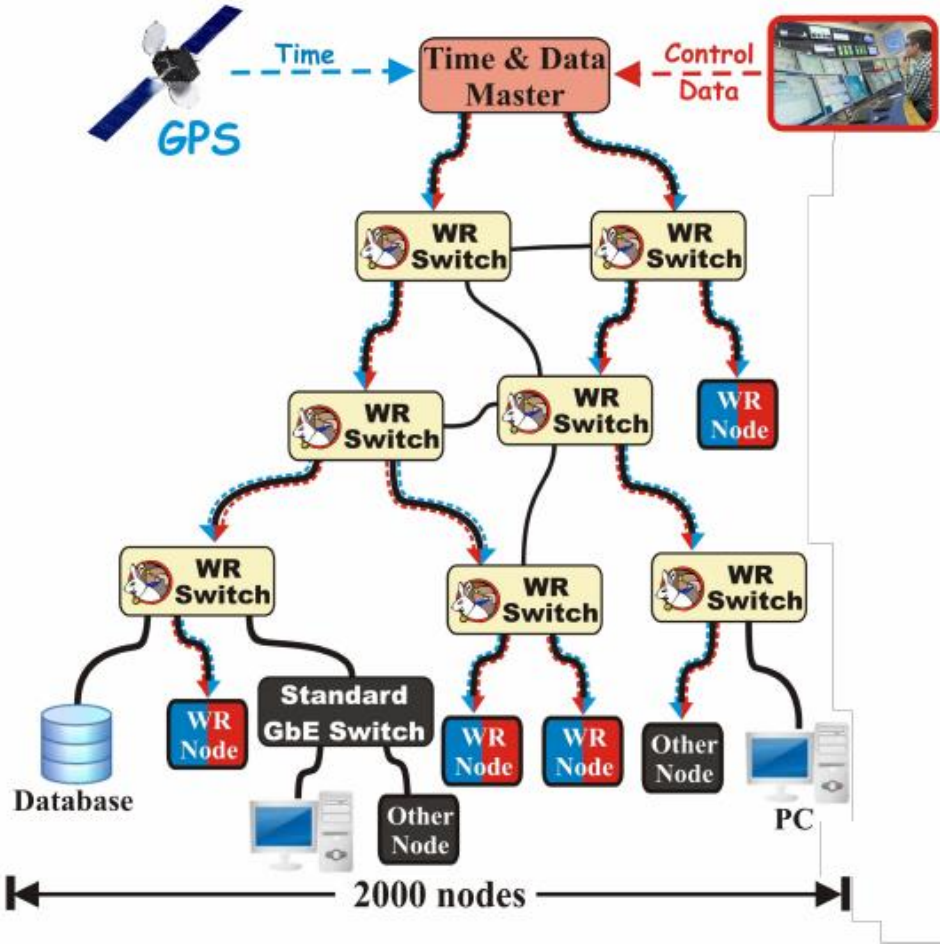




White Rabbit Protocol for Sub-Nanosecond Accuracy

IEEE1588-2019 High Accuracy Profile

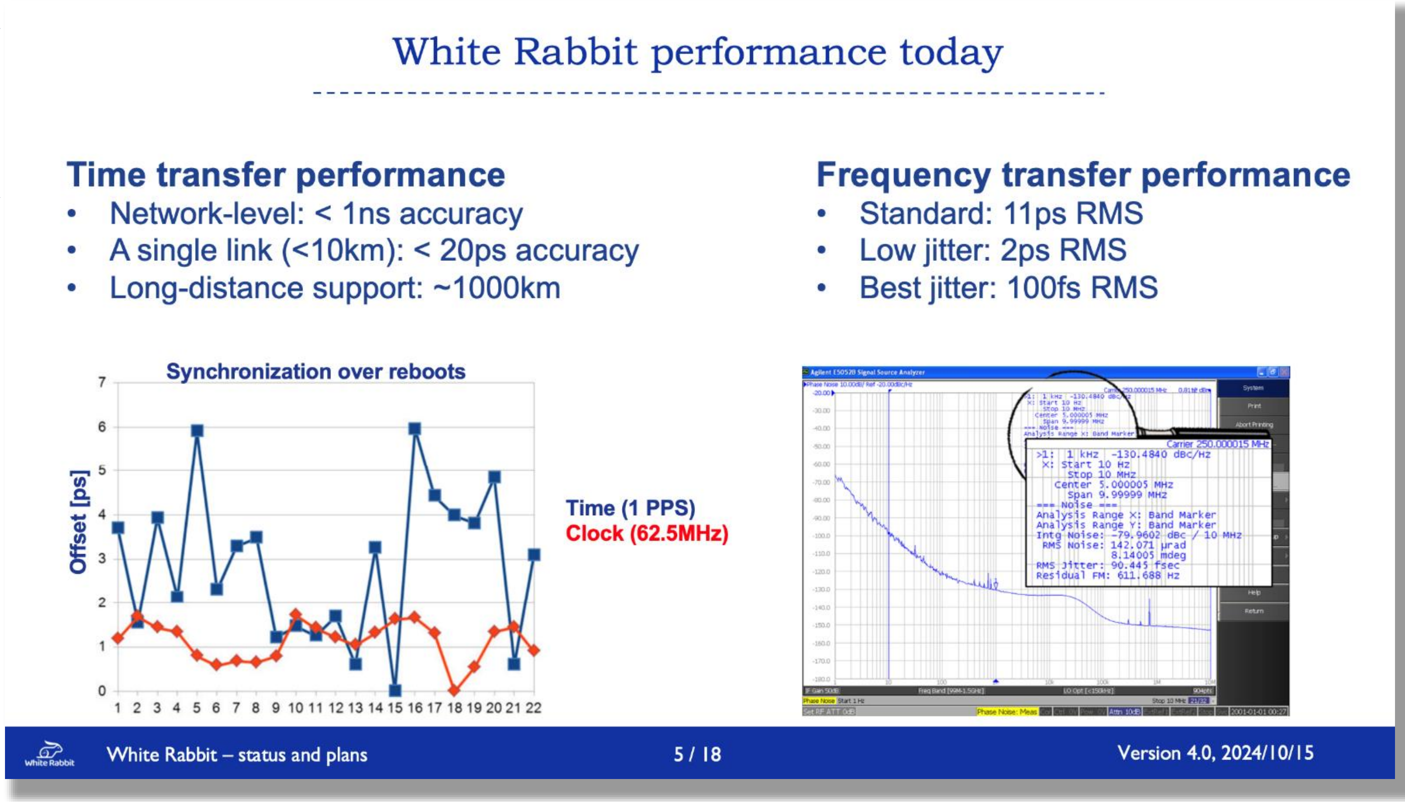
- First developed at CERN in 2008, meant for Big Physics facilities, e.g. CERN, GSI, NIKHEF
- Combination of IEEE1588-2008 with further extensions:
  - Clock syntonization over the physical layer L1Sync (similar to SyncE).
  - Enhancement of timestamps precision through phase measurement.
  - Automatic precise evaluation and compensation of transmission link asymmetry.
  - Backward compatible with PTP IEEE1588-2008.
- Open Source and commercially available
- Initial specs for links < 10km and scalable to 2000 nodes, but for maintaining sub-ns accuracy up to ~20 WR nodes in a chain.



Refer to White Rabbit Collaboration Source: Javier Serrano, GEANT Time and Frequency Workshop

Why is White Rabbit Important?

- WR offers a solution that is unmatched by other technologies
- Gaining rapid acceptance among network operators
- Several system vendors are providing carrier-grade WR switches
- Continuous development with research and industry partners (WR Collaboration).
  - Further possibilities for development, e.g. an ITU-T telecom profile in the future?

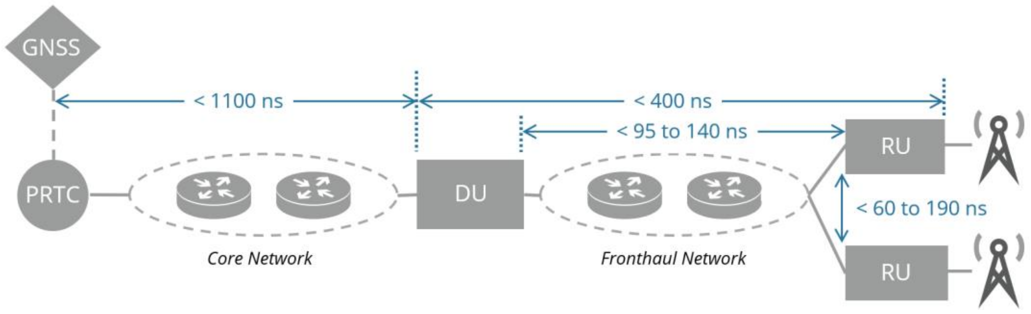


Courtesy: Guy Roberts, SIG-TFN Workshop, Ispra, 2025

Time Distribution in Data Networks

Protocols for packet-based time transfer

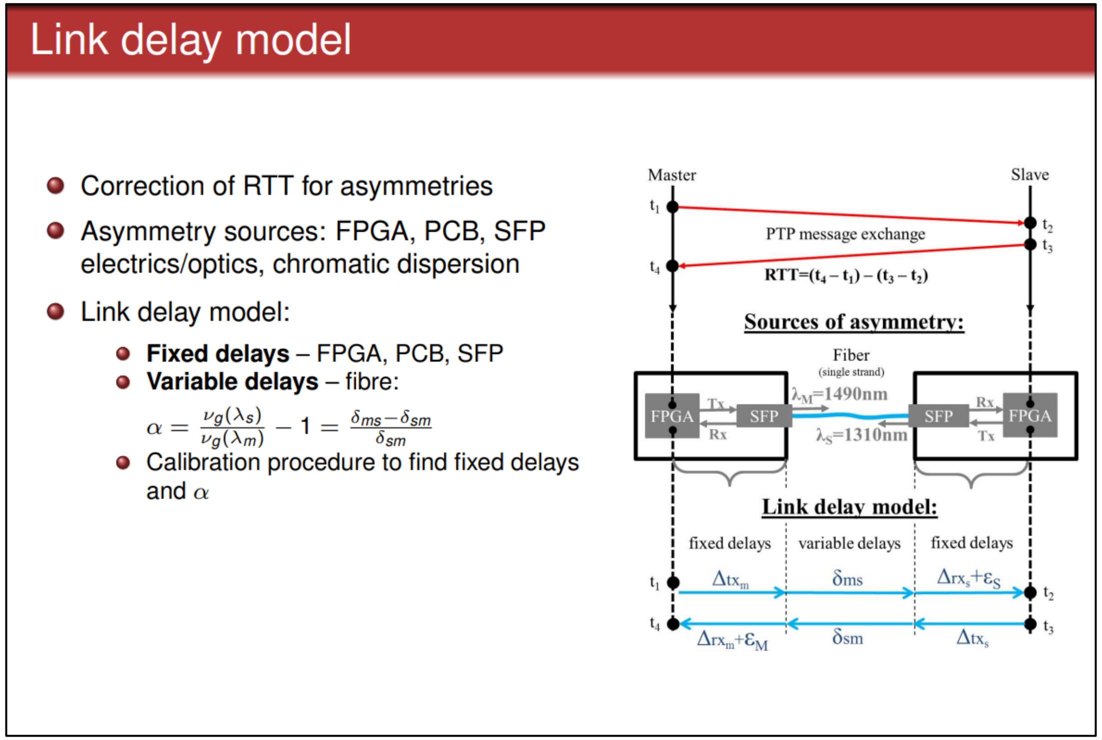
- 1985: Network Time Protocol NTP (your PC time) on Layer 7 (UDP)
  - Time accuracy in the tens of milliseconds on average
  - Heavily affected by delay variation as you are contending for capacity with other IP data packets
- 2002: Precision Time Protocol PTP (IEEE1588-2008, ITU-T profiles) on Layer 2 (Ethernet)
  - Time accuracy in the range of 1millisecond down to hundreds of nanoseconds
  - Heavily affected by transmission path asymmetry, devices have free-running oscillators, etc.
  - Most “legacy” networks partially support it and not good enough for most use cases
    - E.g. Most mobile network operators had big issues during 5G roll out of Time Division Duplex Frequencies(e.g.3.5GHz) requiring end-to-end time accuracy < 1.5µs.



White Rabbit Asymmetry Compensation

Rule of thumb: speed of light in optical fibre ~4.9 ns/1 meter -> 1ns ~20cm

- “Traditional” optical fibre communication uses fibre pairs, one fibre per direction (Tx Rx) using the same wavelength:
  - In practice fibres have different lengths even in the same cable from few to tens of meters. Different transmission time introduces delay variation/time error
  - Pre-calibration is difficult for in-situ as every “fix” of a fibre break will introduce unknown Δ fibre length.
- Single fibre with different wavelengths per direction:
  - Asymmetry is introduced because of chromatic dispersion: different wavelengths travel at different speeds in the fibre medium (e.g. higher wavelengths travel faster).
  - Compensated with calibration.



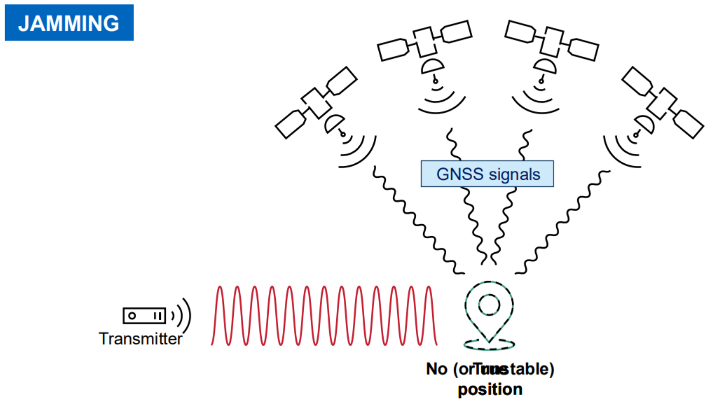
Source: M. Lipinski, GEANT 2022 SIG-TFN WS,

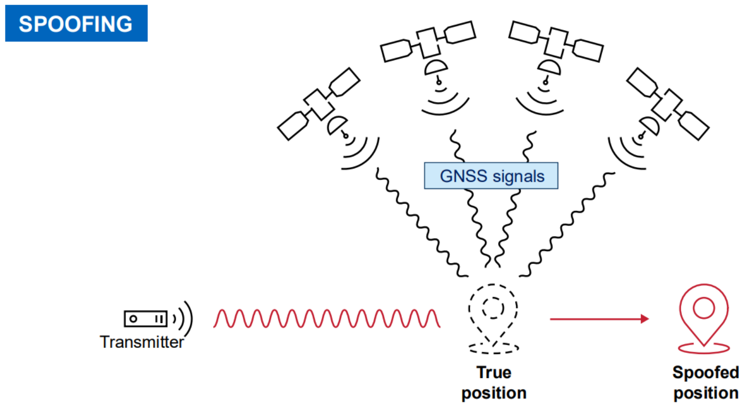
GNSS Vulnerability

Achilles' heel: low power system at Rx

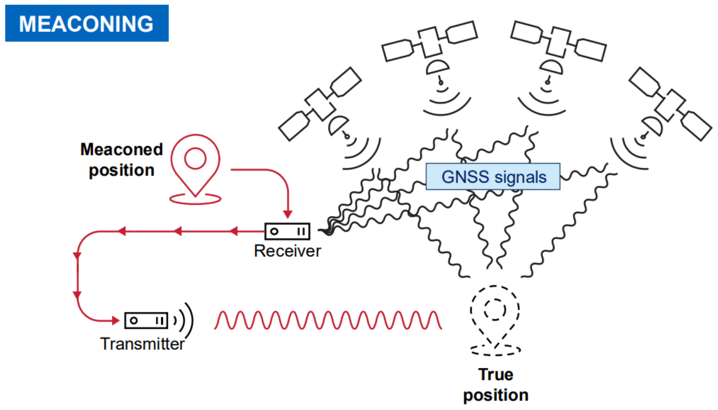
- Multiple type of attacks possible with cheap and accessible devices one can buy easily.

The benefits of GNSS to the UK economy were estimated to be £13.62 billion per annum.
The impact of a loss of GNSS for 7-days was estimated to be £7.64 billion and impact of a loss for 24 hours was estimated to be £1.42 billion.
Report: The economic impact on the UK of a disruption to GNSS





Source: Raimena Veisllari TNC2025



Source: Jammertest 2025 Information Meeting.


EU chief von der Leyen's plane hit by suspected Russian GPS jamming

6 days ago

Share

Maia Davies & Will Vernon BBC News

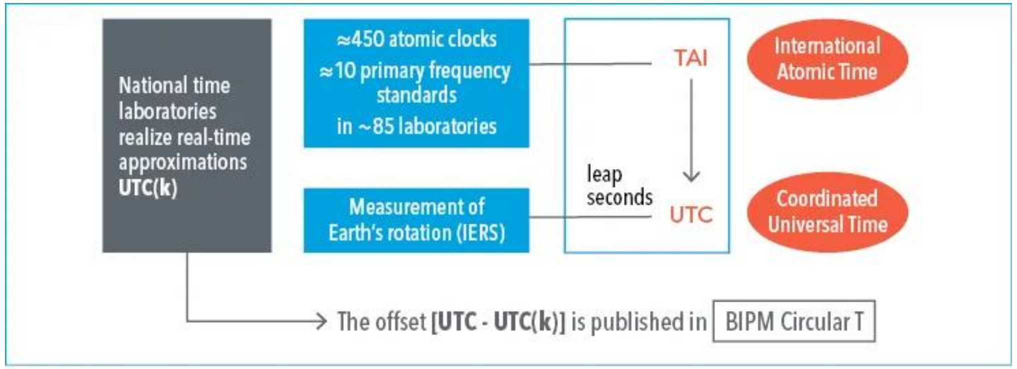
GEANT C-TFN: Many use cases

- **Support the redefinition of the SI second** being carried out between now and 2030+ by NPL, PTB, Syrte and INRIM and other NMIs.
- Perform **fundamental physics research** e.g. gravity wave experiments.
- **Supplement GNSS** with a fibre network to increase reliability of time distribution
- Support **European-wide commercial services** such as very accurate time stamps for banks to validate high-frequency trading.

How Do We Measure and Maintain Time Now?

- Coordinated Universal Time (UTC) is the worldwide reference time scale computed, maintained and improved by the Bureau international des poids et mesures (BIPM) − the international organization focused on measurement science and standards.
  - National Metrology Institutes (NMIs) maintain and distribute the national timescale.
  - Their clocks provide regular measurement data to BIPM, as well as the local real-time approximations of UTC, known as UTC(k), for national use. BIPM compares and gives the NMIs the offset.

> **UTC is based on about 450 atomic clocks, which are maintained in 85 national time laboratories around the world.**



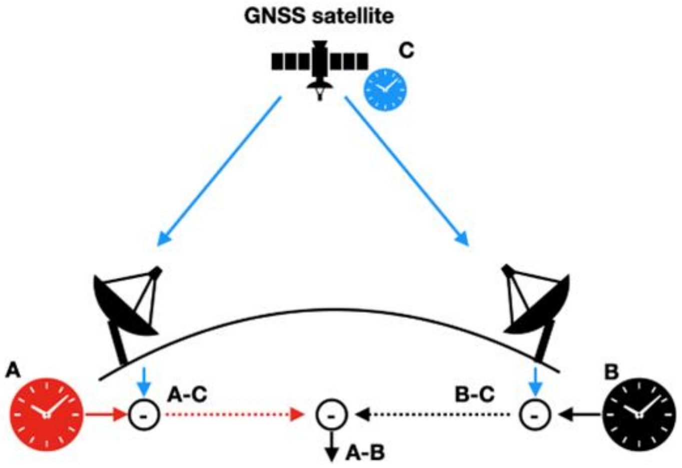
Source: BIPM

Precision timing underpins many features of our daily lives: mobile phones, financial transactions, electric power grids and global navigation satellite systems all rely on time and frequency standards.

Maintaining the Coordinated Universal Time (UTC)

- BIPM organizes the international network of time links to compare national/local realizations of UTC(k) from contributing laboratories.
- The network of time links used is non-redundant and relies on observation of Global Navigation Satellite System (GNSS) and two-way satellite time and frequency transfer.
  - Need to compensate for the delay due to e.g. the ionosphere, the gravitational field, movement of satellites, etc.
- Future: complement with reliable and high-precision distribution through optical fibres.

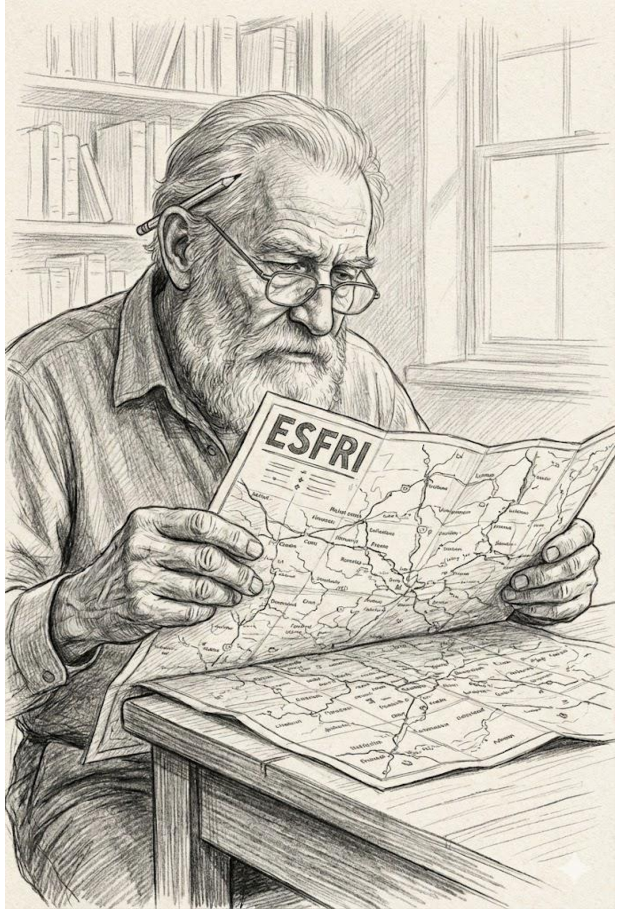
GNSS time-transfer



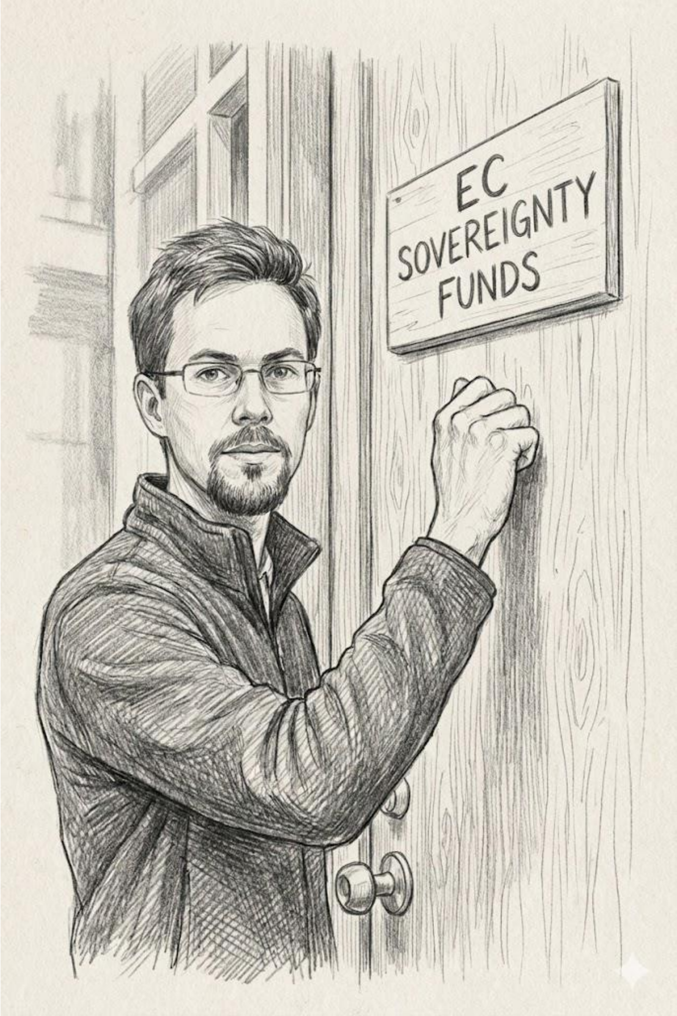
Common View GNSS Time Transfer *Source: NIST*

Comparing remote clocks, A and B with a common GPS clock (C). The time differences are computed using measurements logged by GNSS receivers that are referenced to local clocks A and B.

Funding C-TFN



- Two-pronged approach based on dual use principle that is being pushed by the EC
- Underlying fibre infrastructure will support two overlay services:
  - Research is supported by interconnecting NMIs for cutting edge research optical clock research (ESFRI roadmap).
  - GNSS resilience is supported by a second service built for comparing time. This will be built with White Rabbit (or is successor technology)
- We hope to tap into the dual-use sovereignty funding (from DEFIS?) for the underlying fibre infrastructure.

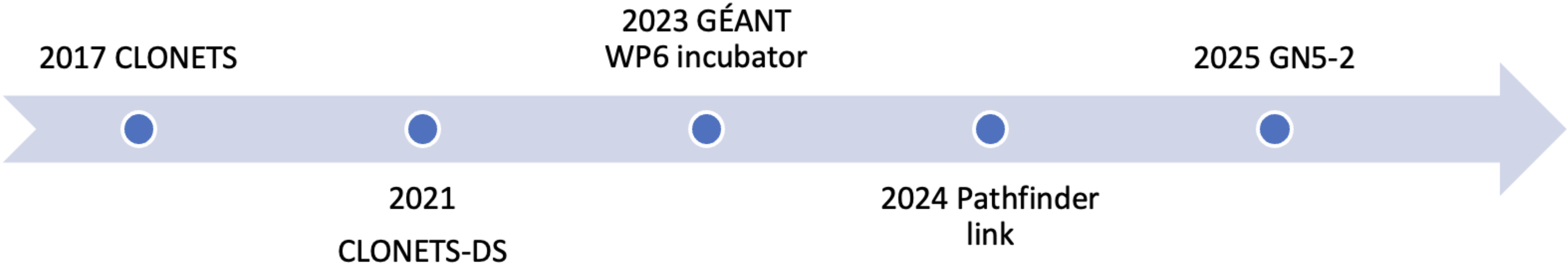


Funding considerations

- Funding is a long-term process, the EC works in seven-year cycles (Multiannual Financial Framework)
- Within the seven-year cycle, annual work programmes are published, these allow the EC to be agile to changing needs
- Don't forgot national funding which work on different timescales (for national investments)
- T/F has been working to obtain funding in the next MFF starting 2028 with both funds for international and national infrastructure
- For example, member states will be providing their feedback to the commission on the 4th December regarding a possible Europe wide expansion of the TF network


A. Jenkins '25

SIGs: Stronger as a community



- NRENs and NMIs have proven to be a great match
- Since 2017 we have been working together towards a European solution
- Current mechanism for this collaboration is the SIG-TFN

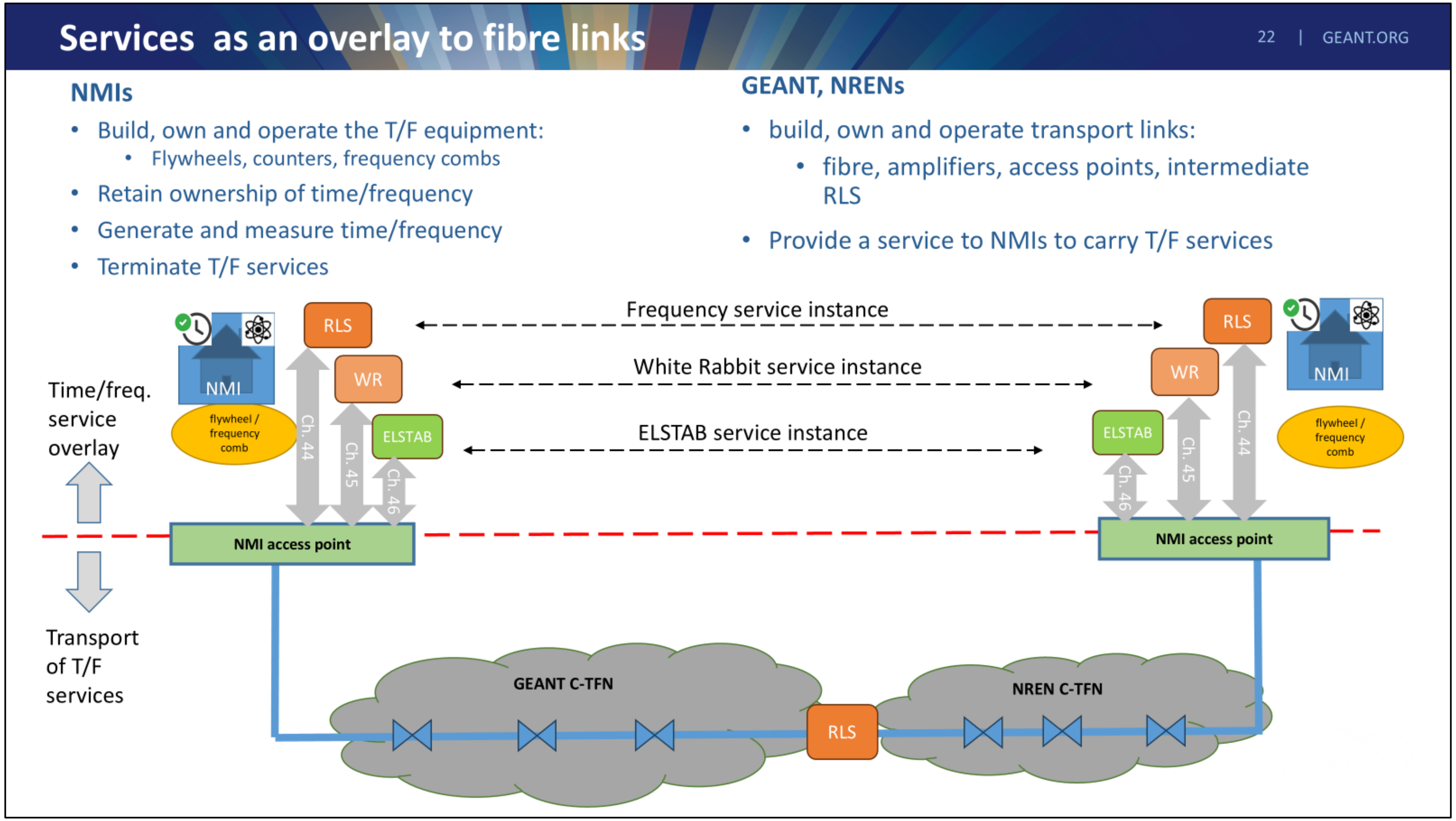
Conclusions

- New services should not just be another tool that competes with existing software projects – we can't beat established services, they have too much of a head start.
- Science community typically is good at getting research funding, but has difficulty building infrastructure
- Collaboration with scientists, look for infrastructure that science needs to become world class.
- Funding model… how does this change GEANT/NREN/Science relationship?
- Seed money to kickstart collaborations… redefine how incubators work?
- Is there a to bring NRENs and science together? (create a new SIG? SIG-TFN, SIG-Quantum)
- A strong community is critical to lobby national ministries
- A strong individual to champion the cause is critical to success
- Matching funding, T/F has managed to get commitments from NMIs to match GEANT project funding. This is done using an MoU.

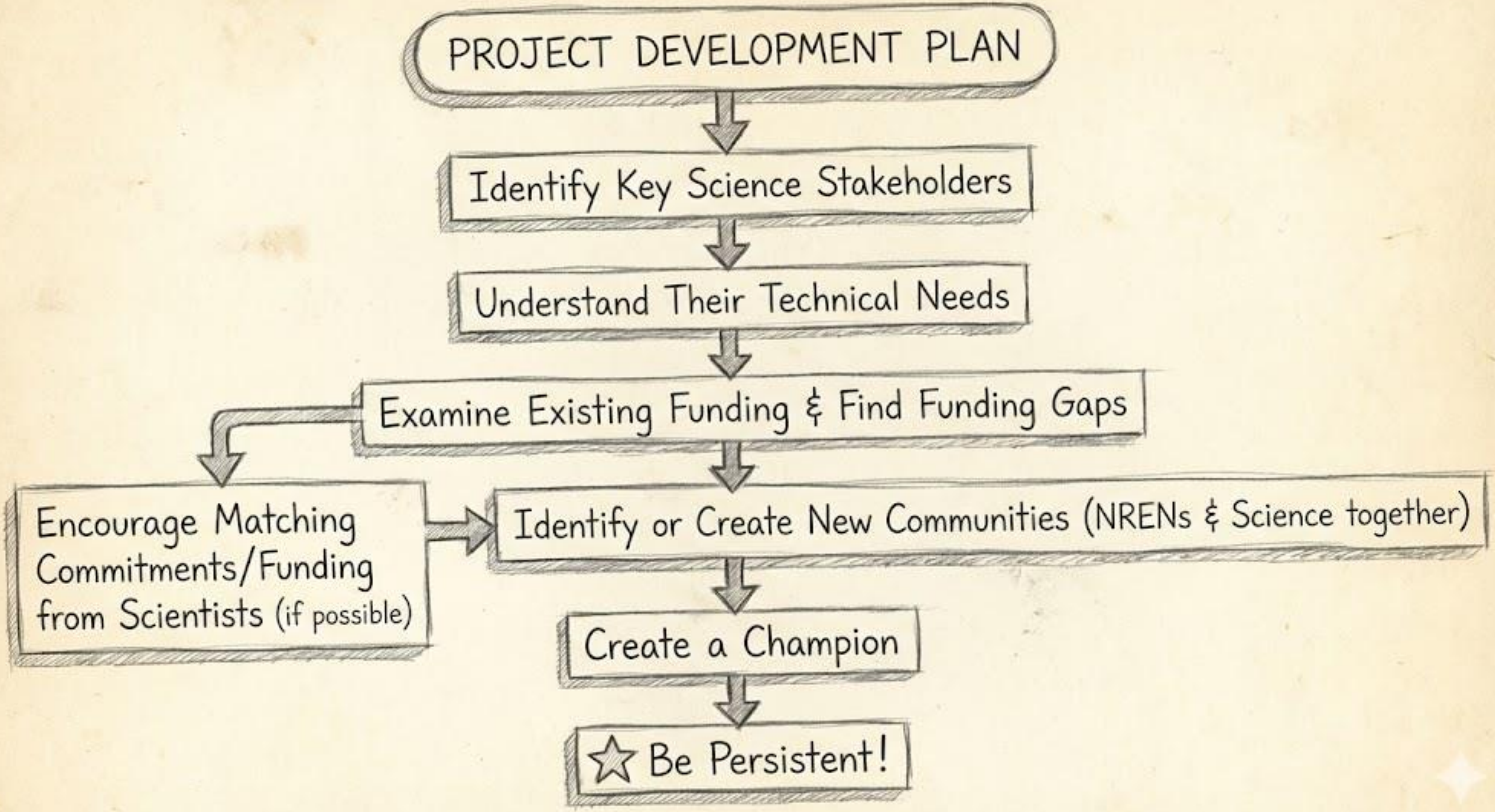
White Rabbit over Dedicated Single Fibre

See outcomes from CLONETS project

- 2024: Build Pathfinder link and prepare C-TFN.
- GN5-2: 2025-27: Build C-TFN northern route .
- GN5-3: 2027-29: continue C-TFN southern route.



Courtesy: Guy Roberts, SIG-TFN Workshop, Ispra, 2025


PROJECT DEVELOPMENT PLAN
Identify Key Science Stakeholders
Understand Their Technical Needs
Examine Existing Funding & Find Funding Gaps
Encourage Matching Commitments/Funding from Scientists (if possible)
Identify or Create New Communities (NRENs & Science together)
Create a Champion
Be Persistent!