White-Rabbit-powered applications that will transform telecommunication networks (as well as White Rabbit itself)

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White Rabbit research in the Netherlands

Many groups active in WR worldwide

WR research in the Netherlands:
- Nikhef Amsterdam (WR hardware, KM3NeT neutrino telescope)
- VSL Delft [UTC(VSL)]
- SURF (NREN)
- JIVE Dwingeloo (VLBI radio astronomy)
- ASTRON (LOFAR radio telescope)
- VU Amsterdam
  ⇒ OPNT bv (spin-off company, founded 2014)

Recent employment history JK:

2008 VU (full time)
2014 VU + OPNT (part time)
2017 OPNT (full time)
2019 VU (full time)
A few WR applications...

... in order of increasing societal impact
WR for fundamental science

• Laser excitation of vibrations of the HD$^+$ hydrogen molecule

• Vibrational frequency measurements with 12 significant digits, traceable to cesium clock

• Lasers, frequency generators, frequency counters, controlled and synchronized through a local WR network (using Cs clock as a reference)

• Led to the most precise determination of the proton-electron mass ratio

\[ \frac{m_p}{m_e} = 1,836.152 \ 673 \ 406(38) \]
WR for VLBI

• Very Long Baseline Interferometry
WR through live SURFnet and VLBI

- Part of H2020 ASTERICS project
- Goals:
  - High-stability White Rabbit*, ** link to synchronize VLBI stations (and save €€€ on H-masers)
  - Proof-of-principle synchronization for multi-messenger astronomy (combine radio + optical + astroparticle + GW + …)
- Implementation: 169 km fiber link Westerbork-Groningen-Dwingeloo (multiplexed in live SURFnet8 network)
  - SFPs 100 GHz DWDM grid around 1511 nm
  - Two bi-di amplifiers (SOAs)

WR link results

Setup before installation in SURFnet8

Results
Time offset 169 km link:
(−0.37±0.13) ns
ADEV (0.5 Hz BW):
10^{-12} @ 1 s
10^{-16} @ 2\times10^5 s

P. Boven, C. van Tour, R. Smets, J.C.J. Koelemeij et al. (in preparation);
VLBI with WR synchronization

- Three telescopes: Westerbork, Dwingeloo, Jodrell Bank (UK)
  - Jodrell Bank, Westerbork: traditional synchronization (H-maser atomic clock)
  - Dwingeloo: synchronized to H-maser Westerbork via 169 km WR link (SURFnet)
- VLBI fringes (signal underlying radio astronomical images such as:               ) observed at both telescopes with good SNR*!

Examples of other VLBI experiments using fiber-optic synchronization:
AUS: Y. He et al., Optica 5, 138 (2018)
WR for **fiber-optic telecom networks**

- More and more use made of (D)WDM
- DWDM systems:
  - Payload channels (data plane) → e.g. C band
  - Supervisory and management channel (control plane) → channel outside C band
- Optical supervisory channel (OSC)
  - Often 100 - 155 Mbps
  - Newer systems: Gb Ethernet ⇒ **could be WR!**
WR for mobile networks

• Mobile network operators (MNOs) need GNSS-level timing
  • WR could be a GNSS back-up/replacement system
• BUT it is often heard that MNOs have solved the GNSS reliability issue, and don’t need WR
• That is true for many mobile network features as described in the 3GPP standards
• However, some of the most advanced 5G features need nanosecond-level timing or better (WR-level)
  • Positioning through mobile networks
  • Probably also enables better capacity and coverage through multi-antenna/cooperative base stations

See e.g. Analysis of the Synchronization Requirements of 5G and Corresponding Solutions, H. Li, L. Han, R. Duan, G. M. Garner, IEEE Communications Standards Magazine, March 2017, 52. DOI: 10.1109/MCOMSTD.2017.1600768ST
WR for **positioning and navigation**

‘SuperGPS’ project: a terrestrial networked positioning system

**Network of the future:**
- Connectivity
- Navigation
- Time/frequency
First positioning trial at “The Green Village” (TU Delft, Sep 2020)

- Wideband radio signals (improves precision)
- 10 cm positioning, sub-ns wireless timing
- Mobile-network compatible!

WR fiber-optic time distribution with 0.2 ns uncertainty (0.2 ns $\equiv$ 6 cm at speed of light)
WR for **quantum key distribution**

- Quantum light source: single photons as qubits
- Quantum detector: detects single photons (and qubit state)
  - One photon $\rightarrow$ one count
  - Detector must be highly sensitive
- Detector produces ‘dark counts’ $\Rightarrow$ reduces SNR
- Solution: switch detector on only when qubit photon arrives (time gating)*
- Requires sub-nanosecond synchronization (and WR is being used for this purpose)
  - Of course WR is also a great classical communication channel!

*See e.g. Buttler et al., Phys. Rev. Lett. 81, 3283 (1998)
What’s (needed) next

• Integration into network management systems
• Automated calibration protocols
• Adaptation of network design and maintenance rules for WR
• Redundant WR
Redundant WR

- Considerable work has been done into this direction (e.g. PhD thesis Maciej Lipinski, OPNT, 7S, ...)
- Fast switch-over between different Masters/Grandmasters
- To avoid timing jumps during switchover, the WR GMs need to be steered such that the 1-PPS outputs stay in sync
Why redundant WR is needed

Reasons why WR is/will be used:

1. Alternative to expensive clocks and external synchronization systems (GNSS)
2. Back-up to GNSS timing systems (for enhanced reliability/resilience)
   - Energy grids
   - Telecommunication networks
3. Synchronization system for new (critical) applications
   - Quantum communication (secure, reliable)
   - Terrestrial positioning systems (for safe self-driving vehicles, GNSS back-up/complement)

For most (future) applications, high reliability is a must
⇒ Reliable and redundant WR needed, at high(est) TRL

Currently only commercially available (it seems) – need to add to WR open source?
Capitalizing on White Rabbit’s *raison d’être*

- WR collaboration (WRC) might partially be funded from the need for GNSS back-up technology
- Similar: Quantum technology
  - CERN Quantum Technology Initiative?
- Since WR was conceived, CERN support has been crucial and arguably *the* reason for the success of WR
  - Impressive support to the community and continuing impressive development😊
- Given the impact of WR and the challenges ahead, CERN support will be highly desirable (if not critical) also in the future
Thank you!

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