High Accuracy Time Distribution with PTP White Rabbit

Anders Wallin, VTT MIKES

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- Timekeeping: Sources for time
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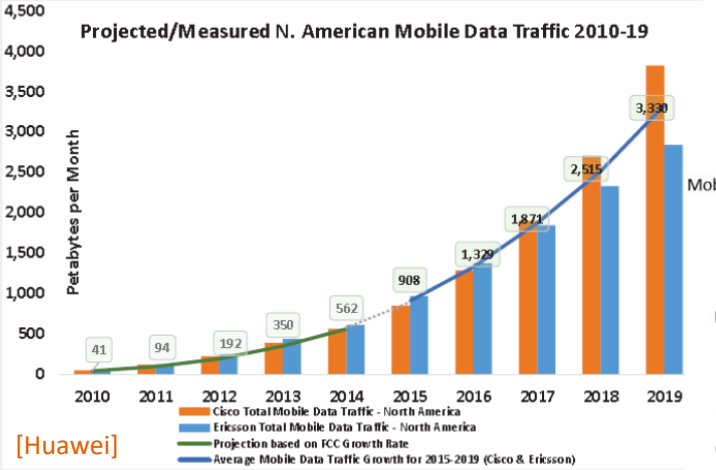
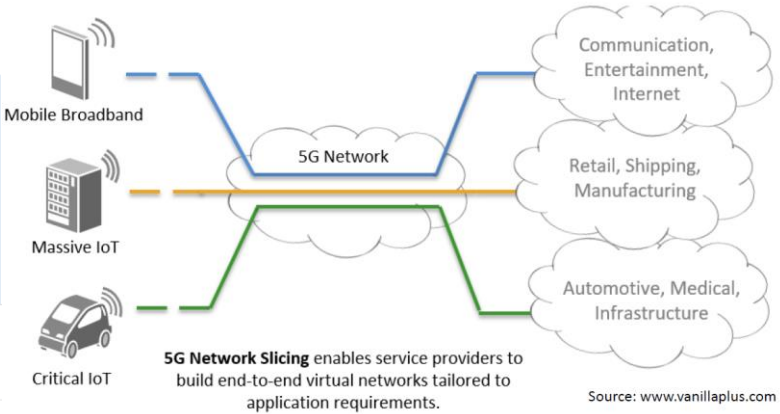
  - White Rabbit a.k.a. PTP High Accuracy profile
  - VTT MIKES time-network
  - Results from long/short links usign 1 or 2 fibers
- Future: distributed, robust, accurate timekeeping

Telecom standards for synchronization





PRC
Primary Reference Clock

→

PRTC
Primary Reference Time Clock

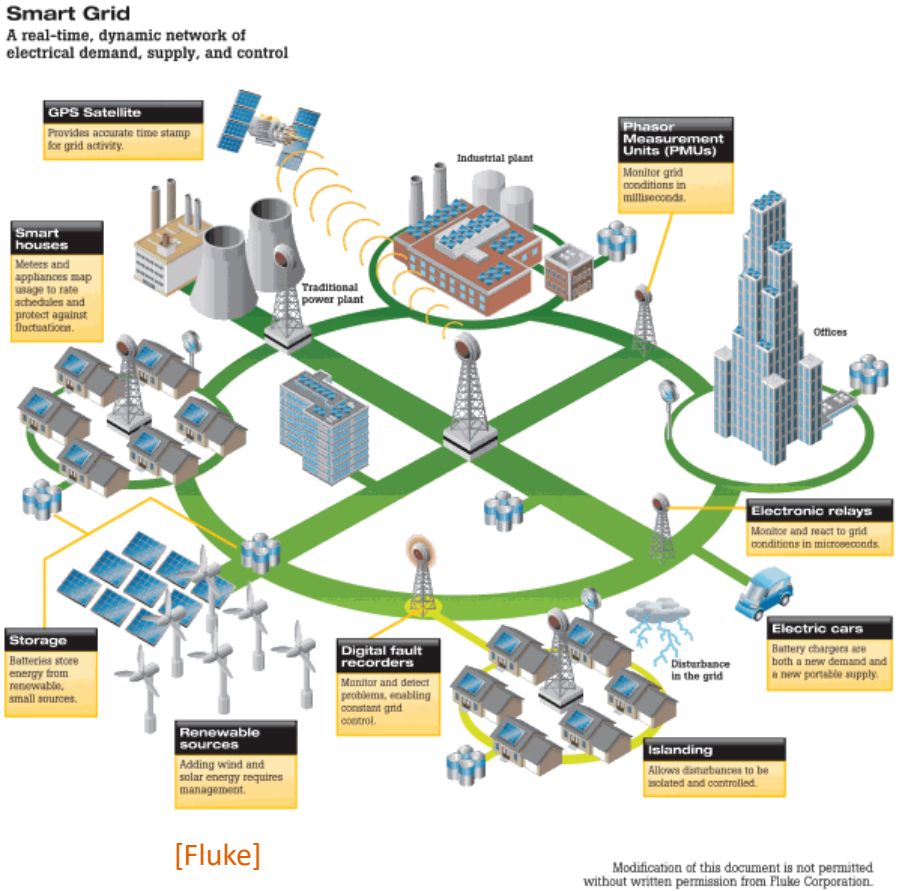
→

ePRTC
Enhanced Primary Reference Time Clock

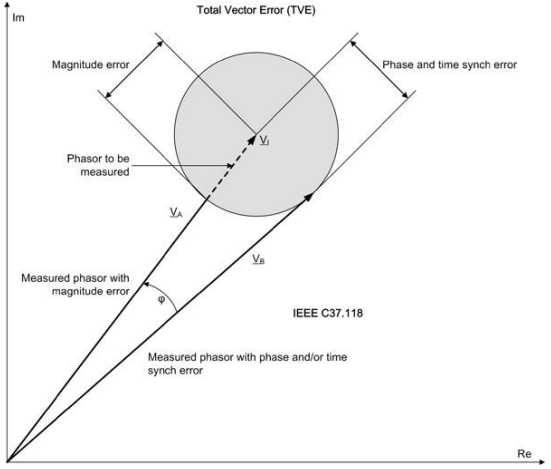
Performance = 1 part in 10^{11} (frequency)	Performance = 100 nS (time, phase, and frequency)	Performance = 30 nS (time, phase, and frequency)
ITU-T G.811 (Pub. 1988)	ITU-T G.8272 (Pub. 2012)	ITU-T G.8272.1 (Pub. 2016)

[Microsemi]

Need for synchronization in Smart Grids



[Fluke]



1% total vector error
-> ~1 µs requirement
on timing.

Synchronization in Finance / e-Commerce

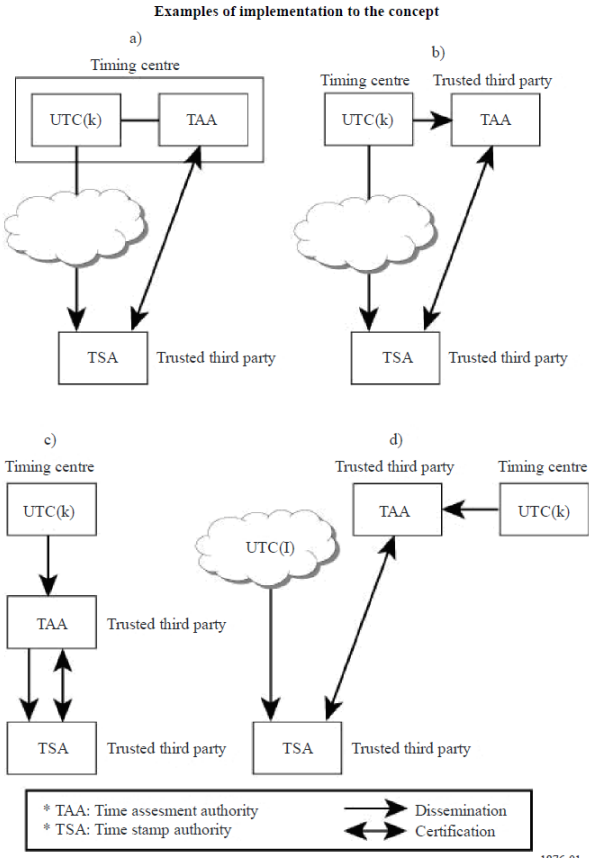
Business Clocks – What requirements will apply with MiFID II?

1. **Reference time**: Operators of trading venues and their members or participants shall synchronise the business clocks they use to record t and time of any reportable event with the **Coordinated Universal Time (UTC)**
2. **Level of accuracy**: Applicable for operators of trading venues and their members

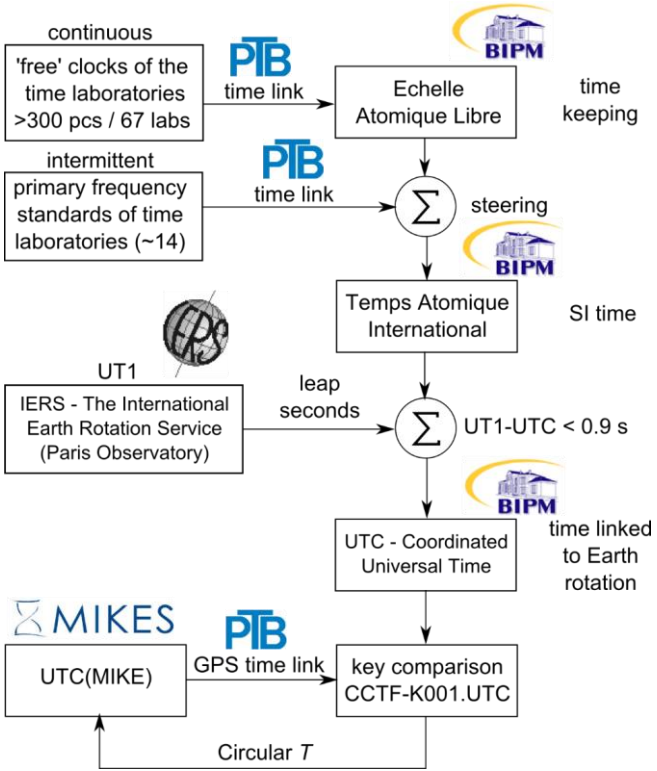
	Gateway-to-gateway latency[1]	Max. divergence from UTC	Granularity of timestamp
Trading venues	>= 1 ms[2]	1 ms	1 ms or better
	< 1 ms[2]	100 µs	1 µs or better
HFTs	-	100 µs	1 µs or better
Voice trading	-	1 s	1 s or better
RFQ	-	1 s	1 s or better
Negotiated Transactions	-	1 s	1 s or better
Other trading activity	-	1 ms	1 ms or better

µs = microsecond, ms = millisecond, s = second

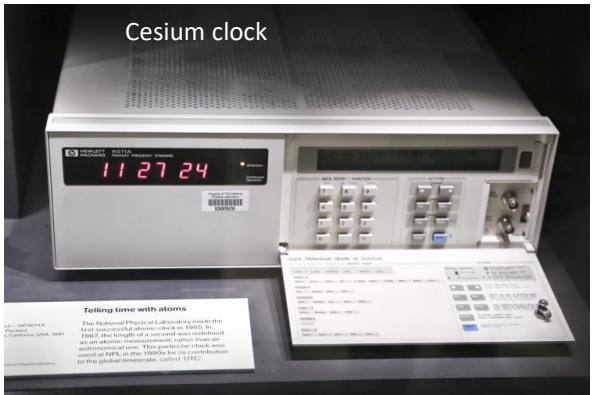
ITU-R TF.1876



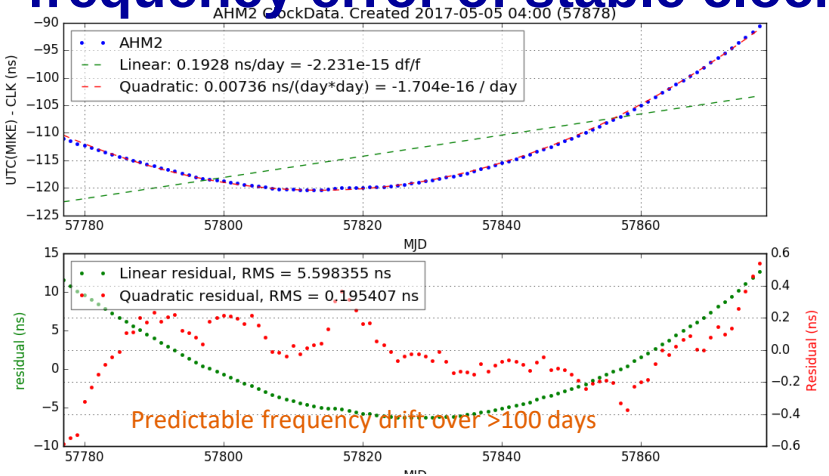
International Timekeeping, UTC-laboratories



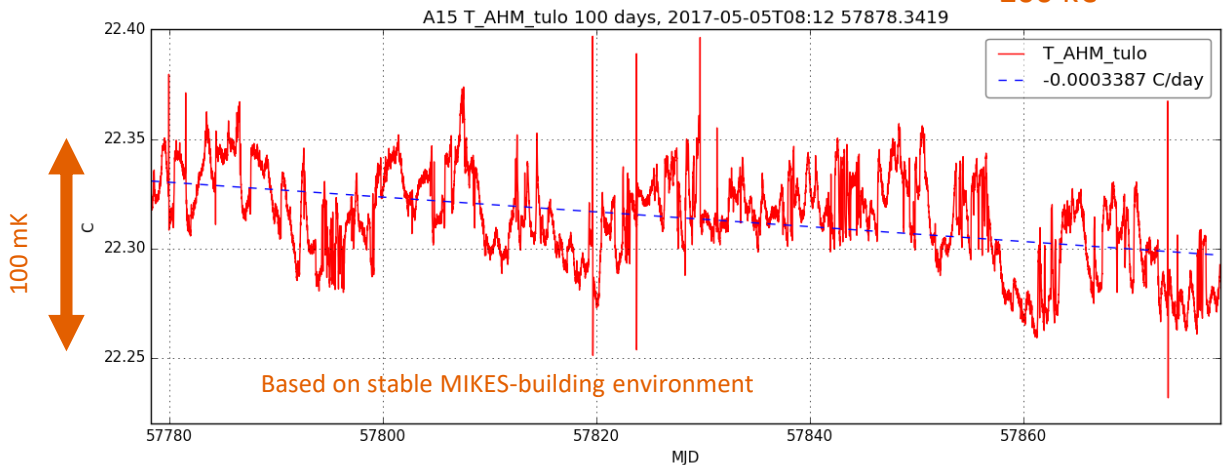
Active hydrogen maser



Timekeeping is based on predictable frequency error of stable clocks



Active Hydrogen Maser
~200 k€



Traceability through Circular-T, published monthly by the BIPM

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BUREAU INTERNATIONAL DES POIDS ET MESURES
ORGANISATION INTERGOUVERNEMENTALE DE LA CONVENTION DU METRE
PAVILLON DE BRETEUIL F-92312 SEVRES CEDEX TEL. +33 1 45 07 70 70 FAX. +33 1 45 34 20 21 tai@bipm.org

The contents of the sections of BIPM Circular T are fully described in the document "Explanatory supplement to BIPM Circular T" available at ftp://ftp2.bipm.org/pub/tai/publication/notes/explanatory_supplement_v0.1.pdf

1 - Difference between UTC and its local realizations UTC(k) and corresponding uncertainties.
From 2017 January 1, 0h UTC, TAI-UTC = 37 s.

Date 2017 0h UTC / MJD / Laboratory k	AUG 29 57994	SEP 3 57999	SEP 8 58004	SEP 13 58009	SEP 18 58014	SEP 23 58019	SEP 28 58024	Uncertainty/ns uA	uB	Notes u
				[UTC-UTC(k)]/ns						
JV (Kjeller)	4.8	-6.2	-17.2	-16.6	-17.6	-19.0	-19.6	0.4	20.0	20.0
KEBS (Nairobi)	-	-	-	-	-	-	-			
KIM (Serpong-Tangerang)	141.1	168.3	169.5	174.4	188.4	200.4	173.8	2.0	20.0	20.1
KRIS (Daejeon)	35.5	40.3	44.3	47.7	50.6	52.2	52.9	0.4	11.1	11.1
KZ (Astana)	-294.7	-322.8	-334.3	-331.1	-313.3	-298.9	-301.0	1.5	9.3	9.4
LT (Vilnius)	158.7	144.0	145.4	157.0	152.5	168.8	181.8	2.0	11.3	11.4
MASM (Bayanzurkh)	-411.6	-428.7	-451.6	-	-	-34.5	-60.0	0.7	20.0	20.1
MBM (Podgorica)	51657.3	51989.6	52323.7	52643.4	52978.9	53335.9	53658.6	1.5	20.0	20.1
MIKE (Espoo)	-0.4	-0.3	0.5	0.5	0.8	-0.2	-0.7	0.7	4.2	4.3
MKEH (Budapest)	-65005.0	-65222.3	-65420.4	-65627.5	-65836.7	-66030.7	-66237.0	1.5	20.0	20.1
MSL (Lower Hutt)	285.3	289.9	309.0	301.6	285.8	300.7	321.8	1.5	20.0	20.1
MTC (Makkah)	1149.2	1164.1	1145.4	1170.6	1149.7	1204.2	1187.0	10.0	7.4	12.4
NAO (Mizusawa)	99.4	86.1	93.0	95.8	97.0	89.5	75.7	2.0	20.0	20.1
NICT (Tokyo)	-5.7	-5.8	-7.5	-6.9	-5.9	-4.2	-1.9	0.4	2.2	2.3
NIM (Beijing)	5.2	4.5	3.8	3.3	3.9	3.7	2.9	0.7	1.9	2.0
NIMB (Bucharest)	1813.1	1816.1	1803.5	1816.4	1818.9	1814.2	1808.5	0.4	7.2	7.2
NIMT (Pathumthani)	203.3	208.9	214.5	217.7	219.5	218.6	221.5	1.0	20.0	20.1
NIS (Cairo)	11.9	8.4	2.4	-19.9	-30.1	-48.5	-55.3	1.6	20.0	20.1
NIST (Boulder)	0.5	0.6	1.1	1.7	2.2	2.2	1.4	0.4	4.9	4.9

>75 laboratories in total

Network Time Transfer Techniques

NTP: milliseconds

(software time-stamping, unpredictable delays in routers/switches/gateways)

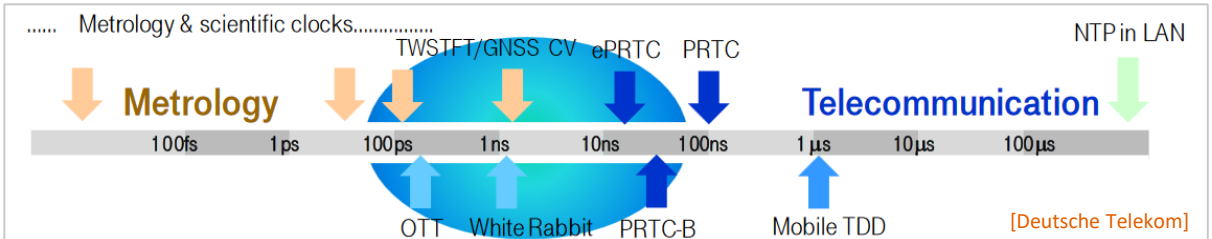
PTP: microseconds

(hardware time-stamping)

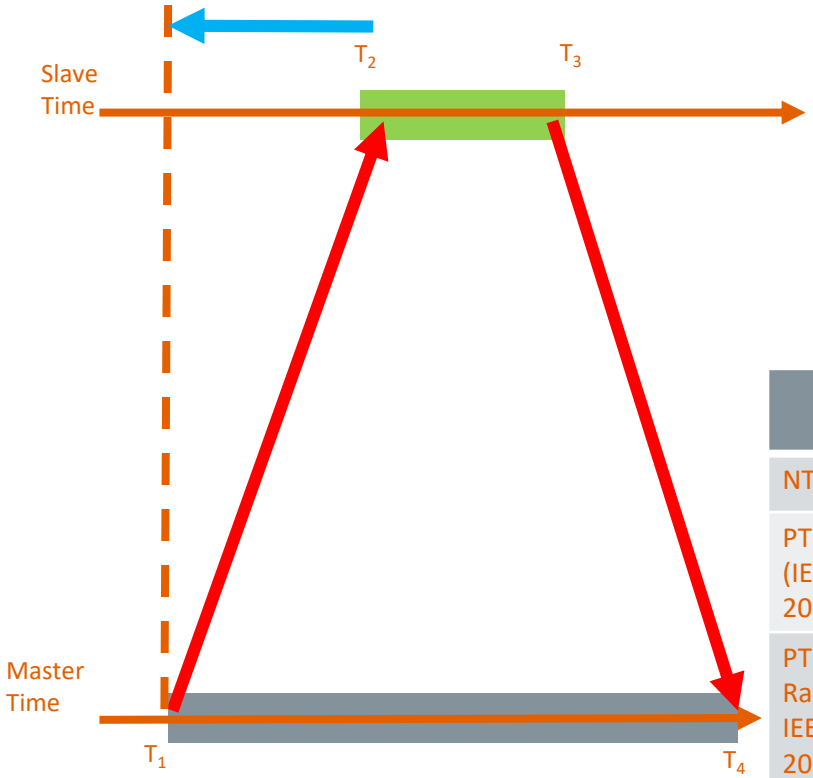
PTP = Precision Time Protocol
(IEEE 1588-2008, PTPv2)

PTP White Rabbit: nanoseconds
(IEEE 1588-2018 High Accuracy profile)

(hardware time-stamping enhanced by precise phase-measurement)



Time-transfer (principle)



Round-Trip-Time
= (T4-T1) – (T3-T2)

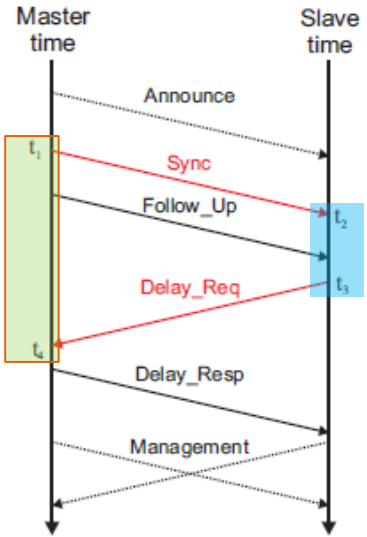
Master-Slave-Delay
= ~ 1/2 Round-Trip-Time

	Time-stamping	Time-stamp Accuracy	Allow for Link asymmetry?
NTP	Software	~ms	No
PTPv2 (IEEE1588-2008)	Hardware	~5-10 ns?	Usually no.
PTP White Rabbit IEEE1588-2018	Hardware SyncE + phase-measurement	< 1 ns	Allow for constant asymmetry

Symmetry essential for good accuracy!
1-fiber links with BiDir optics are best. 2-fiber (long) links often need calibration before use.

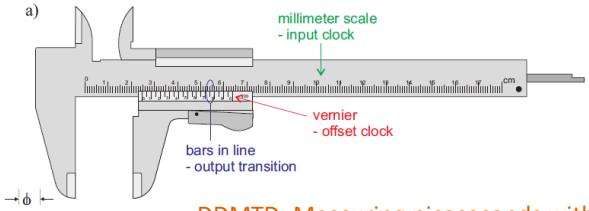
White Rabbit: Precision Time Protocol + Synchronous Ethernet

Step 1.
Hardware time-stamping of t_1-t_4
Gives coarse (8 ns) RTT

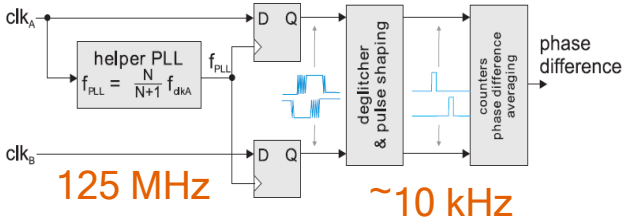


$$delay\_coarse = (t_4 - t_1) - (t_3 - t_2)$$

Step 2.
Phase measurement to enhance T2 and T4



DDMTD: Measuring picoseconds with ~125 MHz clocks on FPGAs

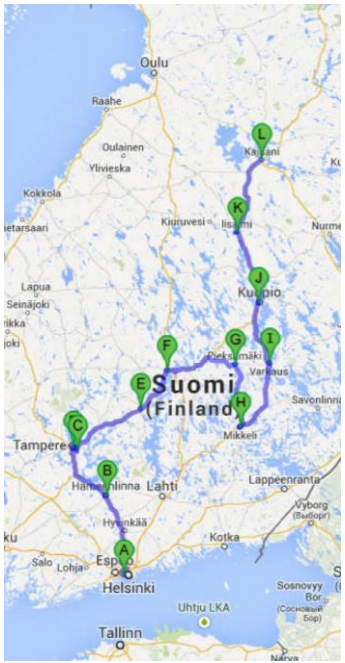


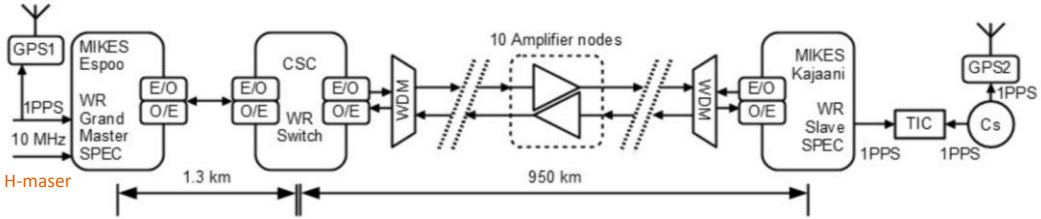
-> Round-trip-time measurement with sub-nanosecond precision

NOTEs for PTP High Accuracy

- Point-to-Point links between WR/HA-devices
- No optical/electrical conversion on path
- No legacy switches
- Best performance in 1-fiber
- Asymmetries of ~1 us per 100-300km 2-fiber links observed

1000 km Espoo - Kajaani White Rabbit link

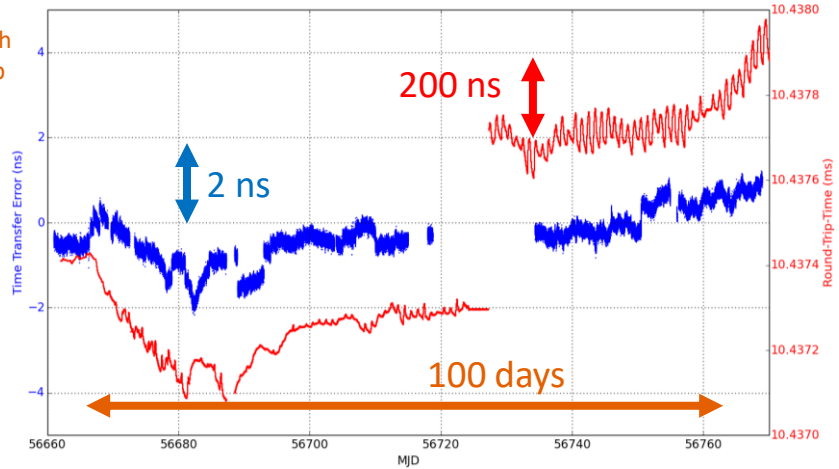




- ~~bidir~~ duplex SFPs and link
- ~~10 km~~ ~1000 km link length
- 10.4 millisecond round trip
- Uplink – downlink = ~4 us
- 12 amplifiers/multiplexers
- Longest span ~140 km

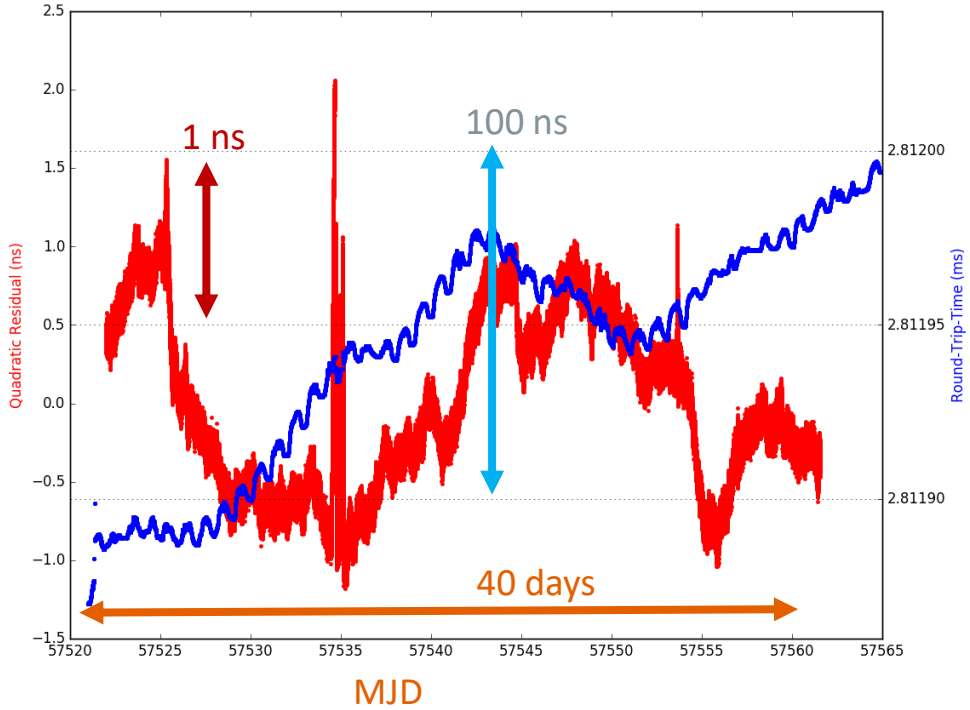
Issues:

- Network maintenance changes asymmetry
- Stability limited by Cs-clock and GPS-PPP



[Dierikx et al. http://dx.doi.org/10.1109/TUFFC.2016.2518122]

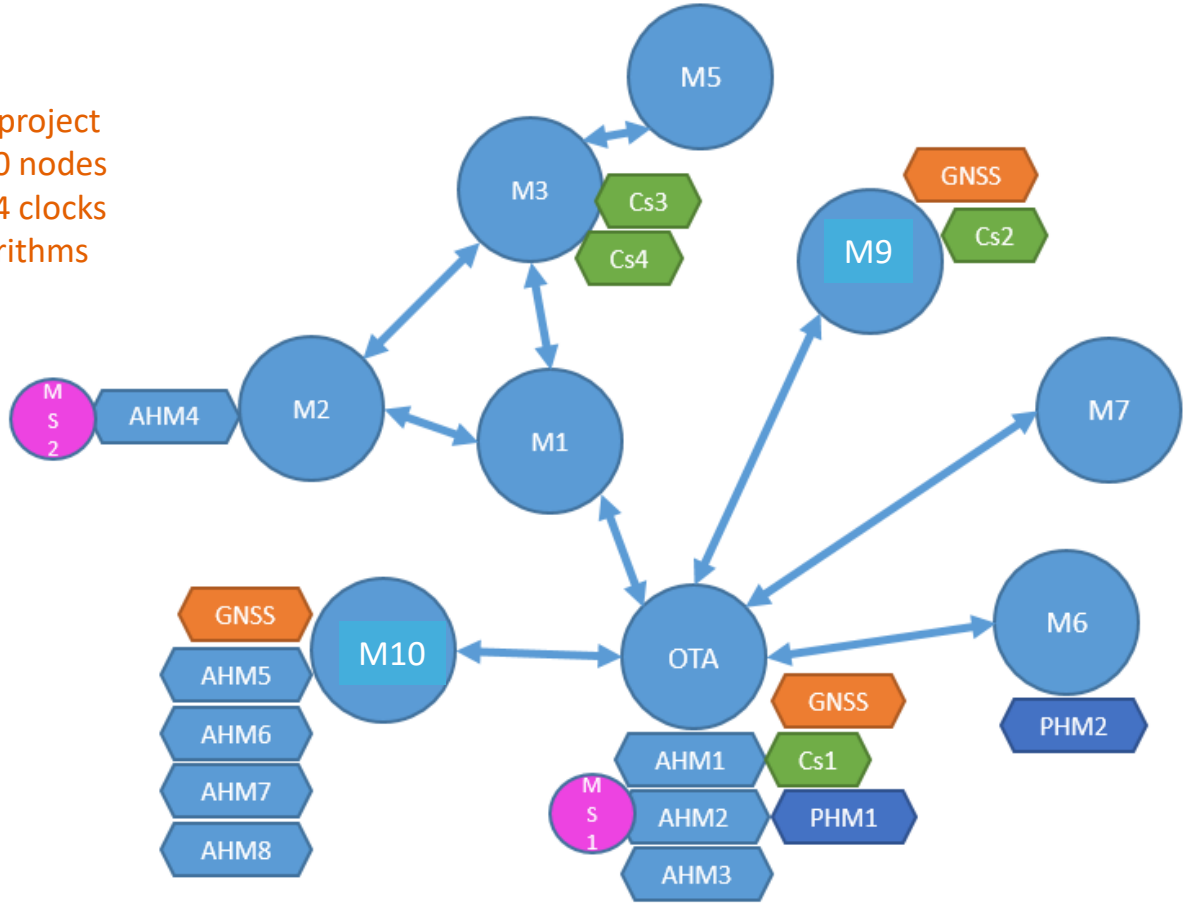
280km Link between H-maser clocks



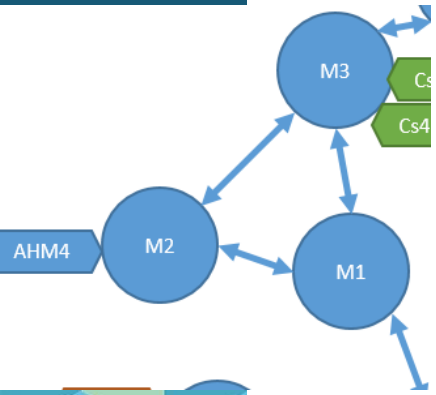
-> Almost like having the remote clock
In the lab next door! ☺

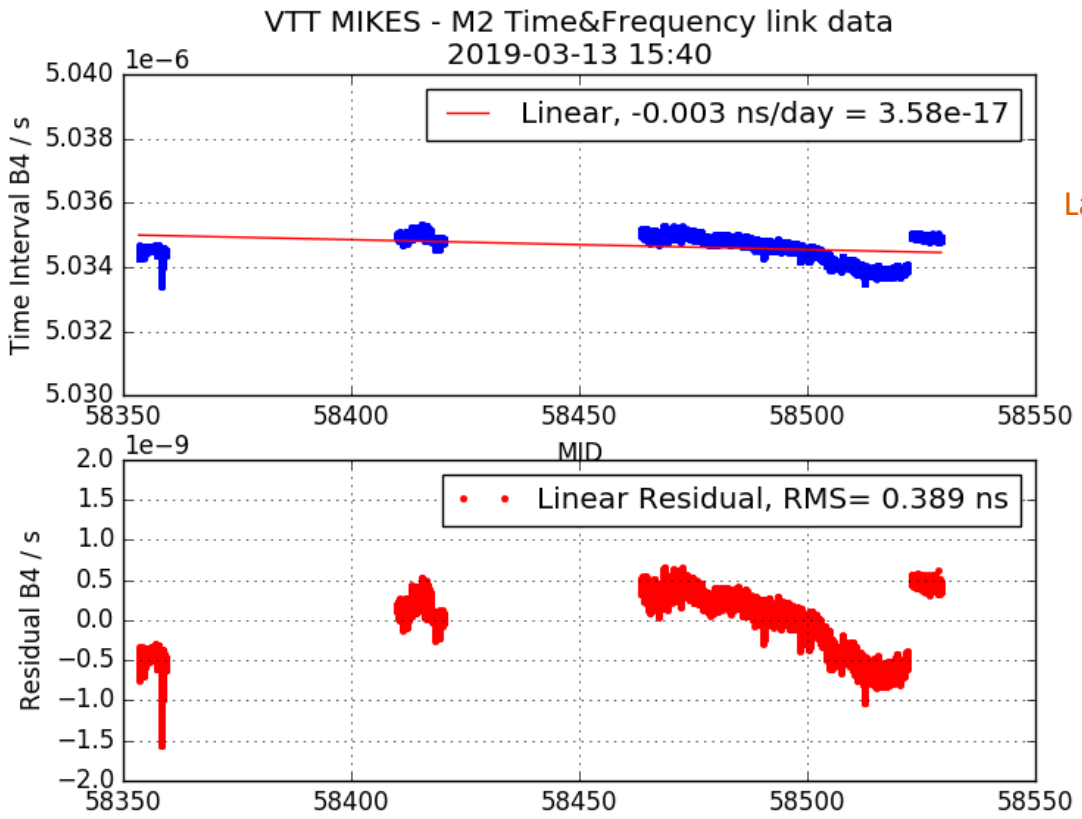
Future: Clock Network, as of 2019-04

MATINE-project
- Ca 10 nodes
- Ca 14 clocks
- Algorithms



Loop M1-M2-M3 closure error





Large offset of 5 us!

But very small Instability!
+/-0.5 ns during 200 days

Conclusions & References

- ePRTC requirements approach the level of national UTC-labs!
  - GNSS is widely used – but can be spoofed/jammed!?
- PTP White Rabbit / High Accuracy can be used for ePRTC-level distribution.
  works with ns stability and offsets limited by the network
- Timekeeping in the future will be distributed and redundant
- VTT MIKES operates around 1700 km of time-links, mostly for research at the moment.
  - Do we need/want a national reliable operational timekeeping-network?

References

Hajautetut vikasietoiset kelloverkot
https://www.defmin.fi/files/4563/2500M-0099_Tiivistelmaraportti_Wallin.pdf

GSA: Report on Time & Synchronisation User Needs and Requirements
https://www.gsc-europa.eu/system/files/galileo_documents/Time-Synchronisation-Report-on-User-Needs-and-Requirements-v1.0.pdf

White Rabbit best practices guide
https://www.ohwr.org/project/white-rabbit/wikis/Documents/wr-good-practice-guide

PTP White Rabbit on ~1000 km Otaniemi-Kajaani link
https://ieeexplore.ieee.org/document/7383303

Thank You!