

Pulsar: A Wireless Propagation-Aware Clock Synchronization Platform

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RTAS '17, Pittsburgh PA
April 19, 2017

Accurate Timekeeping



Antiquity:
Navigation



Communication:
GSM

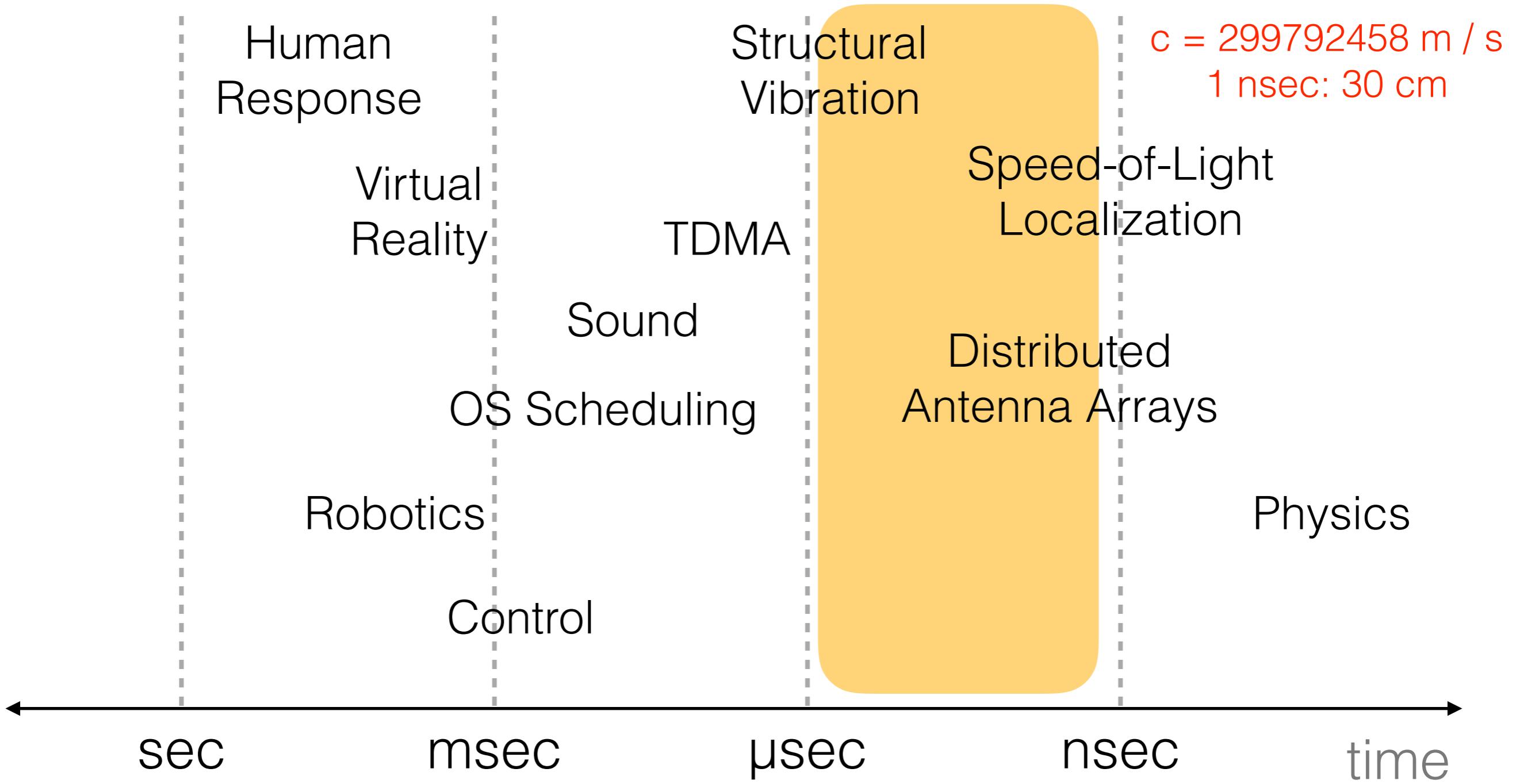


Sensing:
LIGO



Databases

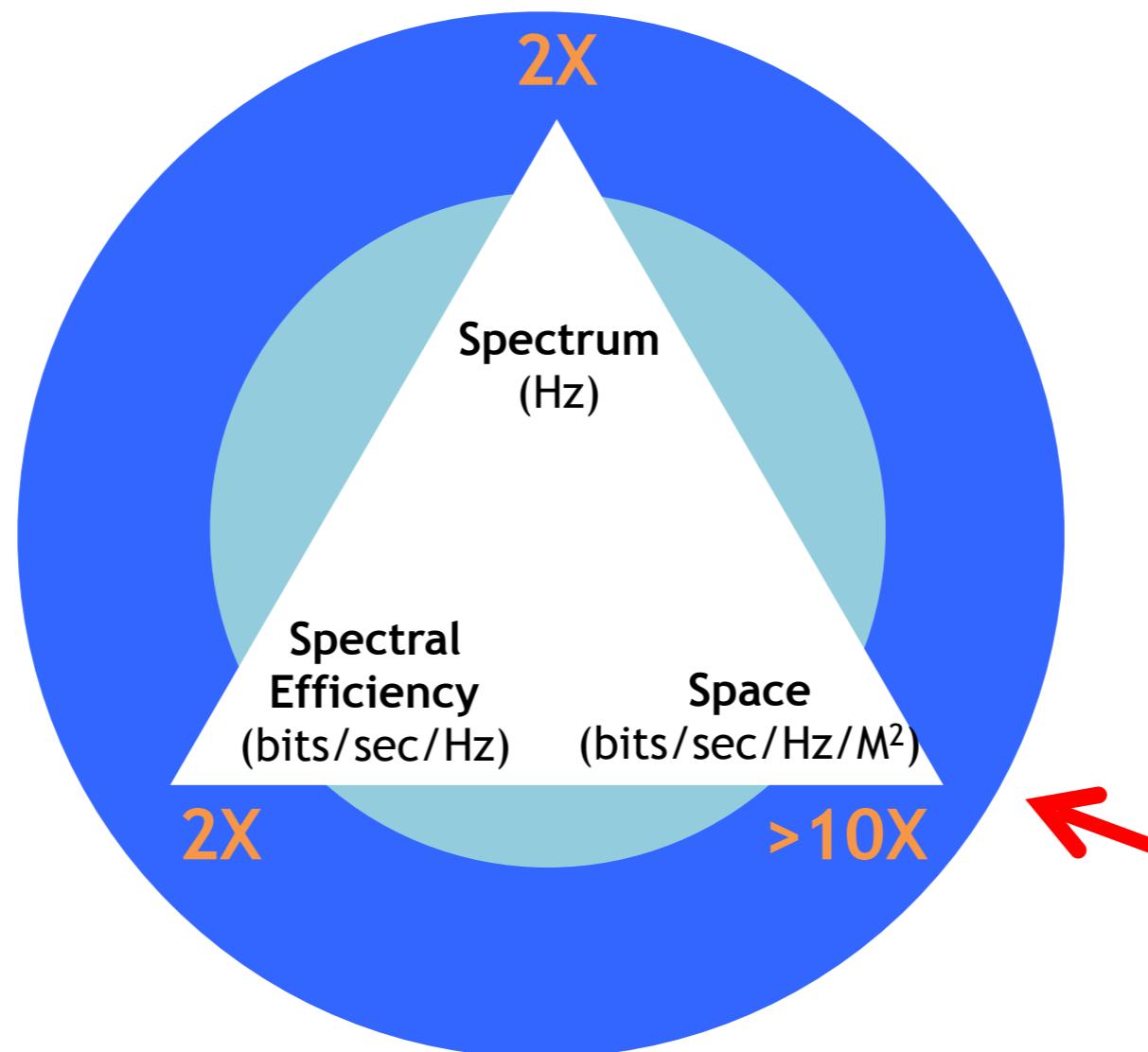
Motivating Applications



Overview

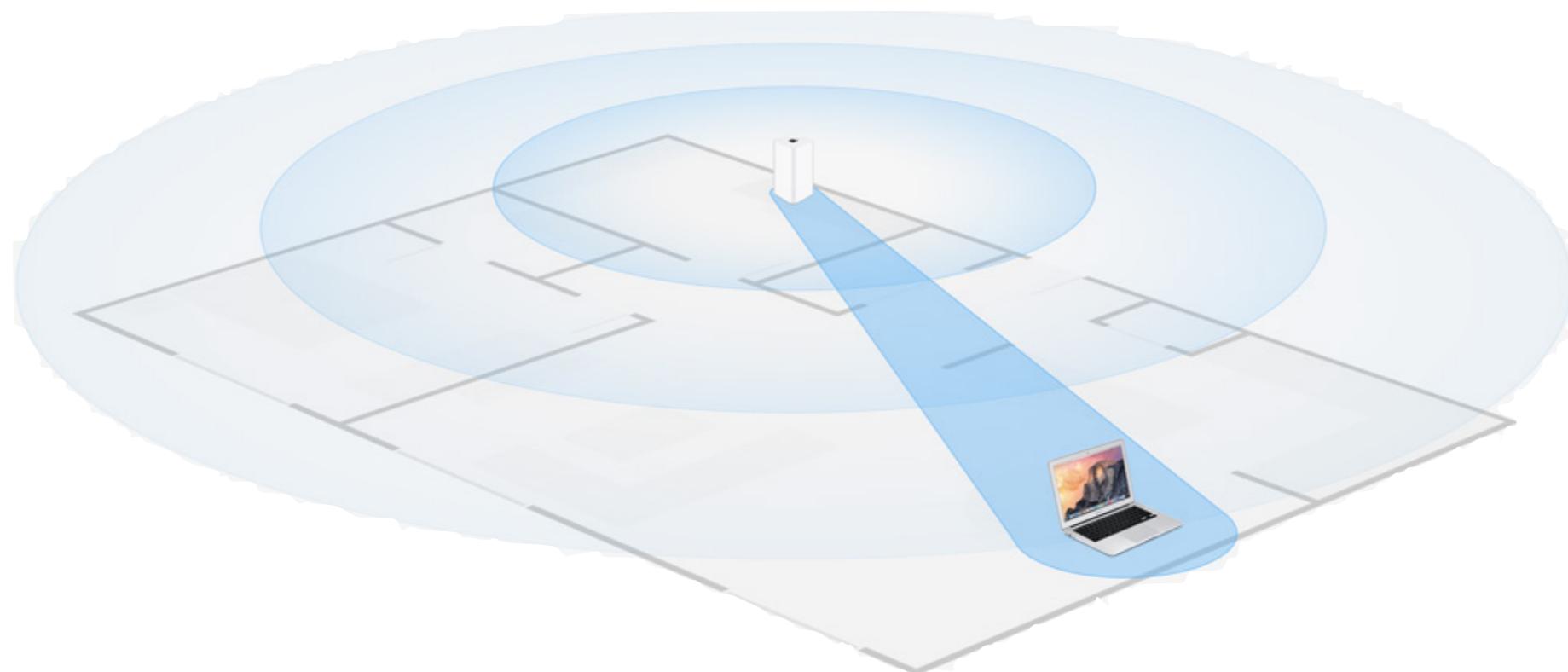
- Motivation
- The Pulsar Platform
- Analysis and Evaluation

Focus: Next-Generation Wireless (1/2)



Bell Labs, "The Future X Networks", 2016

Focus: Next-Generation Wireless (2/2)

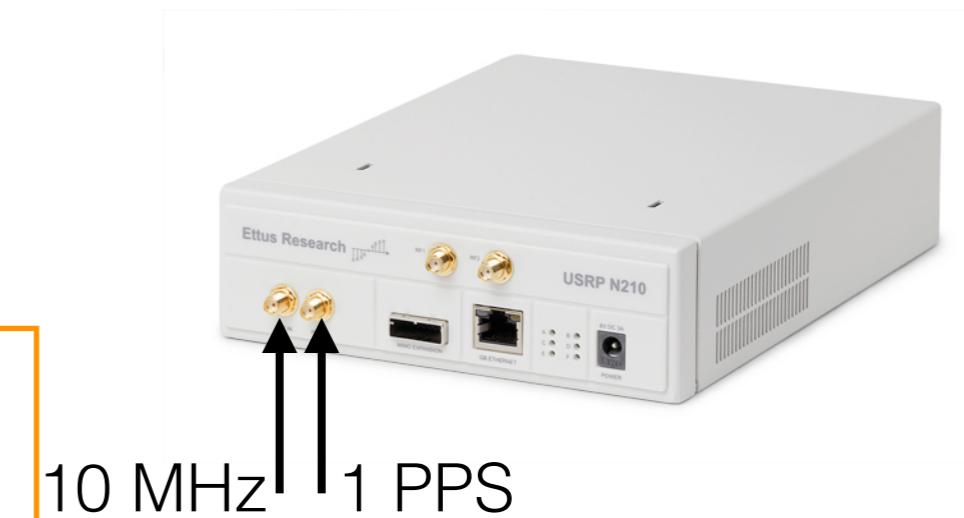


Spatial Multiplexing

apple.com, airport extreme

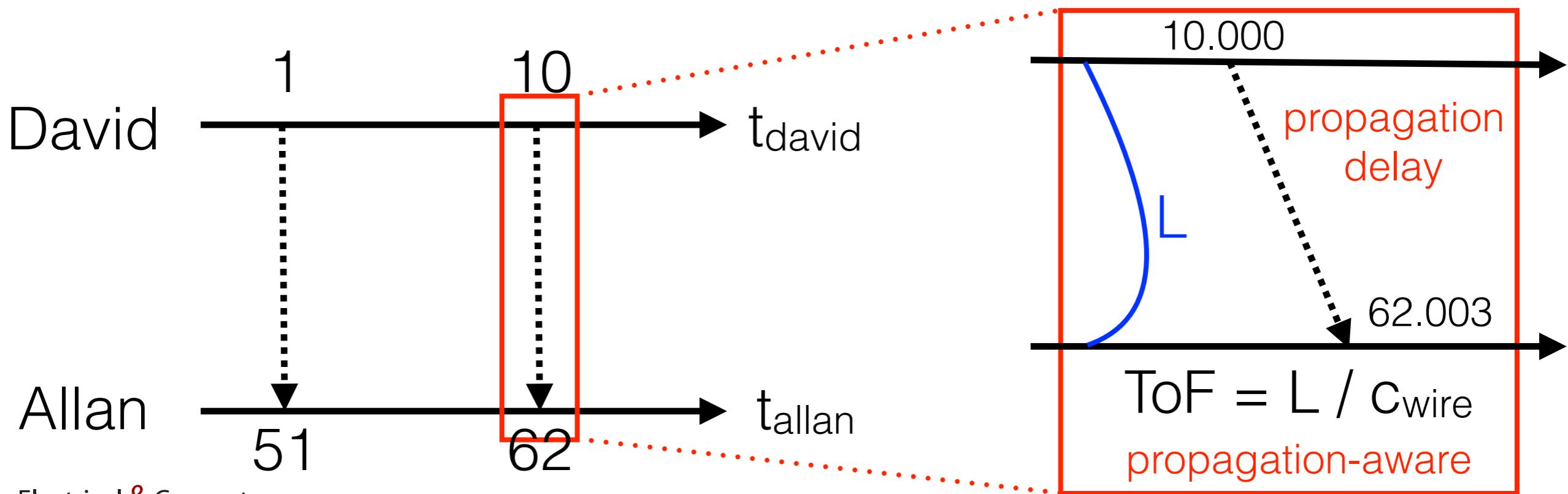
How Is It Done Today?

- Currently
 - Multiplexing on **single access point** (AP)
 - Carefully matched signal path
- **Software-defined radios** (SDR) are popular research platforms
- Accurate synchronization → Multiplexing on **multiple APs**



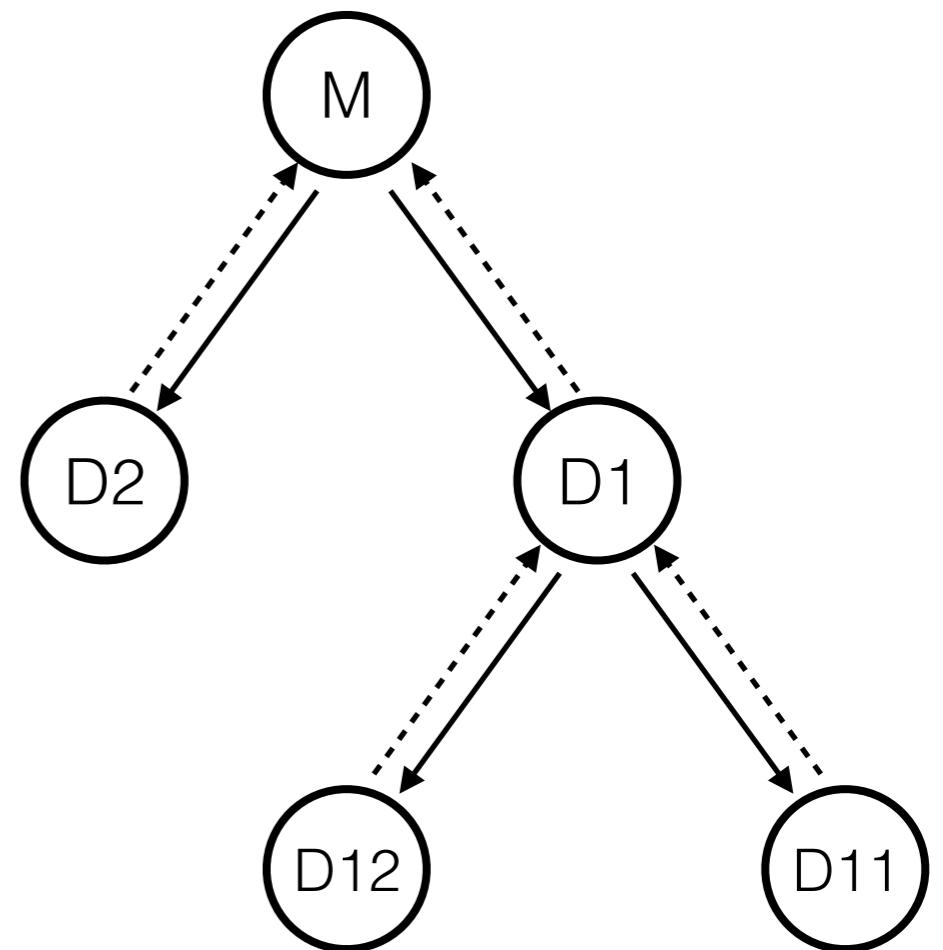
Clock Synchronization

- **Time** → events
- **Clock** → counting “regular” events
- **Clock synchronization** → agreement on **start & counts per epoch**
- **Time synchronization** → agreement with standard reference (like UTC)



Propagation Delay

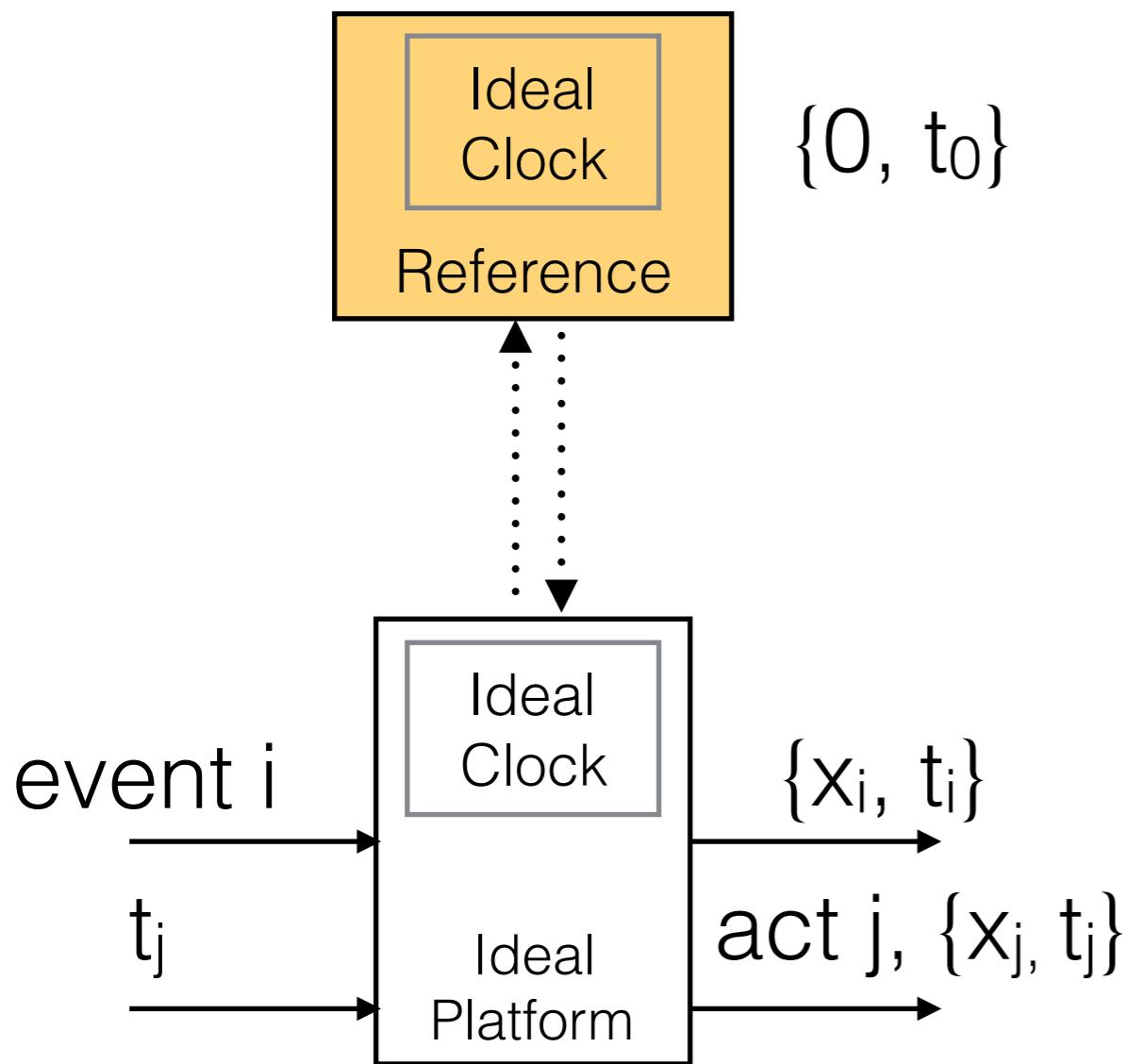
- Two-way messaging
 - Network Delay (e.g. NTP)
 - Propagation Time Delay
- Can compensate for propagation delay if distances are known



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Ideal Time-Transfer Platform



Objective: Time-transfer - sharing a time reference across locations

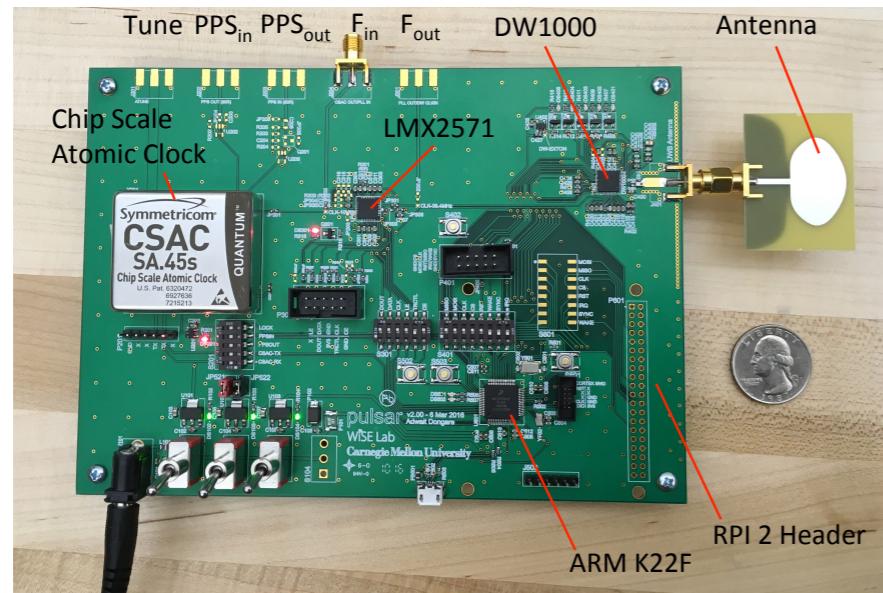
Capabilities

- Perfect event timestamps $\{x, t\}$
- Perfectly-timed actions with timestamp

Requirements

- *Timing*: Ideal clocks
- *Ranging*: Infinite bandwidth

Our Pulsar Platform



- **Stable clock:**
Chip-scale atomic clock
- **Ultra-wideband ranging radio:**
15.6 ps hardware timestamps
- *Glue logic:*
 - Low-jitter phase-locked loop
 - ARM processor
 - Phase measurement unit
- We implement *time-of-flight (propagation-aware) clock synchronization*

Hardware repository:

<https://upverter.com/WiselabCMU/eab20f02c4d4f096/Pulsar-V2/>

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Problem: Message Passing for Clock Synchronization

- **Frequency** estimation:
one-way messaging

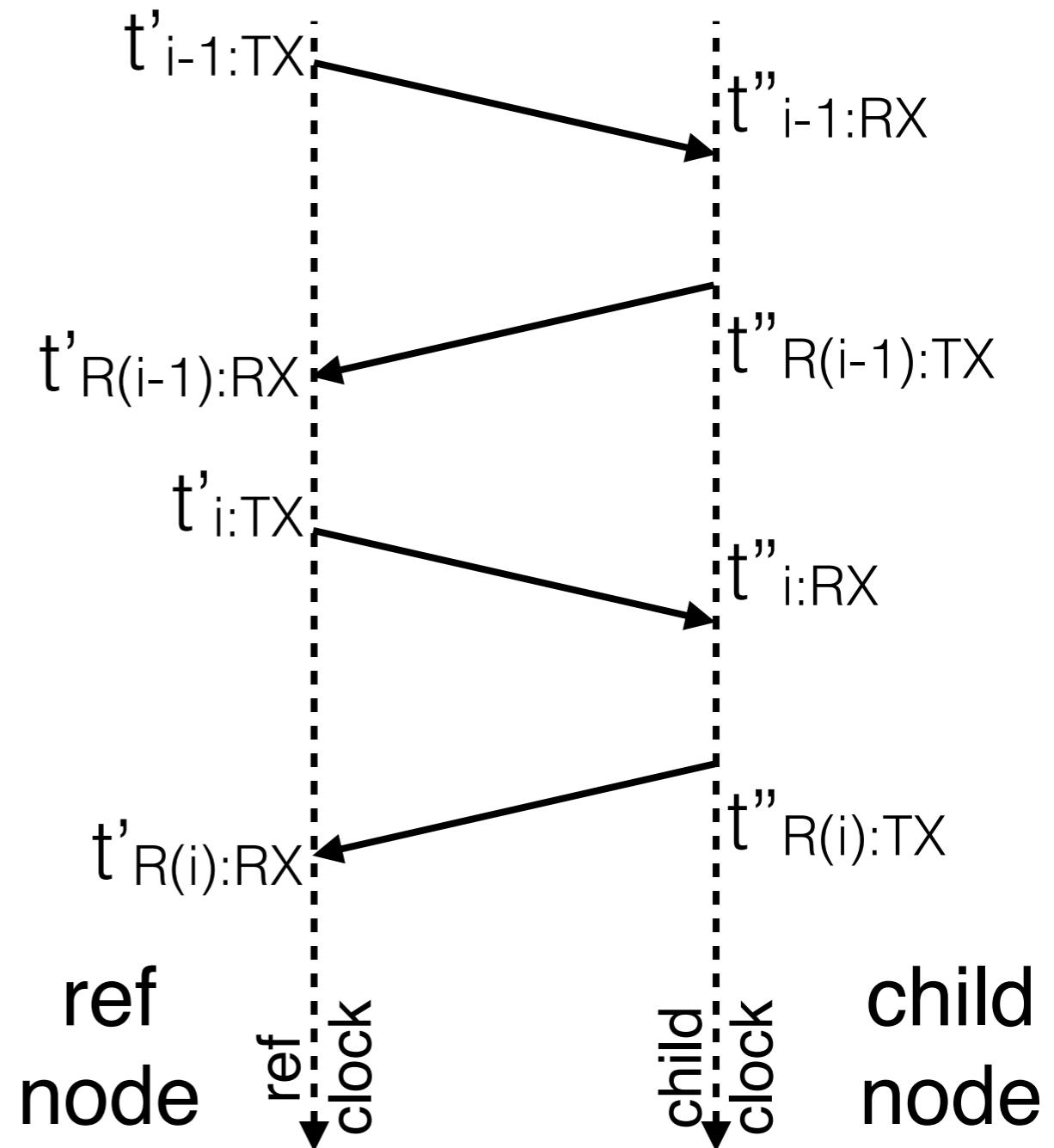
$$y_i = \frac{f_i^{\text{child}}}{f_i^{\text{reference}}} = \frac{t''_{i:\text{RX}} - t''_{i-1:\text{RX}}}{t'_{i:\text{TX}} - t'_{i-1:\text{TX}}}$$

- **Time-of-flight** estimation:
two-way messaging

$$\Delta t_{\text{TOF}}^i = \frac{(t'_{R(i):\text{RX}} - t'_{i:\text{TX}}) - (t''_{R(i):\text{TX}} - t''_{i:\text{RX}})}{2}$$

• Accurate timestamps

- Clocks must remain **stable** between message exchanges

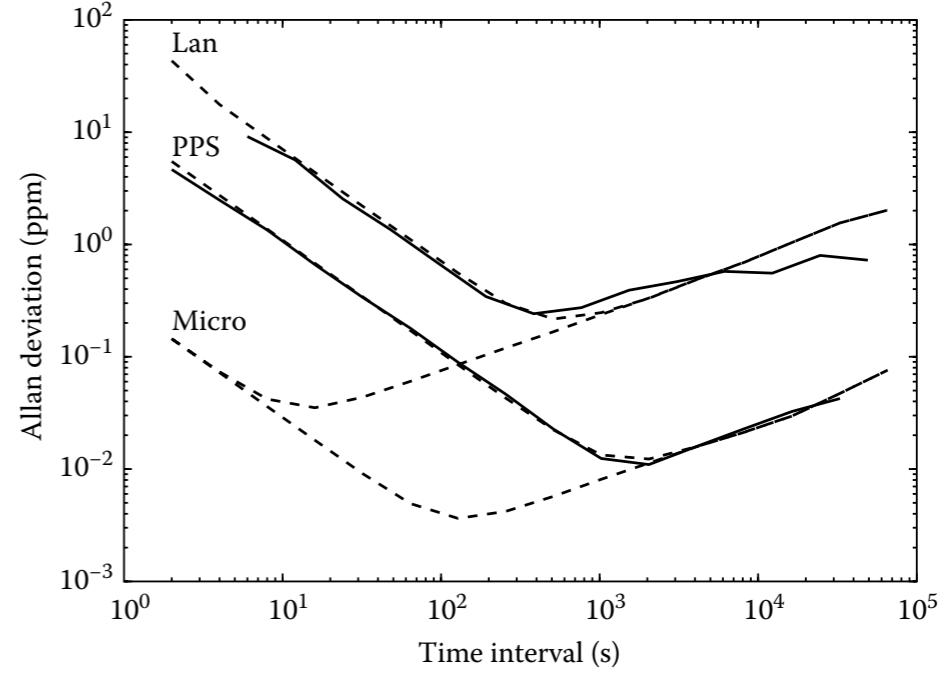
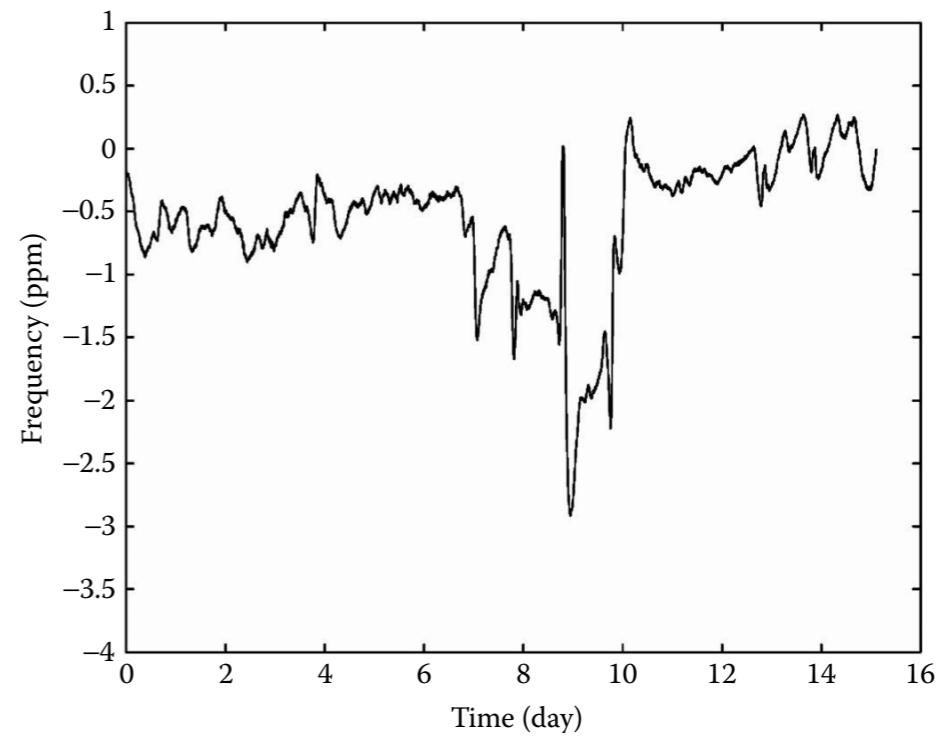


Problem: Clock Stability

- Clock accuracy $\rightarrow \delta f/f$ (*ppm*)
- Clock stability \rightarrow accuracy over time: **Allan variance**

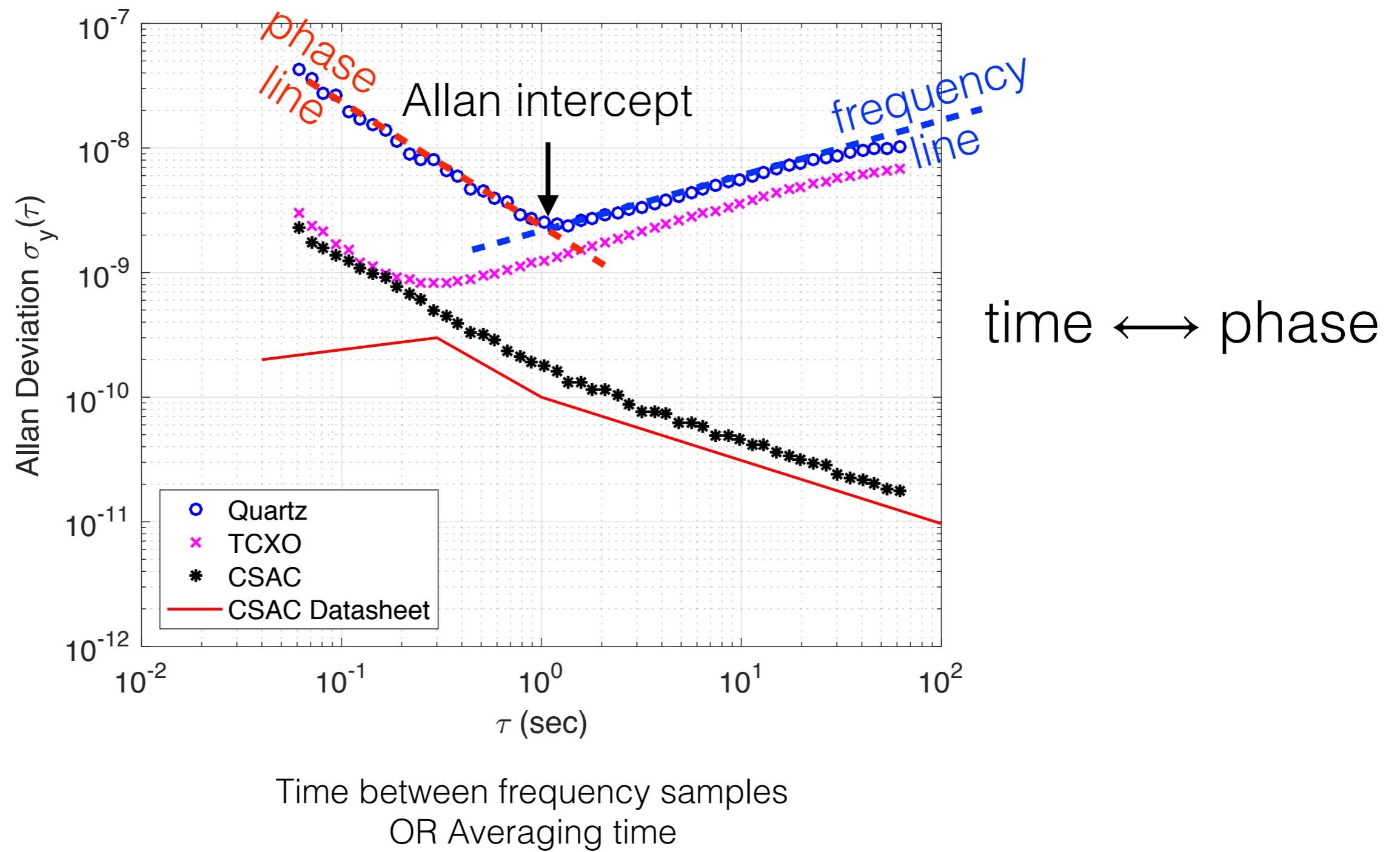
$$\sigma_y^2(\tau) = \frac{1}{2} \left\langle (\bar{y}_i - \bar{y}_{i-1})^2 \right\rangle_i$$

- Clock synchronization **will degrade over time**

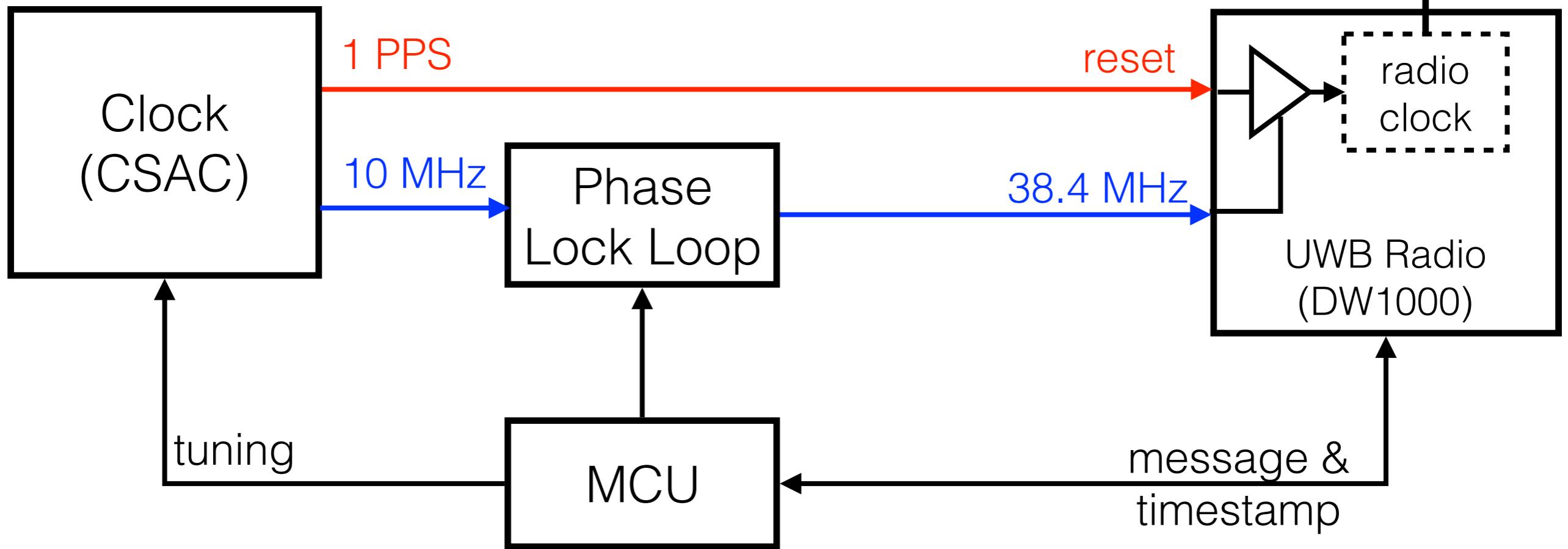


Time between frequency samples(y_i, y_{i-1})

Allan Deviation



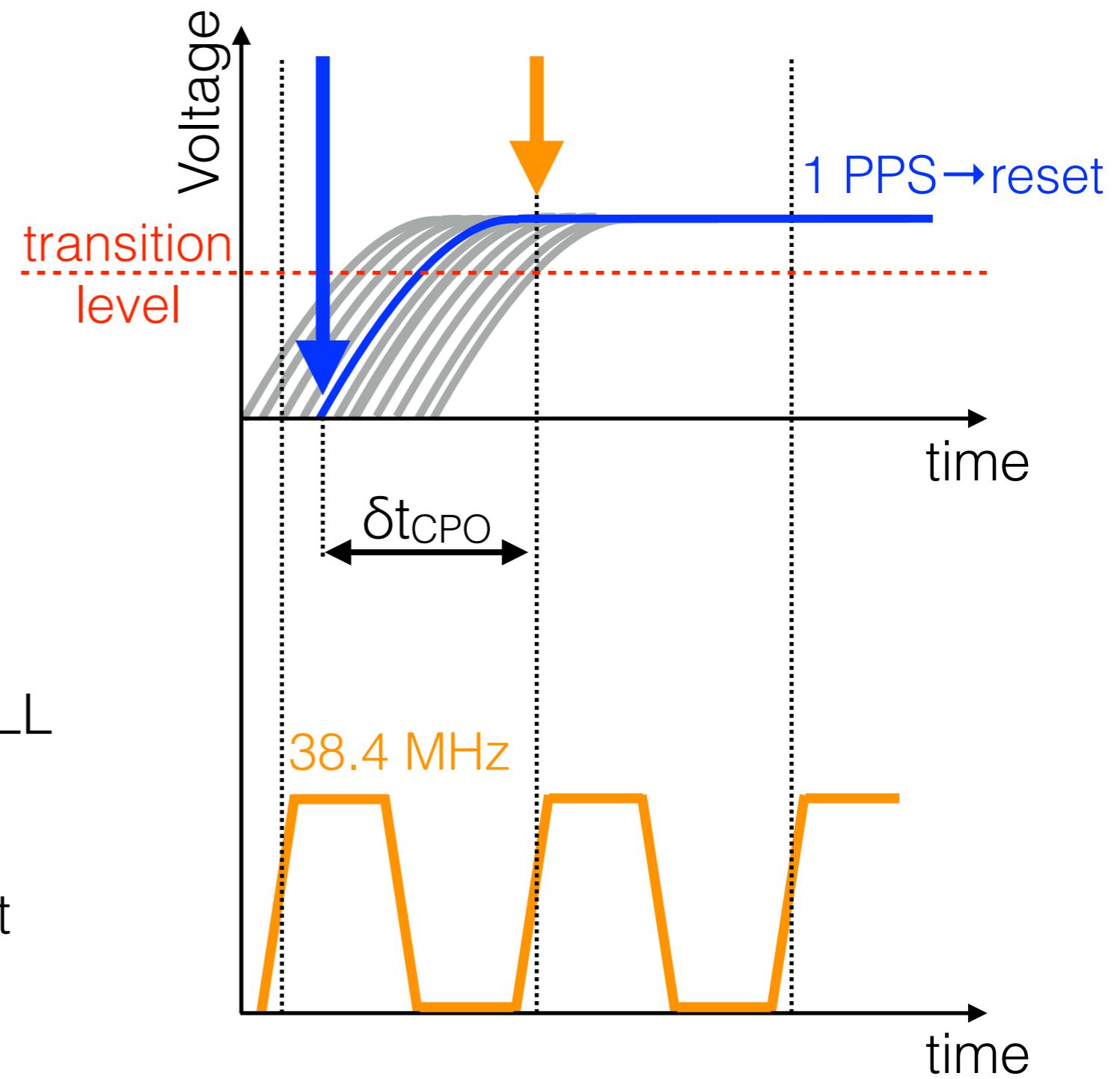
Problem: Phase Synchronization



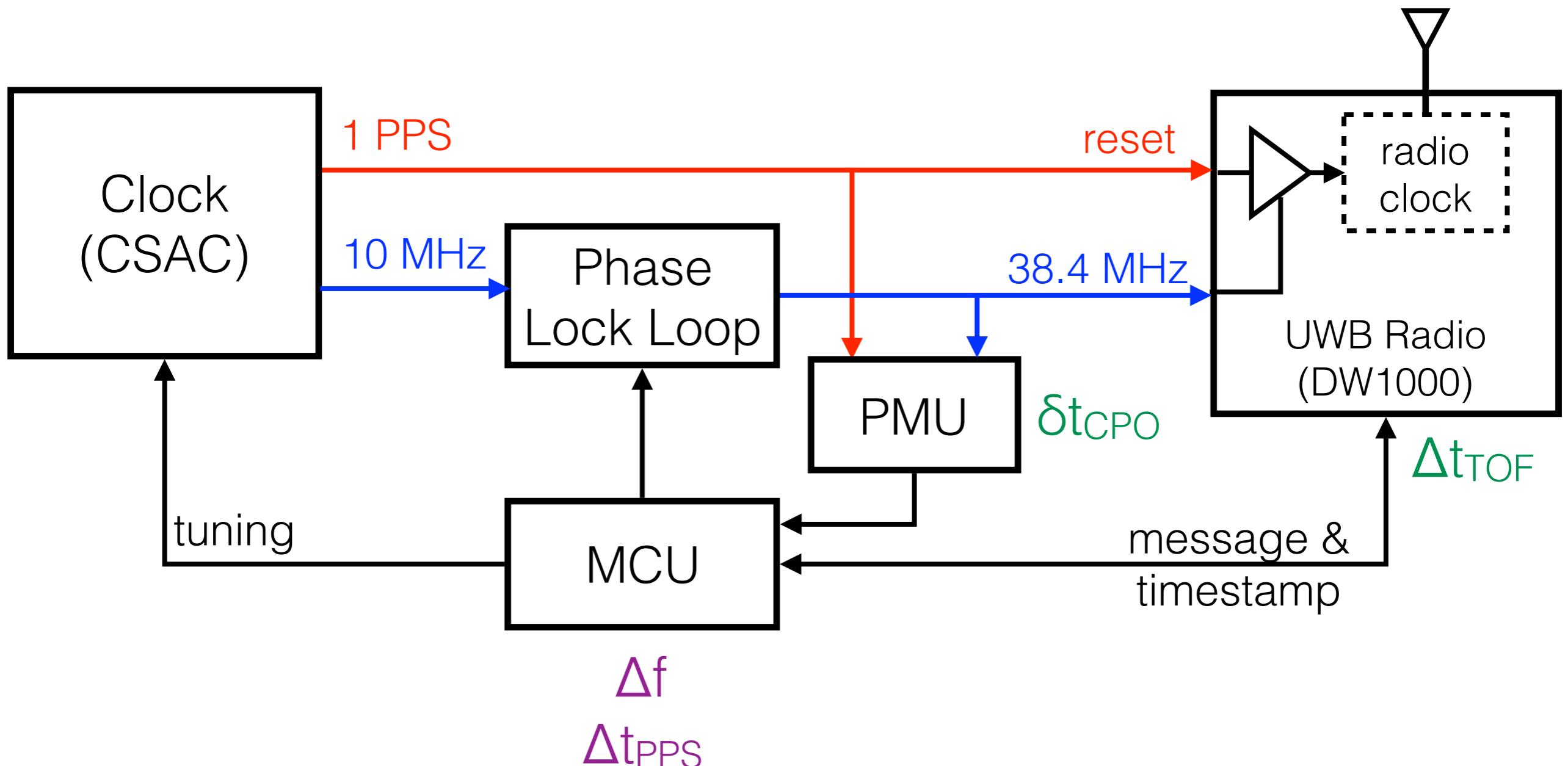
- Precise timing for e.g. SDR
 - Frequency input: **10 MHz** ✓
 - Phase/time input: **1 PPS** ??

Problem: Clock Phase Offset

- Radio clock does not reset *exactly* at desired time
 - Electronic rise time
 - Digital I/O time discretization (38.4 MHz \sim 26 nsec)
- Offsets are constant after PLL lock
- PMU for δt_{CPO} measurement

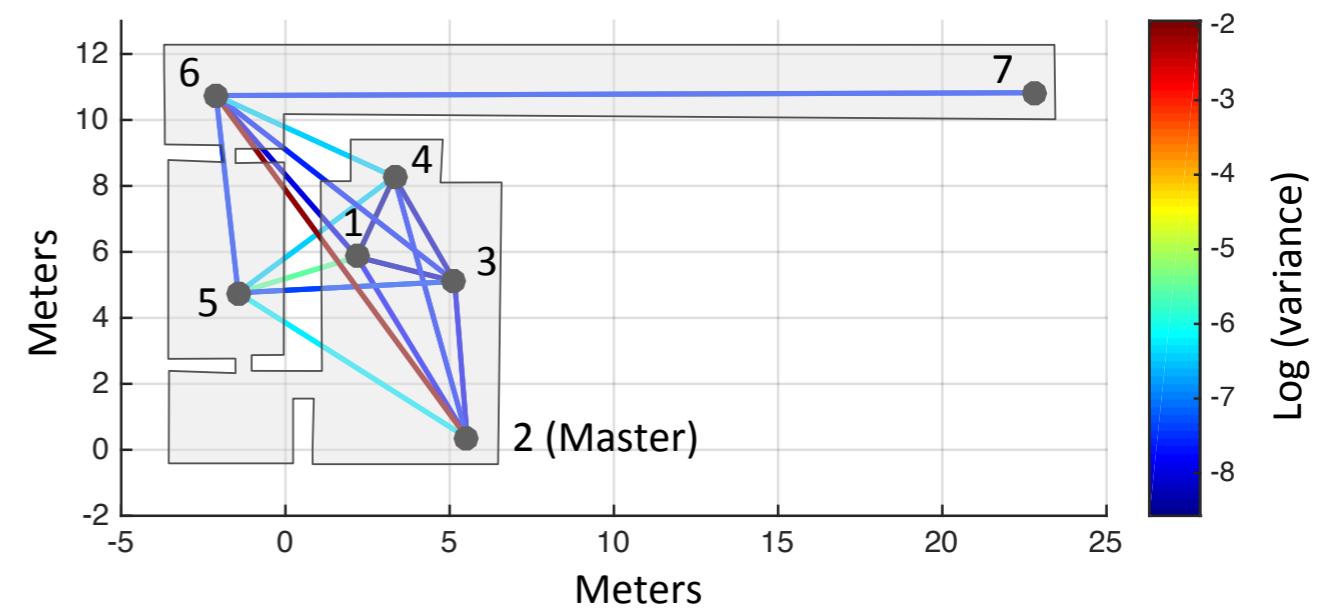
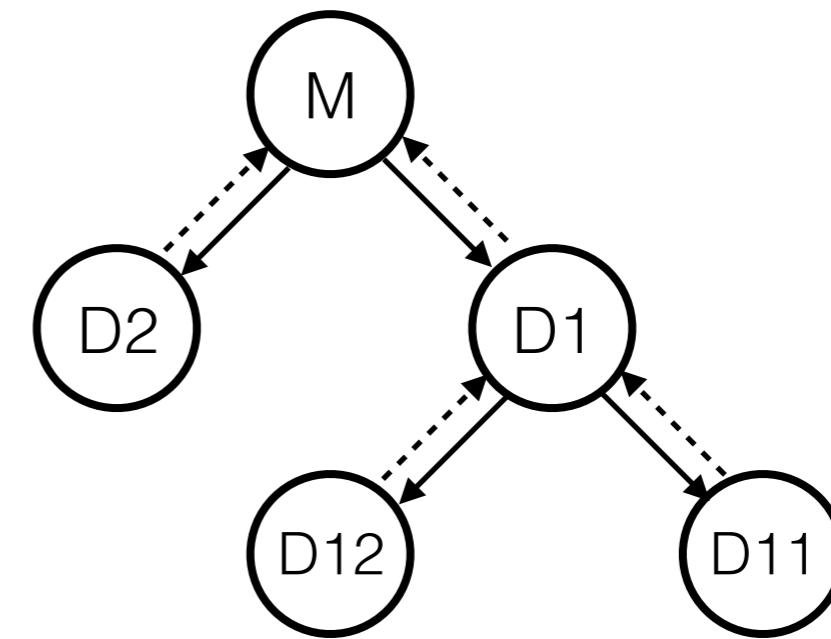


Pulsar Architecture

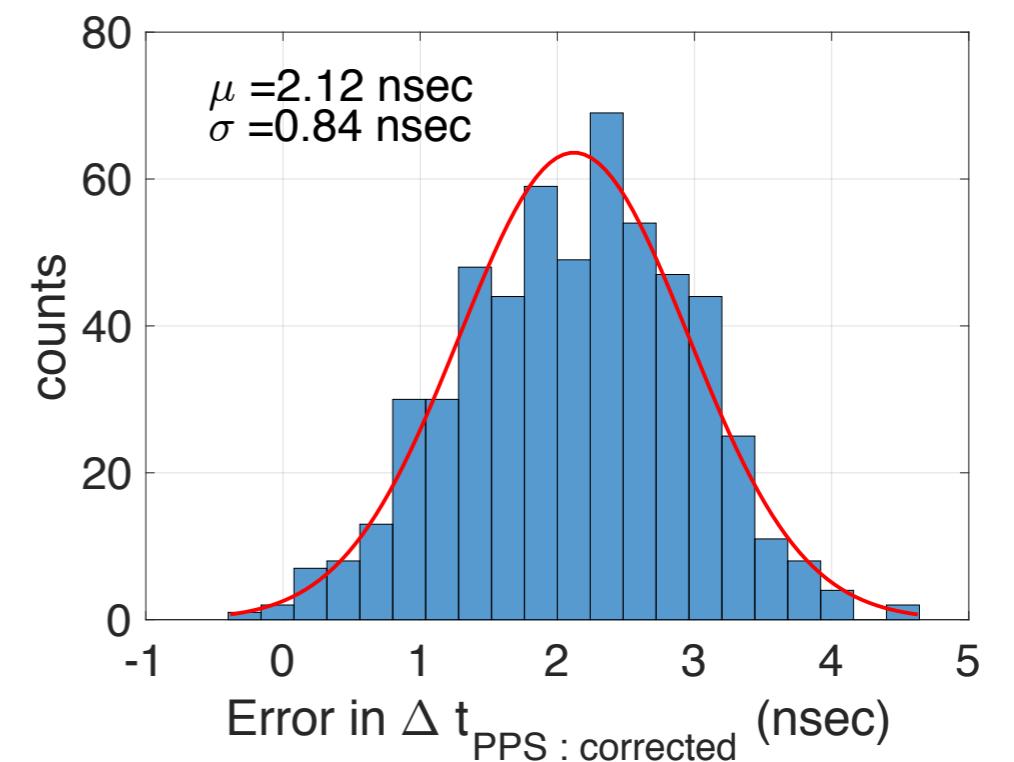
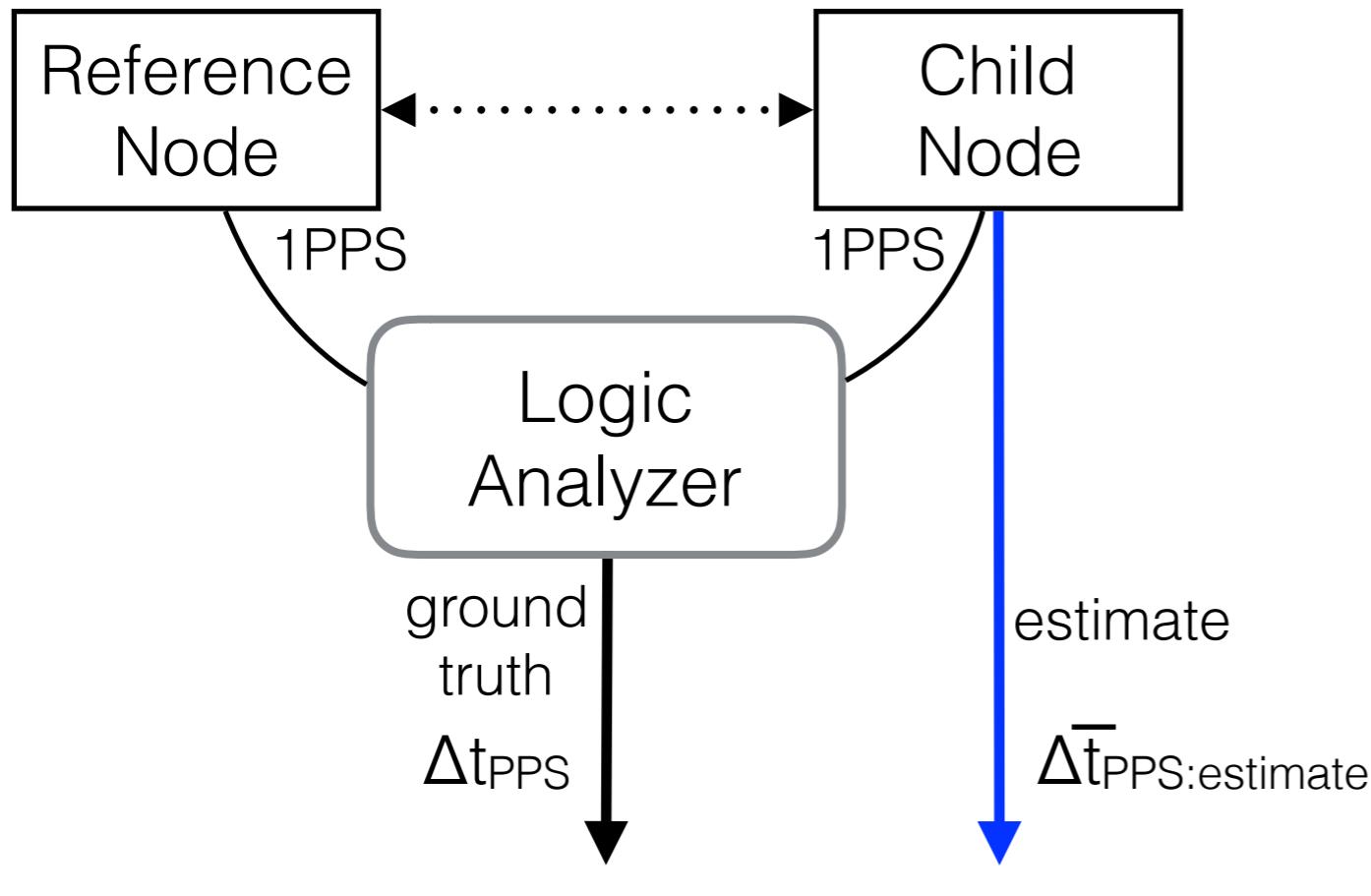


Synchronization Protocol

- Proof-of-concept protocol
- Algorithm
 - Frequency synchronization
 - Phase synchronization
 - Phase bootstrap
- Time distribution tree
- Timestamp variance as a simple link metric



Evaluation


 ϵ_t

$$\Delta t_{PPS} = \Delta t_{PPS:\text{estimate}} + \epsilon_t$$

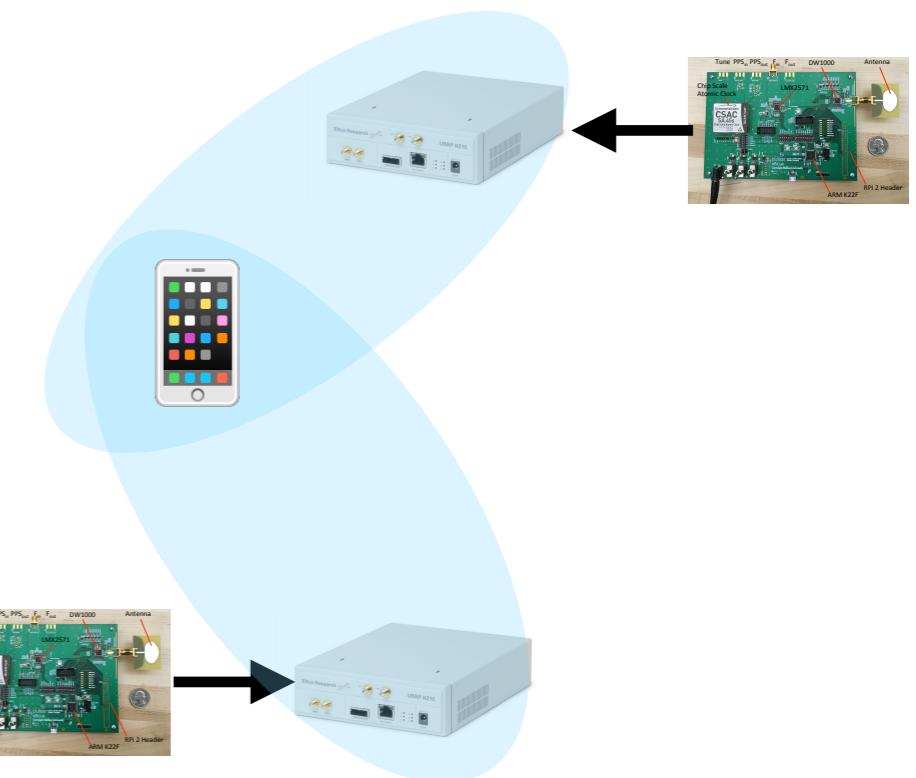
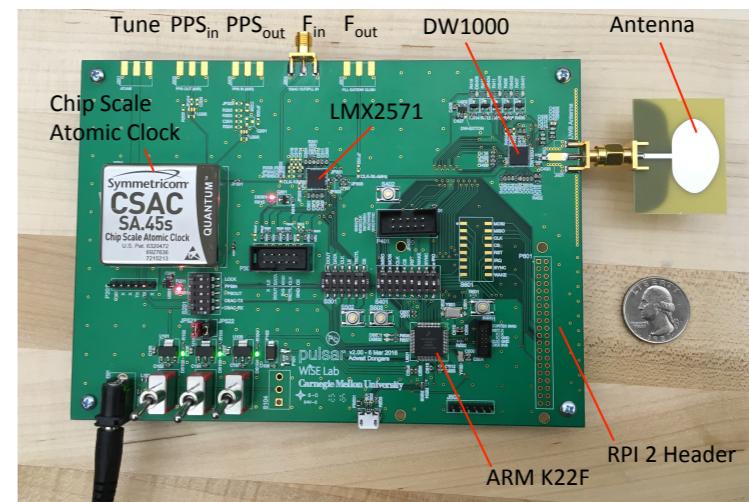
Future Work

- Testing lower cost OCXOs (~\$100/clock)
e.g. CW-OH200 Series
- Phase-measurement unit integration
- Testing other flexible and robust synchronization protocols
- SDR synchronization with Pulsar



Conclusions

- Pulsar: Platform & protocol for better than 5 nsec clock synchronization (below 26 nsec digital time discretization of radio components)
- End-to-end evaluation and analysis of timing errors
- Provide precise timing for an application (SDR) to enable spatial multiplexing



Thank you