Pulsar: A Wireless Propagation-Aware Clock Synchronization Platform

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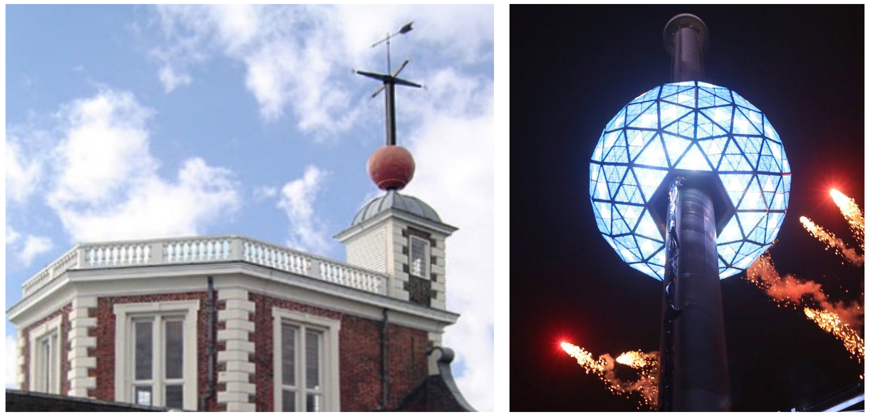
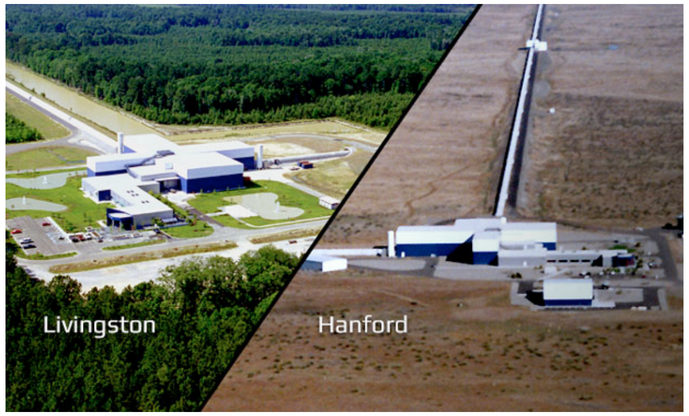
RTAS '17, Pittsburgh PA
April 19, 2017

Accurate Timekeeping



Antiquity:
Navigation

Communication:
GSM



Sensing:
LIGO

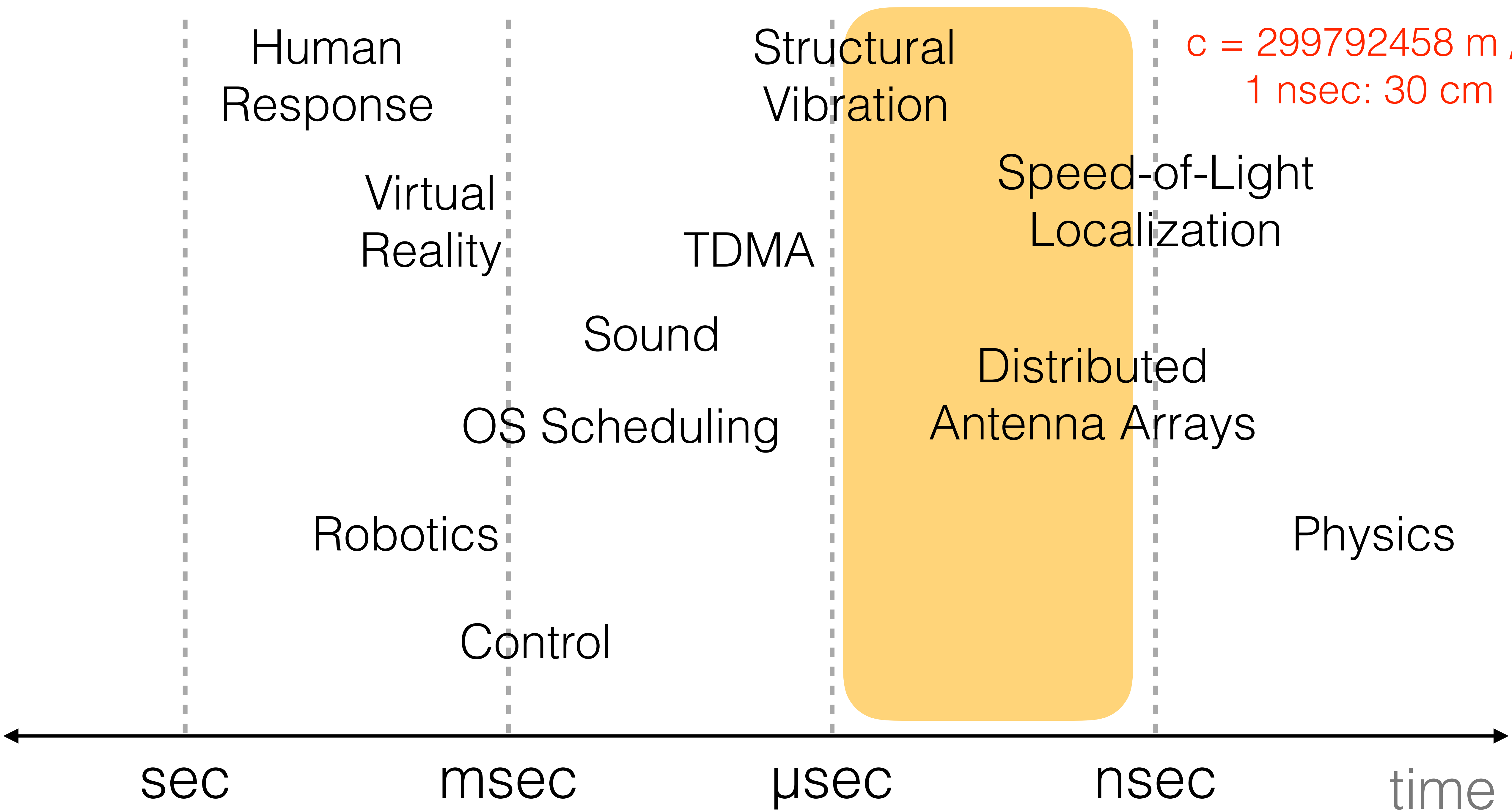
Spanner

Kdb+

cassandra

Databases

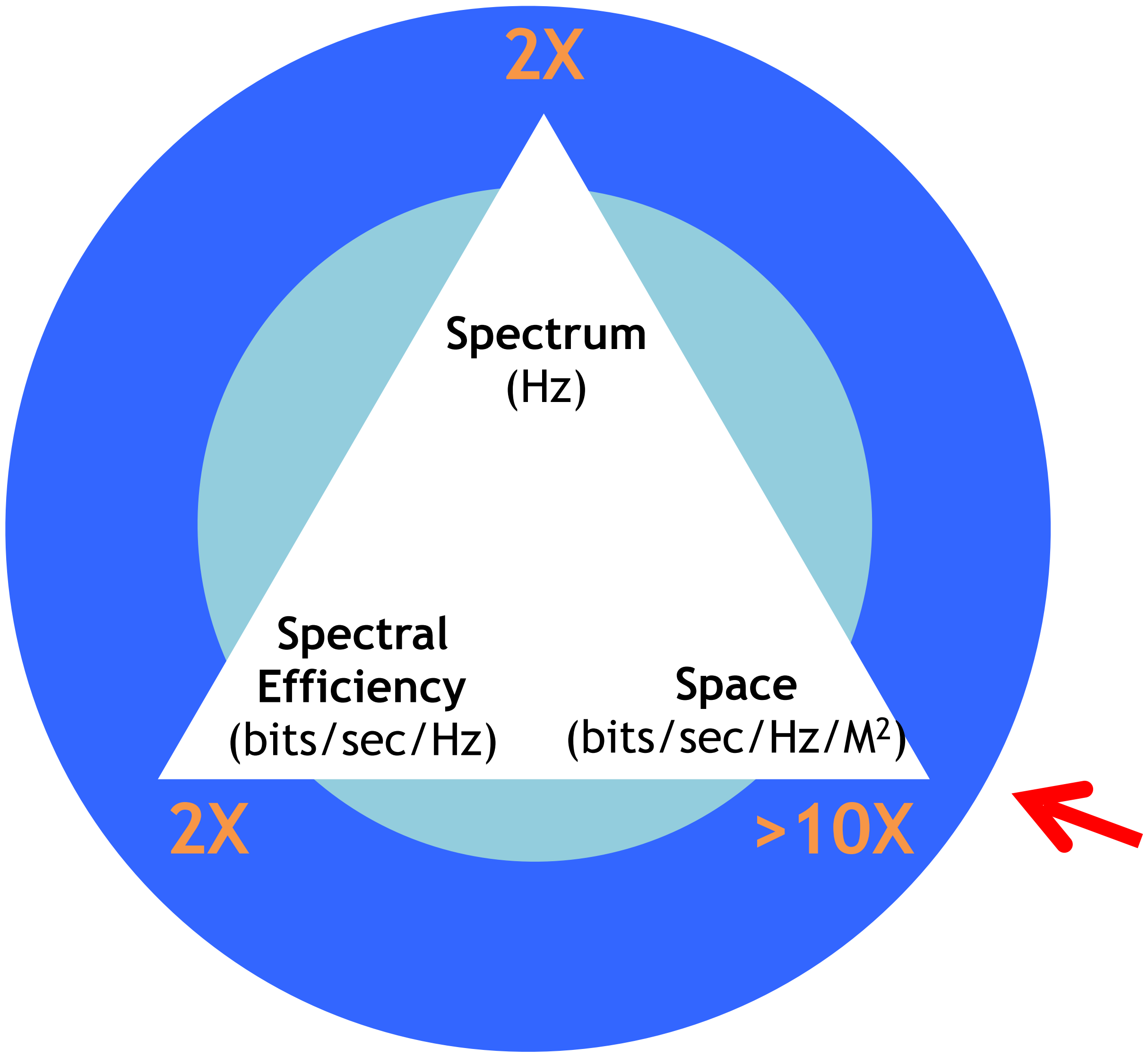
Motivating Applications



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)

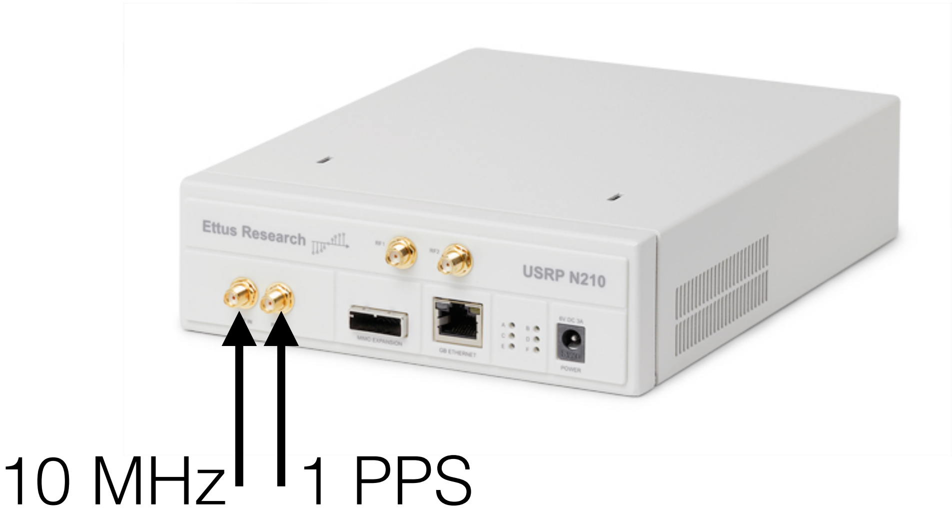
Spatial Multiplexing

apple.com, airport extreme

How Is It Done Today?

- Currently
  - Multiplexing on **single access point** (AP)
  - Carefully matched signal path

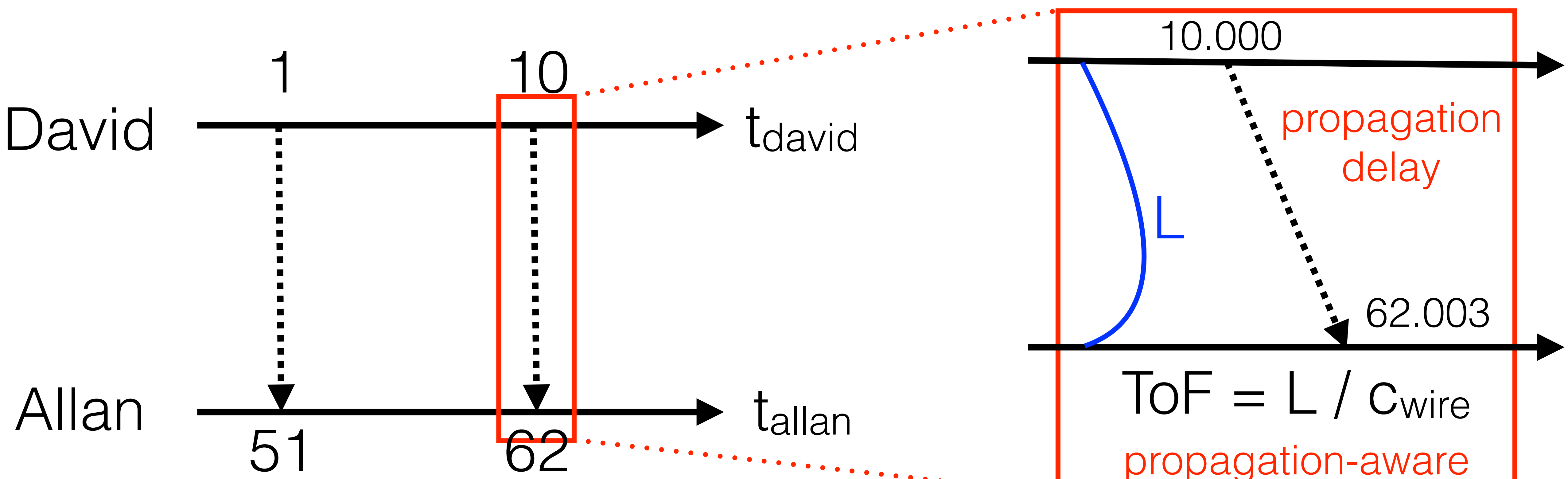
- **Software-defined radios** (SDR) are popular research platforms



- Accurate synchronization → Multiplexing on **multiple APs**

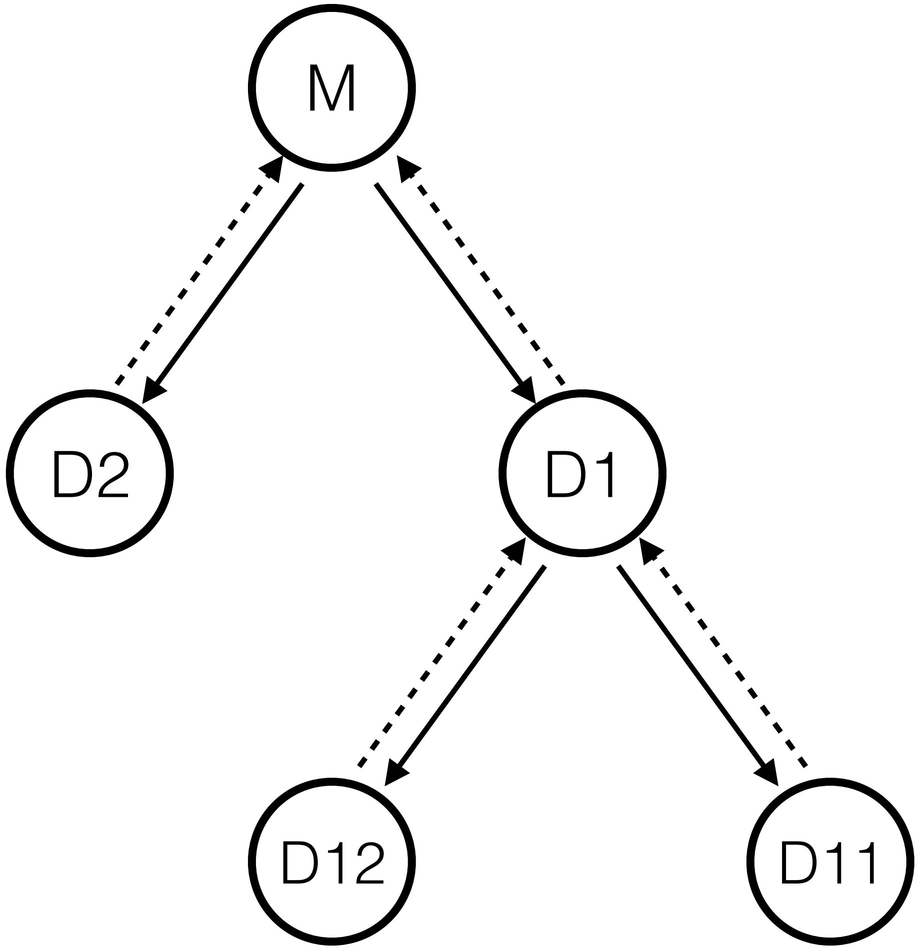
Clock Synchronization

- **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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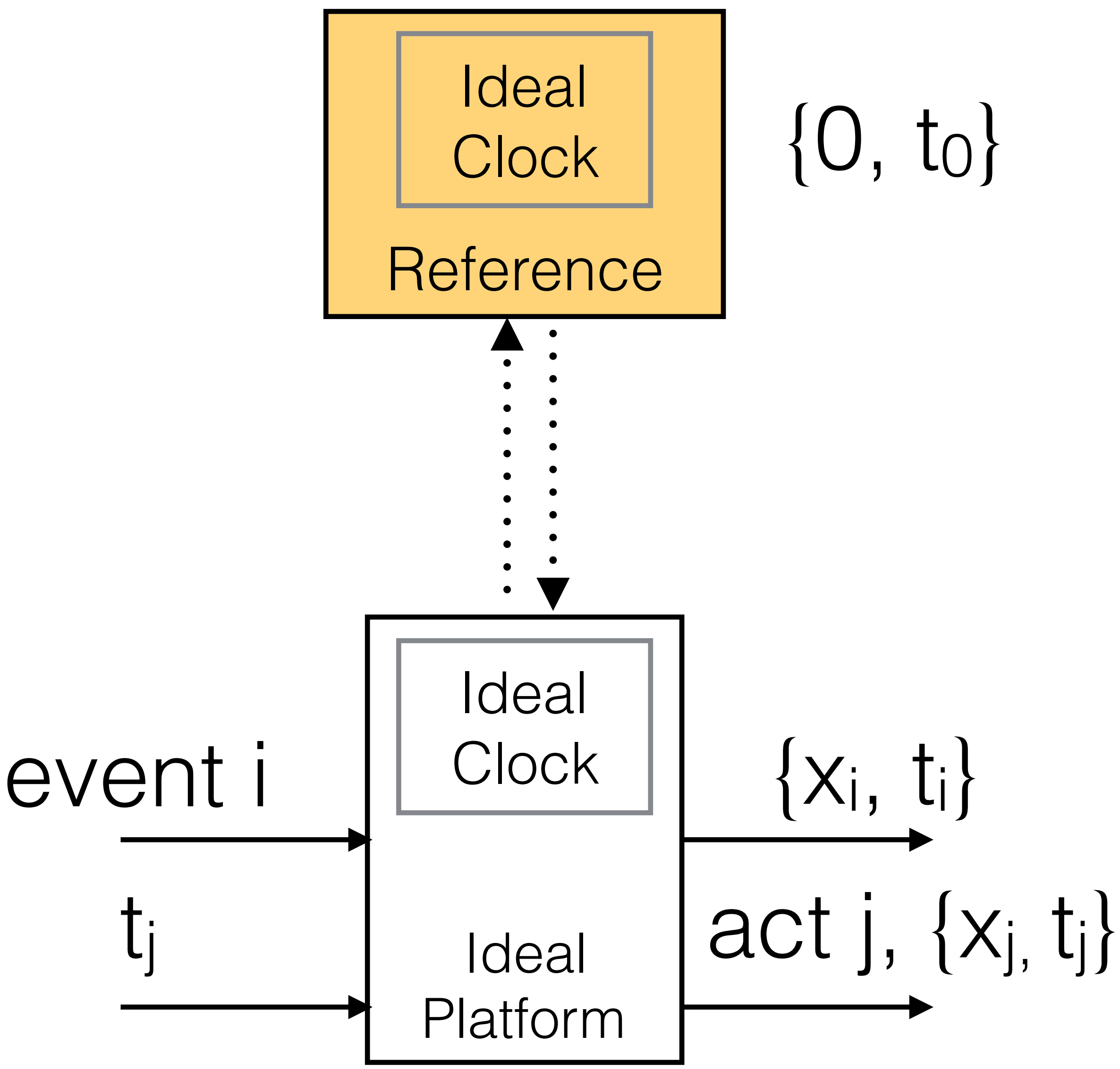
Ideal Time-Transfer Platform



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

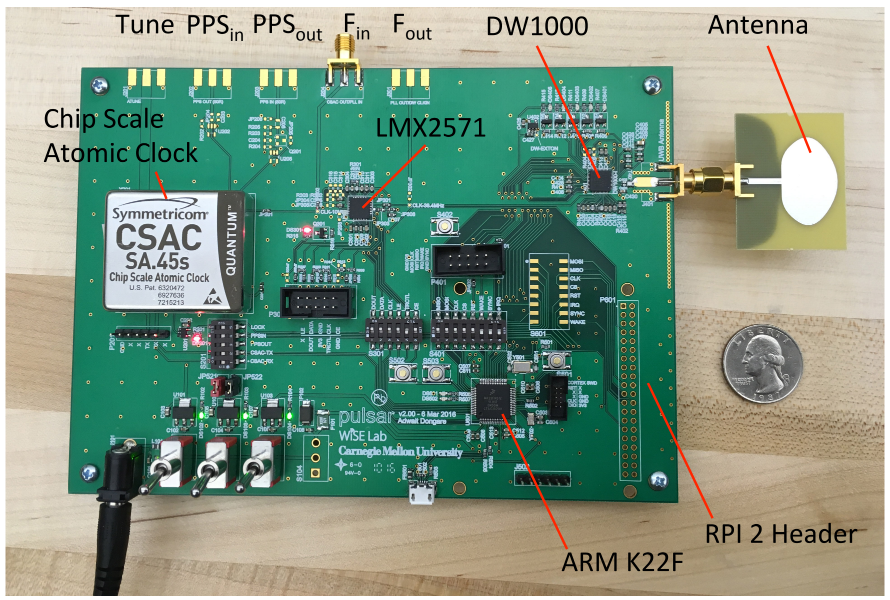
Capabilities

- 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

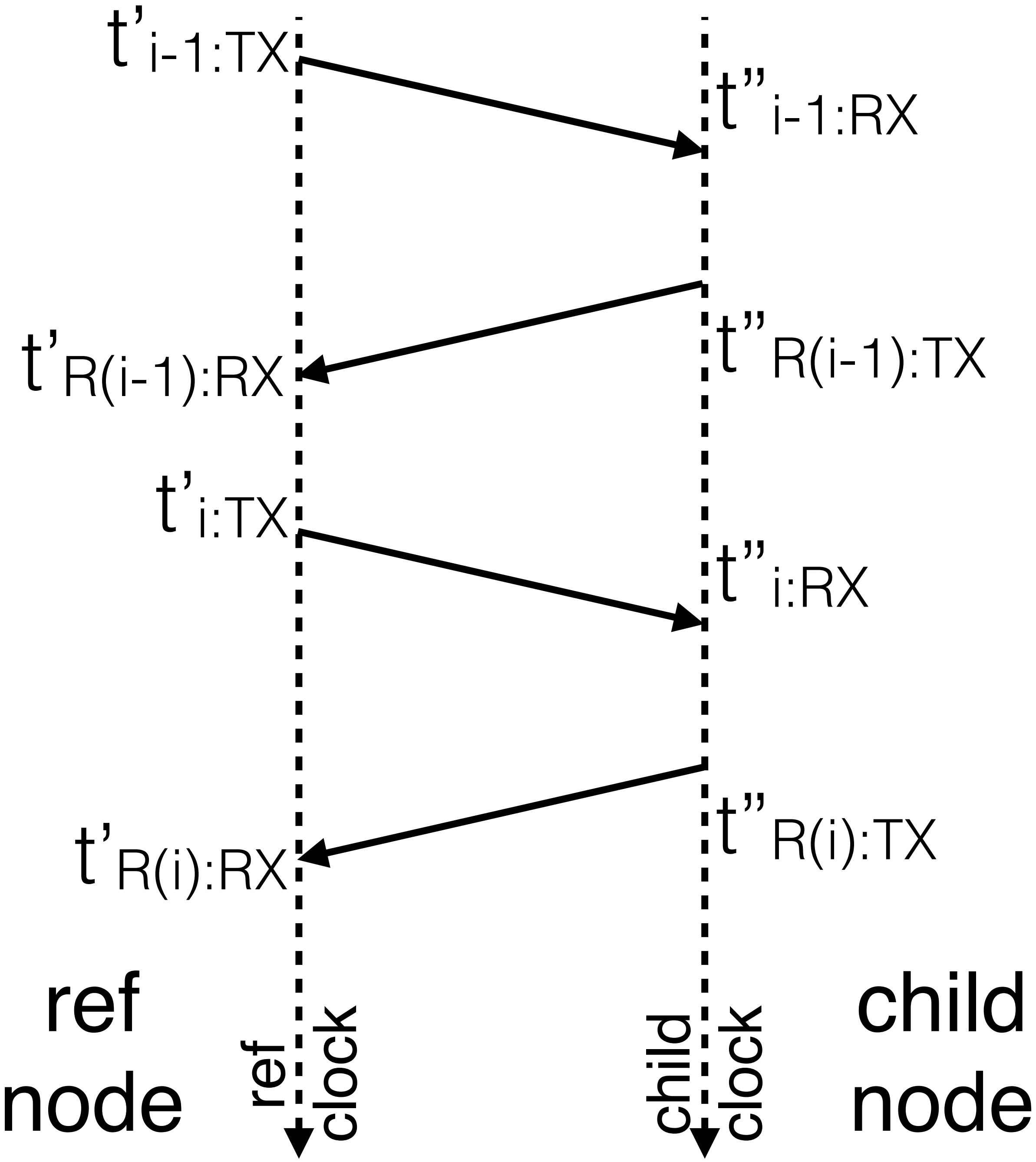
$$y_i = \frac{f_i^{\text{child}}}{f_i^{\text{reference}}} = \frac{t''_{\text{i:RX}} - t''_{\text{i-1:RX}}}{t'_{\text{i:TX}} - t'_{\text{i-1:TX}}}$$

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

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

- **Accurate timestamps**

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

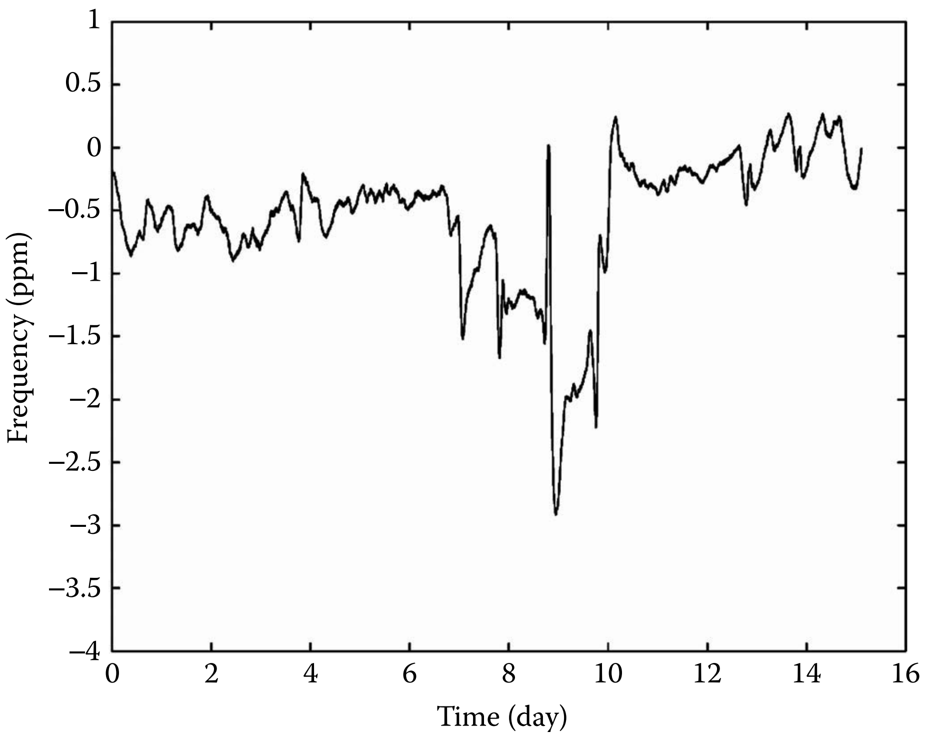


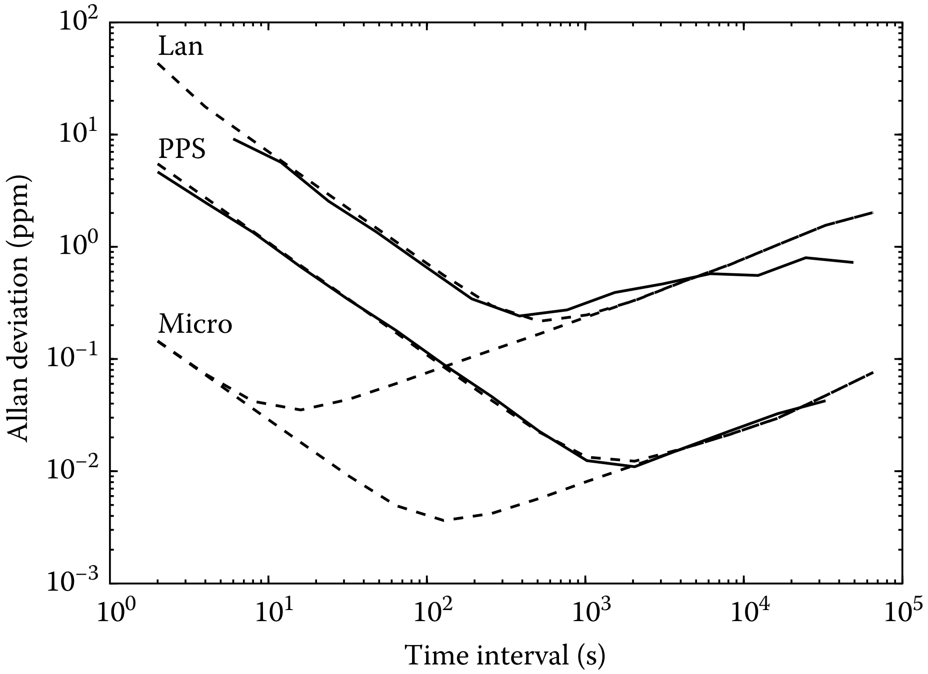
Problem: Clock Stability

- Clock accuracy → δf/f (*ppm*)
- Clock stability → 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**

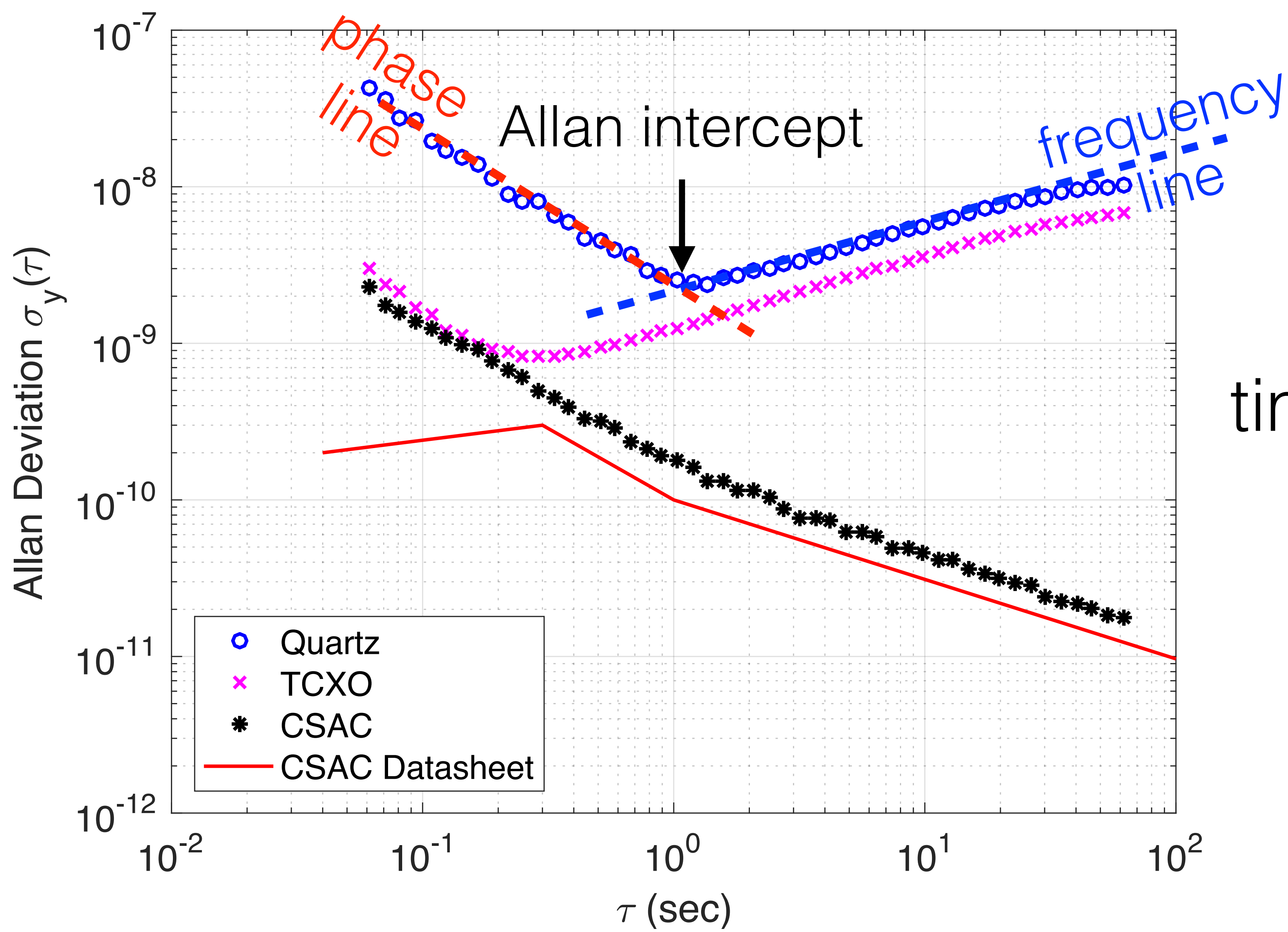




Time between frequency samples(y_i, y_{i-1})

D. Mills, Computer Network Time Synchronization

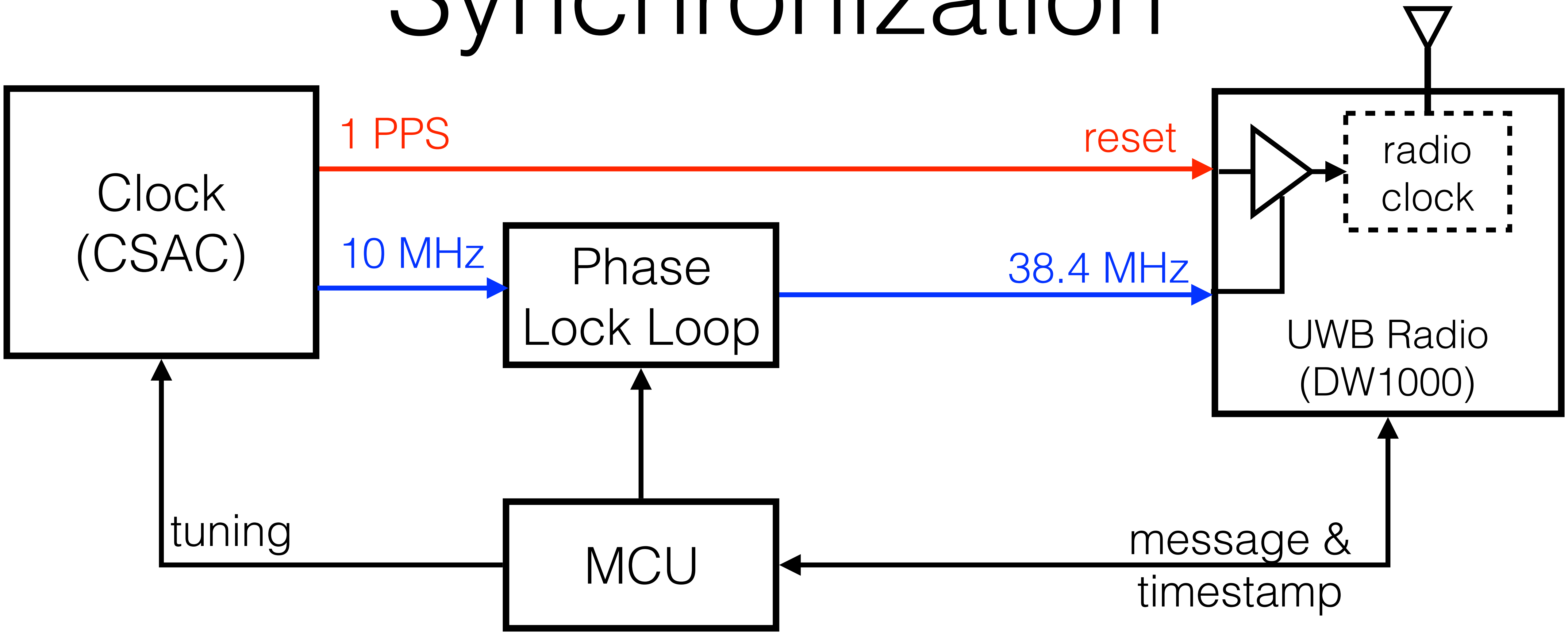
Allan Deviation



time ⟷ phase

Time between frequency samples
OR Averaging time

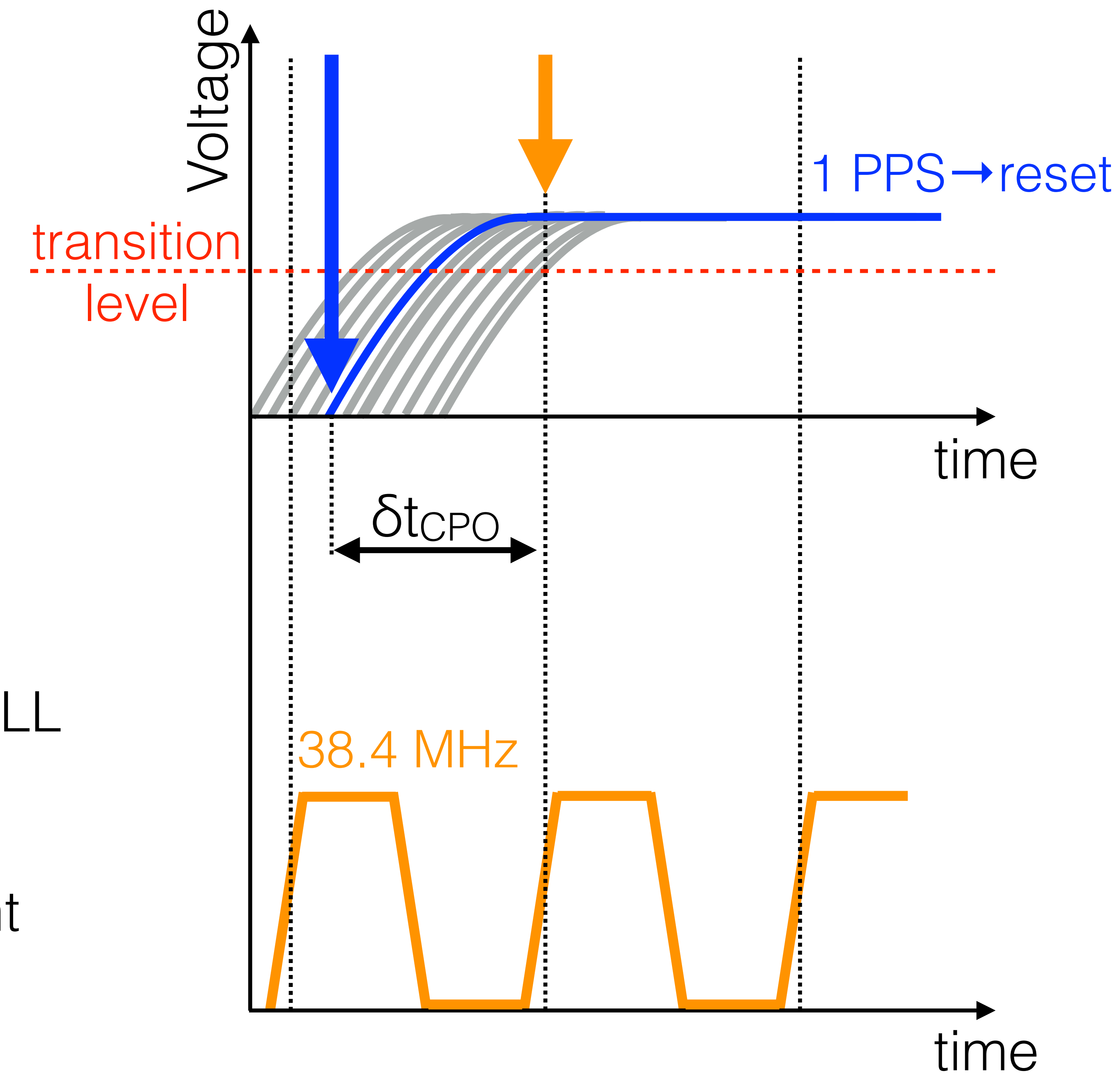
Problem: Phase Synchronization



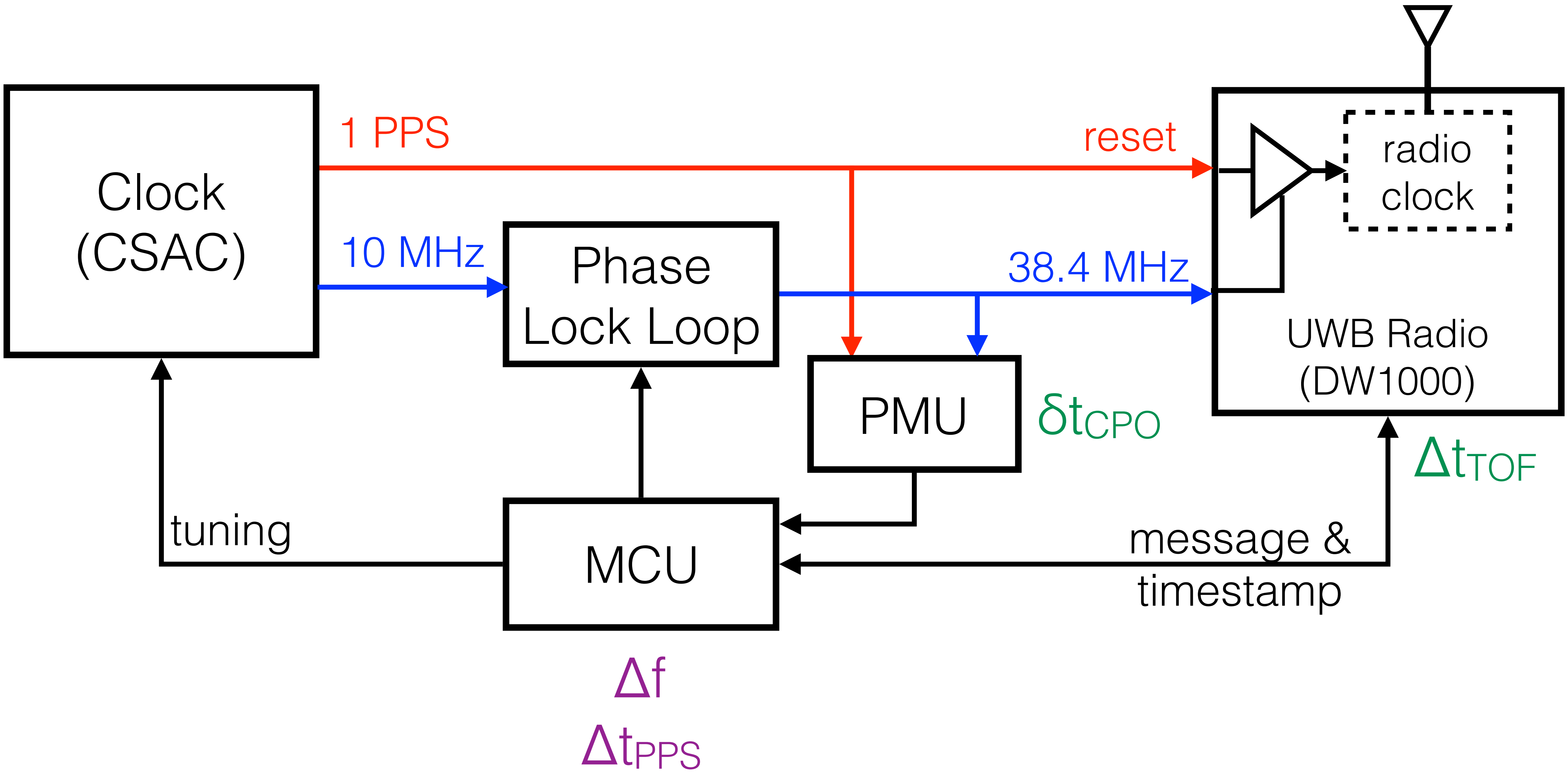
- Precise timing for e.g. SDR
  - Frequency input: **10 MHz** ✓
  - Phase/time input: **1 PPS** **??**

Problem: Clock Phase Offset

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

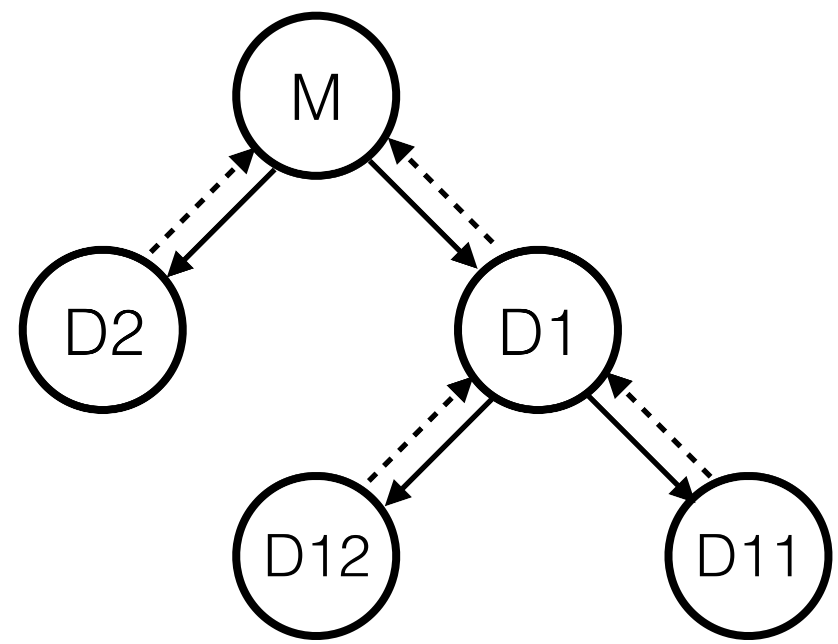


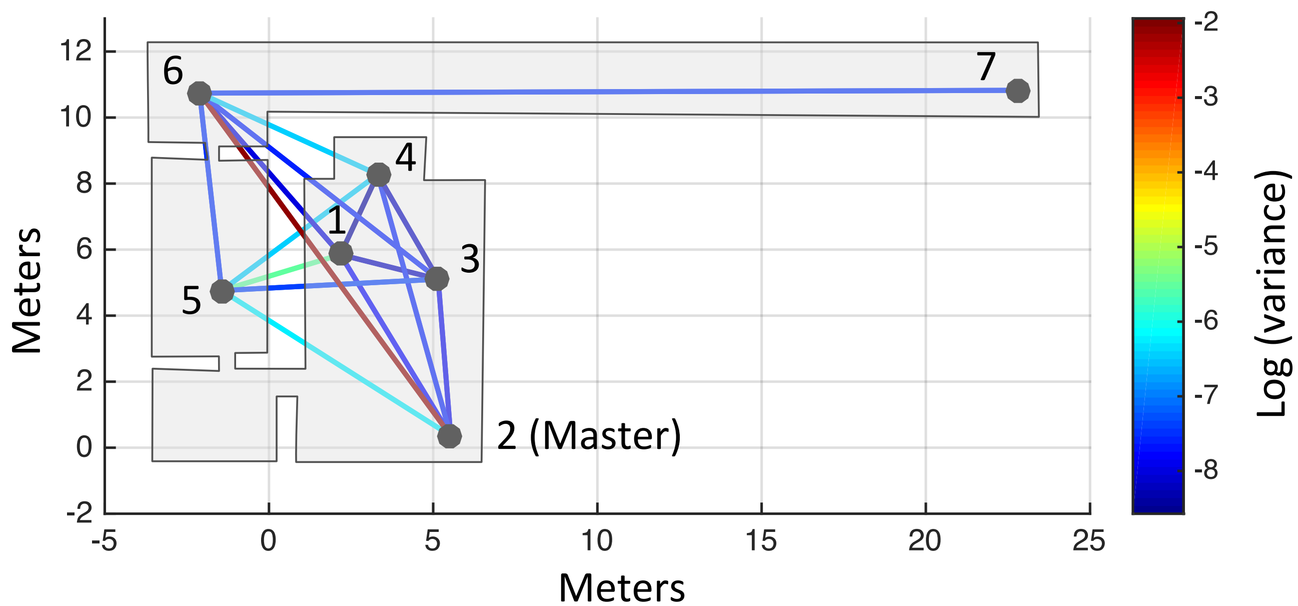
Pulsar Architecture



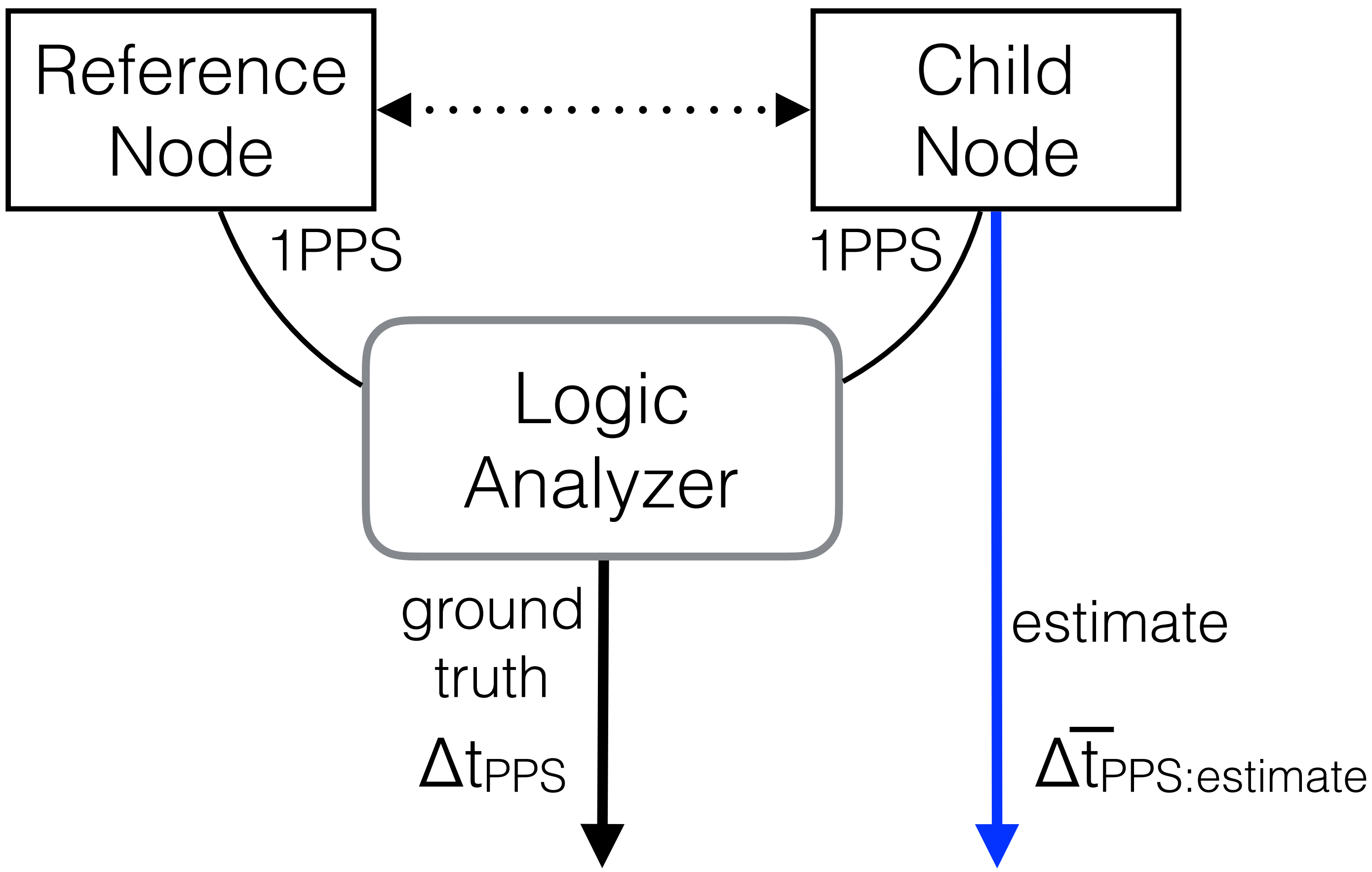
Synchronization Protocol

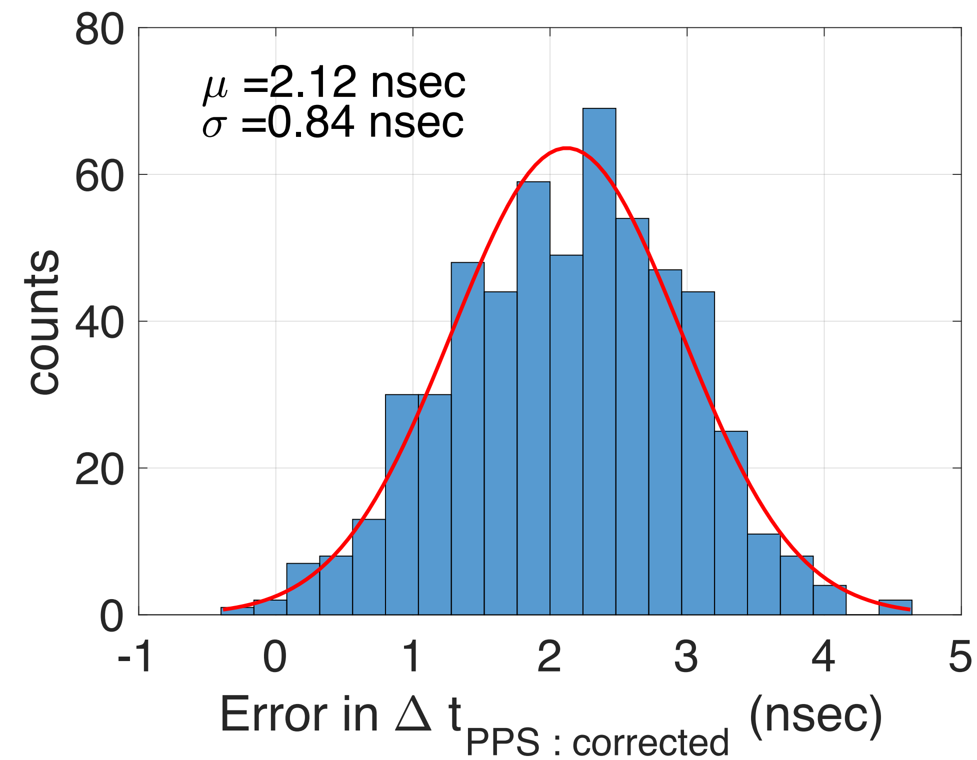
- Proof-of-concept protocol
- Algorithm
    - Frequency synchronization
    - Phase synchronization
    - Phase bootstrap
- Time distribution tree
- Timestamp variance as a simple link metric





Evaluation





ϵ_t

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

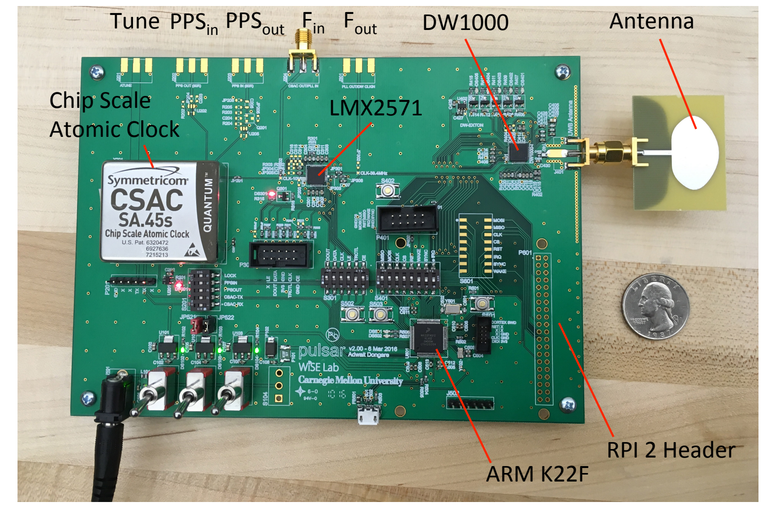
Software repository:
http://git.wise.ece.cmu.edu/adwait/pulsar_freertos

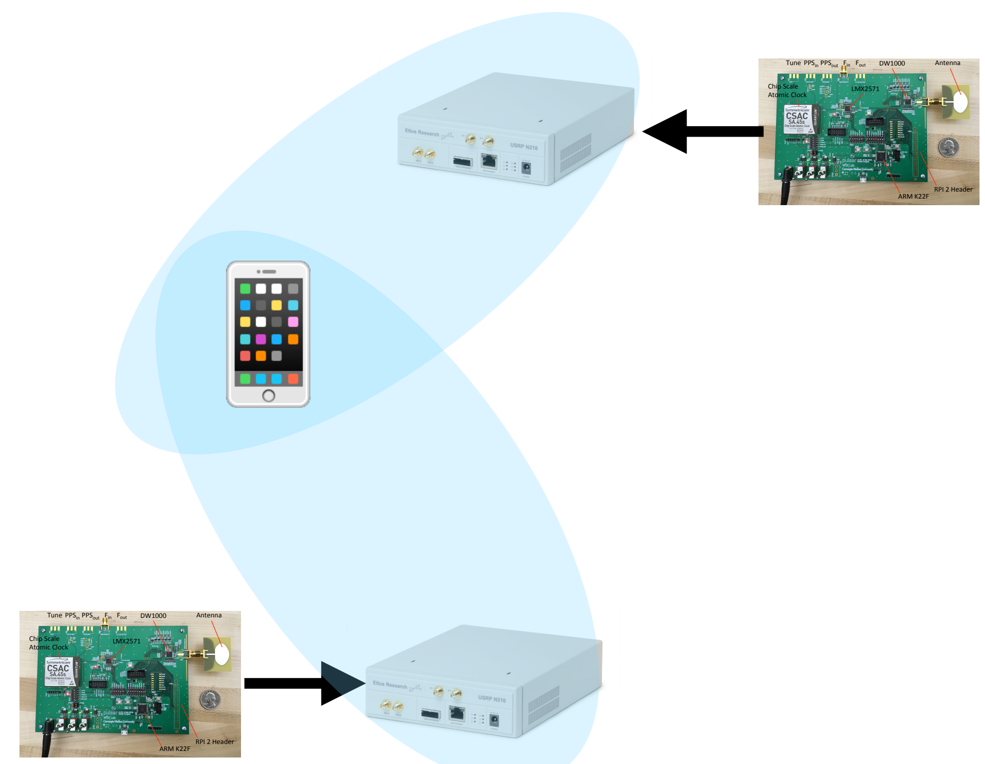
Future Work

- 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





Electrical & Computer ENGINEERING

Thank you