Application-Layer Clock Synchronization for Wearables Using Skin Electric Potentials Induced by Powerline Radiation

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Tight Clock Synchronization for Wearables

Multiple real-time audio streams
[PATENT US 20150092642 A1]

Muscle fatigue & activation monitoring
[UbiComp’15, IPSN’16]

(Multi-user) gaming
[atomicbands]

https://thenextweb.com/apple/2017/01/24/good-news-apple-will-help-find-inevitably-lost-airpods/#.tnw_fCyjRKE2
http://insidescientific.com/webinar/webinar-series-exercise-physiology-sports-science-biomechanics/

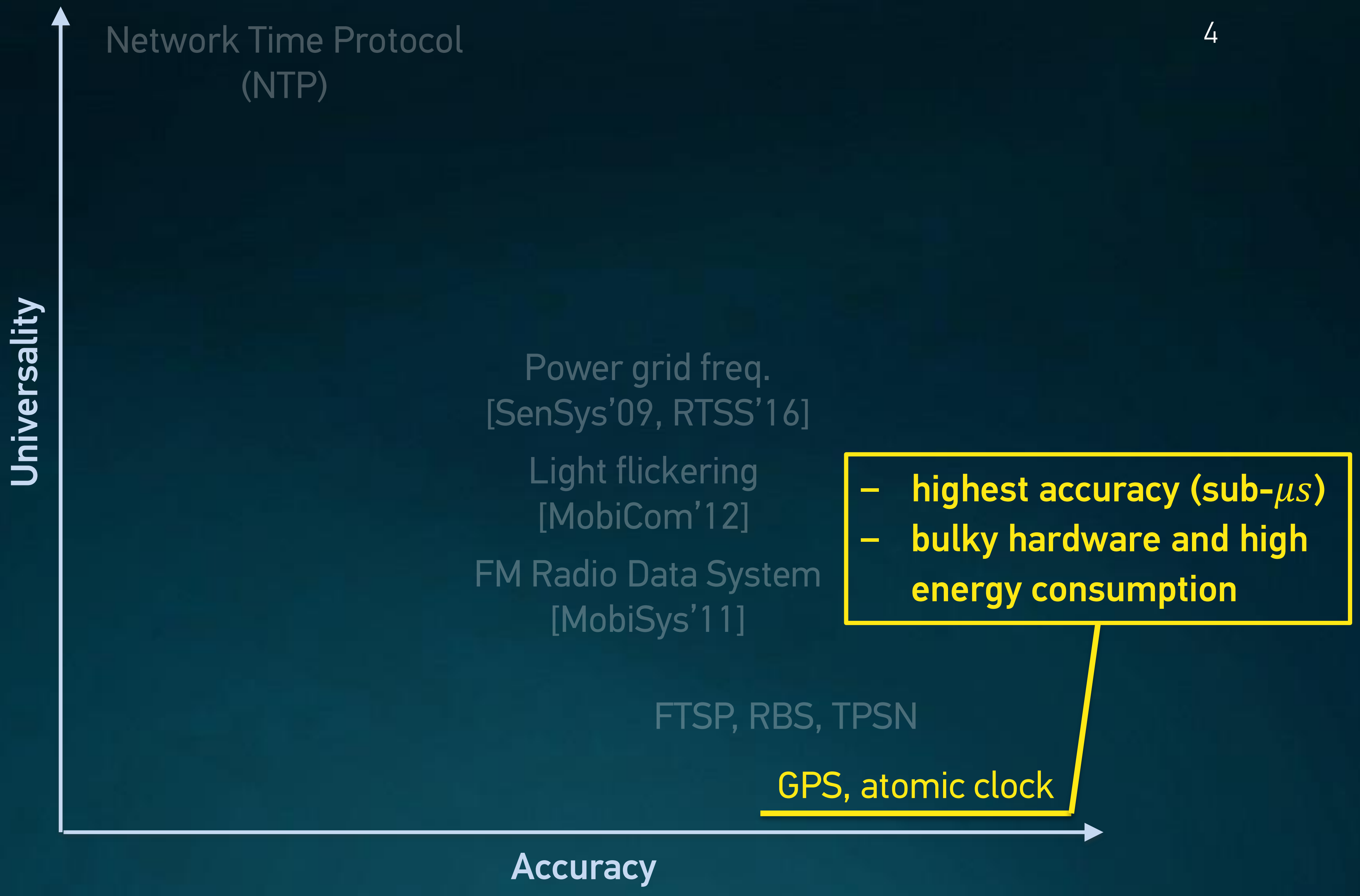
Accuracy vs. Universality

- Millisecond accuracy
  - Can be achieved by design
  - Customized protocols

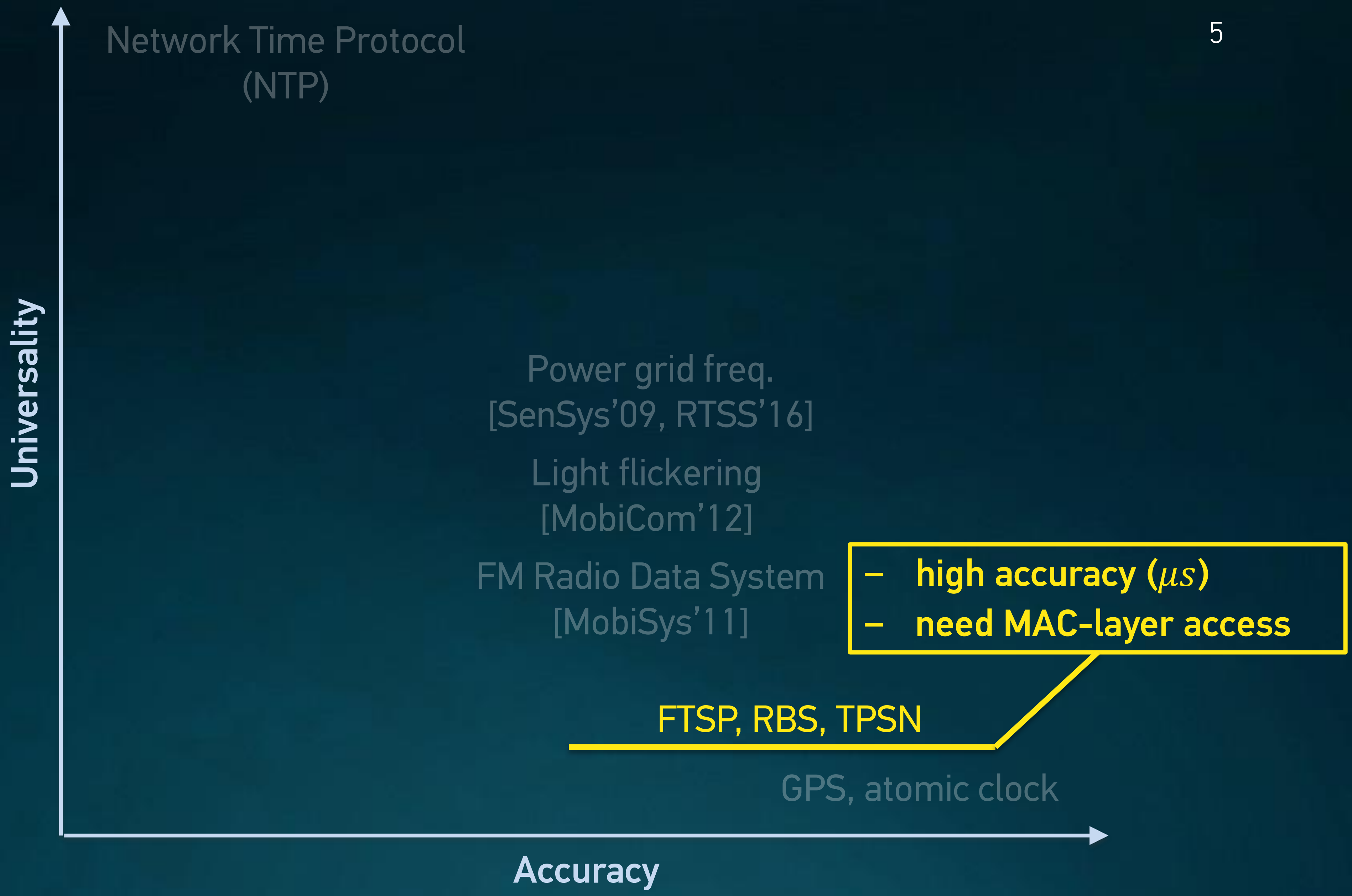
- Universality
  - Diversified brands/platforms

As App developers, can we tightly sync heterogeneous wearables?

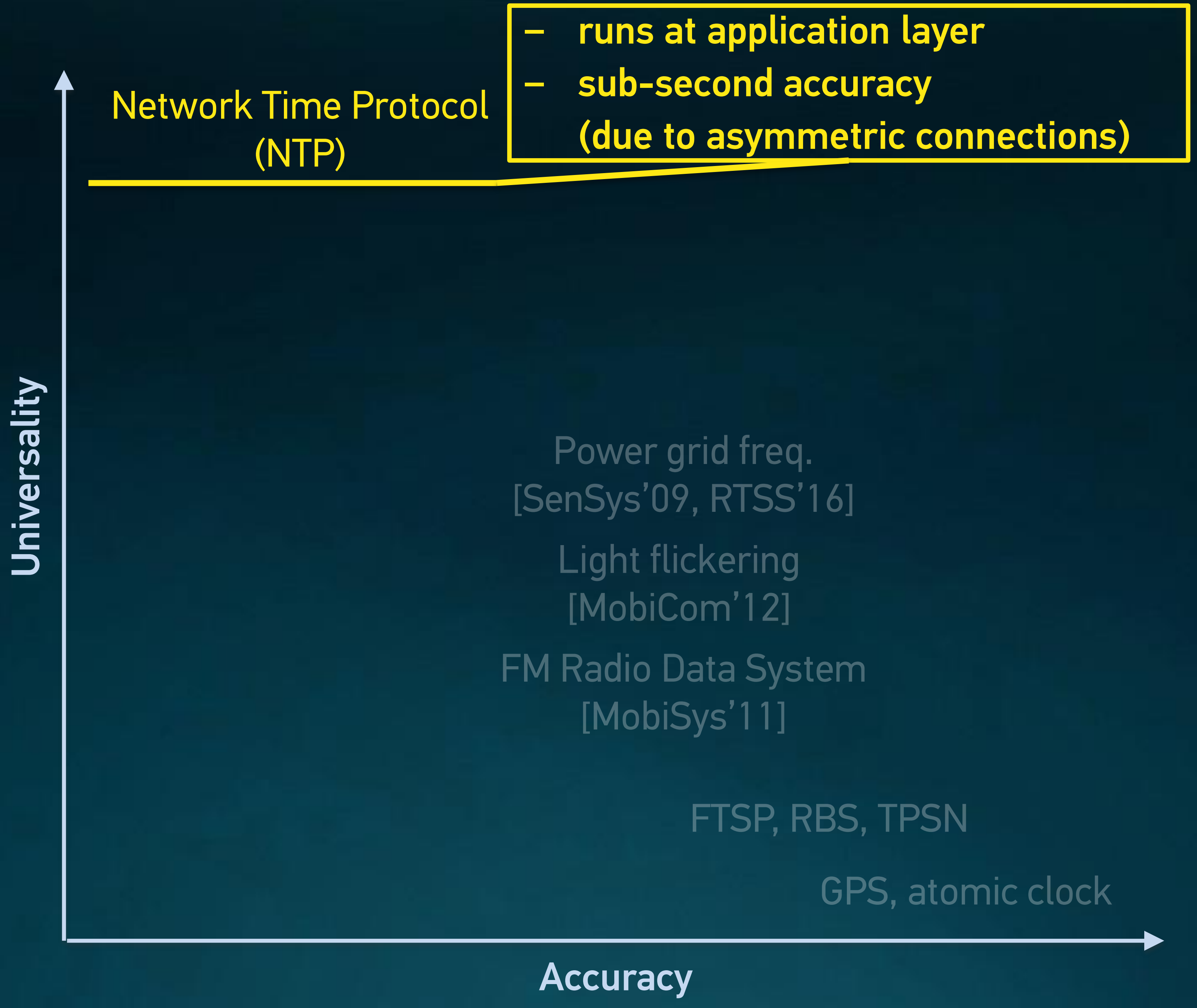
Related Work



Related Work



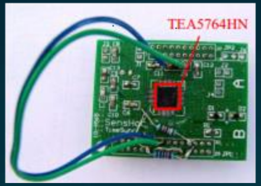
Related Work



Related Work

Network Time Protocol (NTP)

Universality



Power grid freq. [SenSys'09, RTSS'16]

Light flickering [MobiCom'12]

FM Radio Data System [MobiSys'11]

- **ms accuracy**
- **extra sensors**

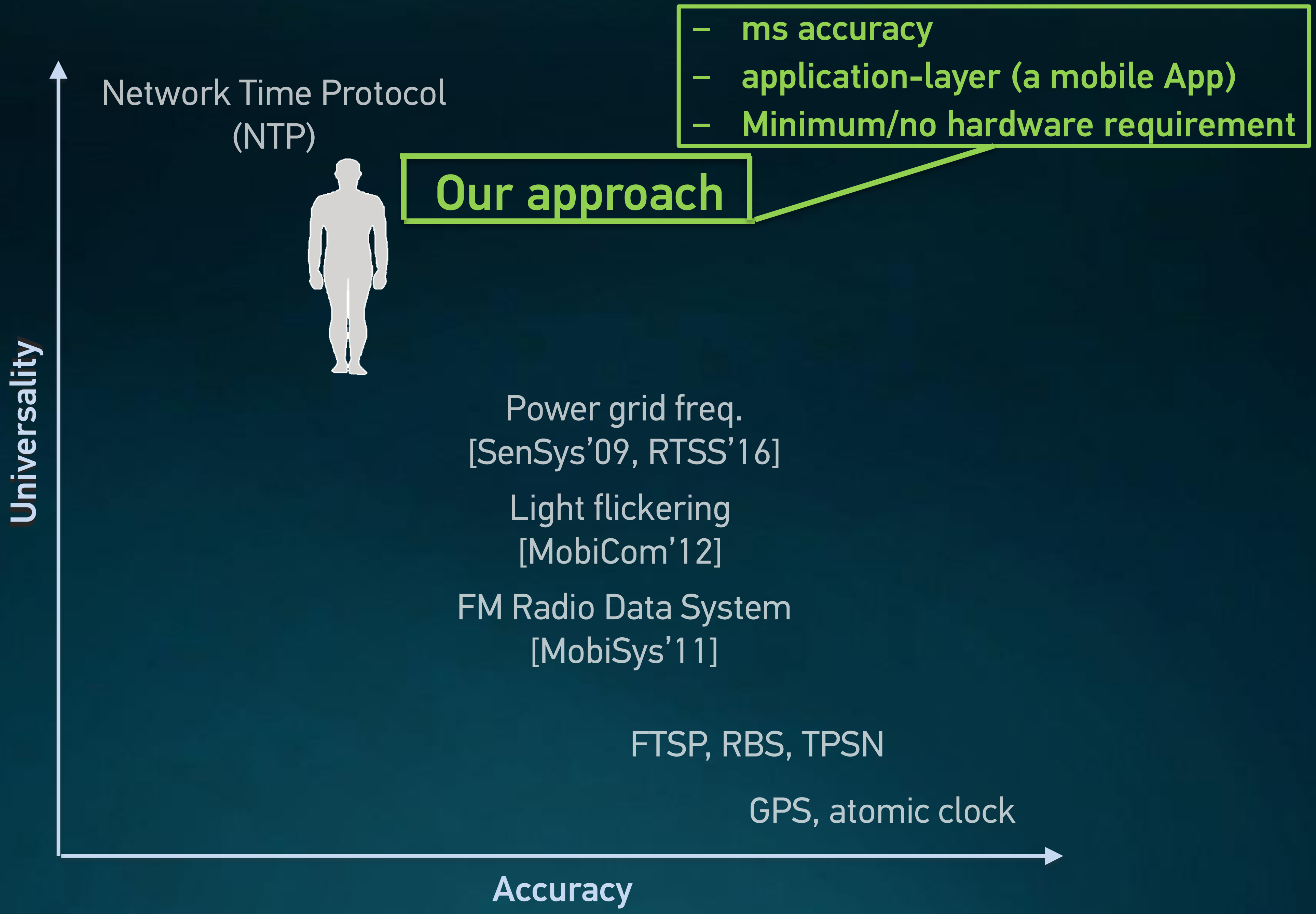
(large coil, FM receiver)

FTSP, RBS, TPSN

GPS, atomic clock

Accuracy

Related Work



An external signal?

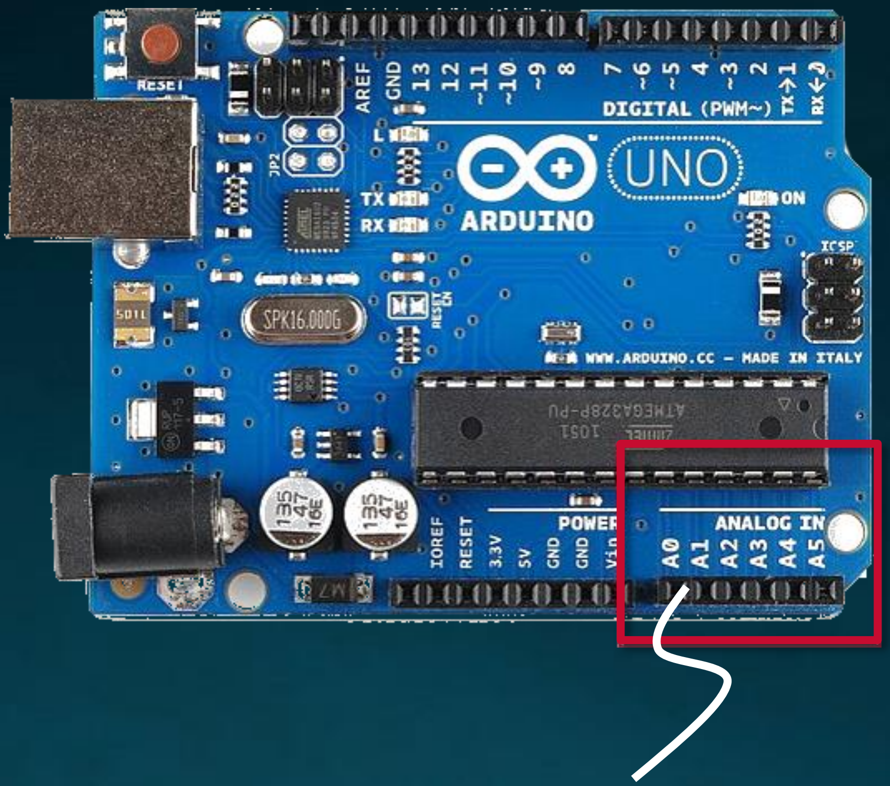
- Widely available to human body area
- Highly synchronous
  - different wearables
  - different persons
  - different locations
- Easy capture by wearables

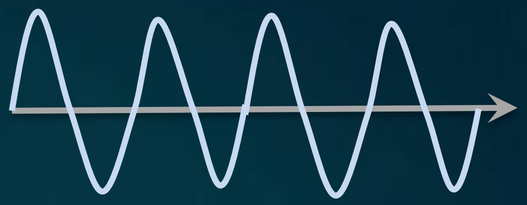
Outline

- Background and related work
- Skin electric potential (SEP)
- TouchSync
- Evaluation

Powerline Electromagnetic Radiation (EMR) *[IPSN '17]*

Powerline EMR
(50Hz or 60Hz)





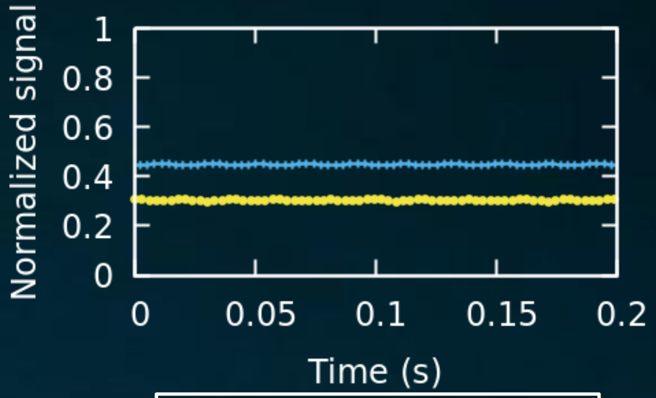
A conductive wire
attached to an
analog-to-digital converter (ADC) pin

Body as an EMR antenna generating
Skin Electric Potential (SEP)

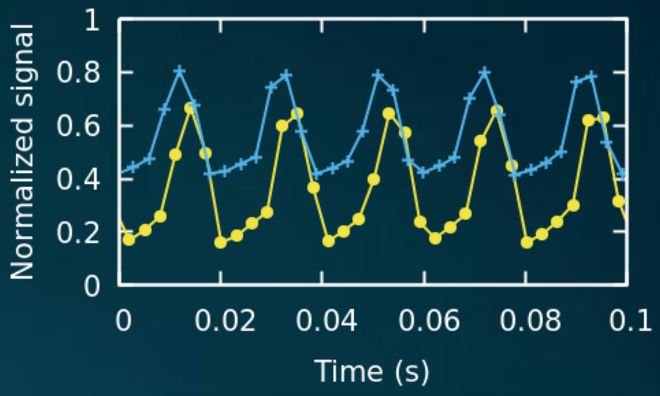
Powerline EMR
(50Hz or 60Hz)

Node 1

Node 2

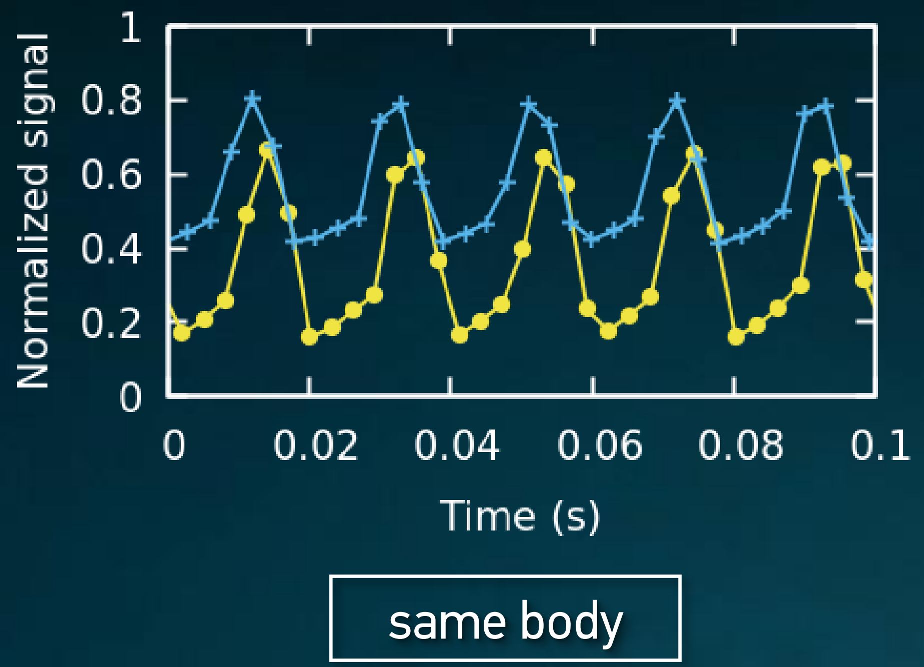


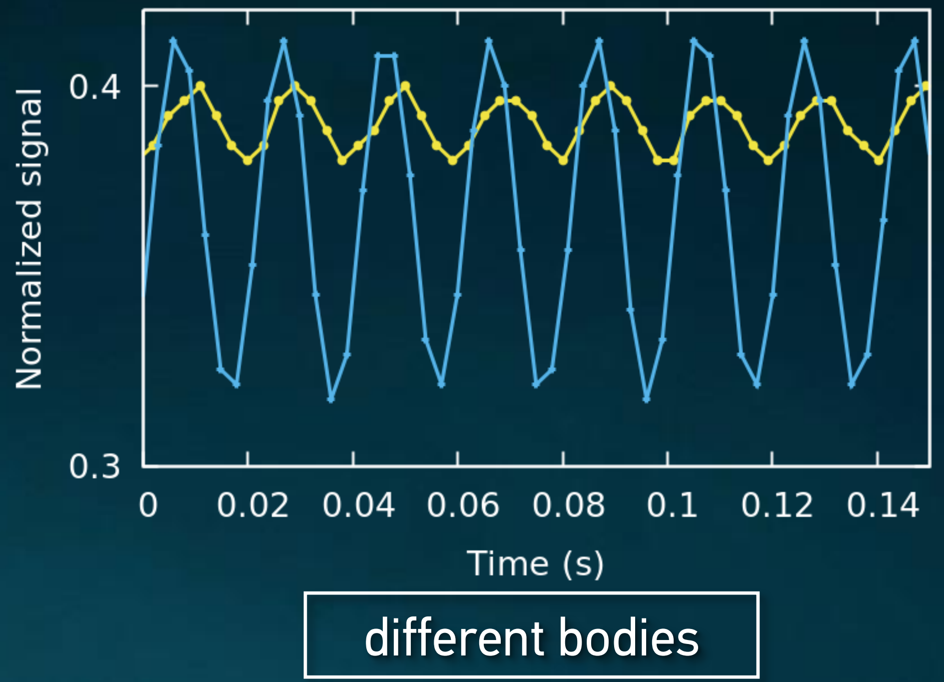
no human antenna



with human antenna
(left and right hand)

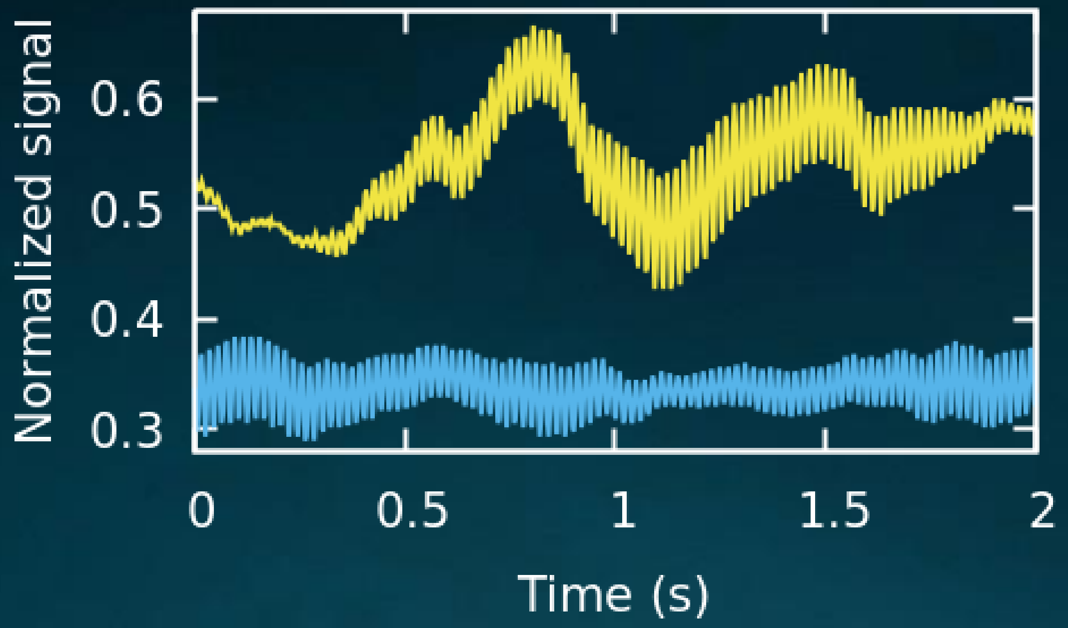
SEPs on Different Human Bodies





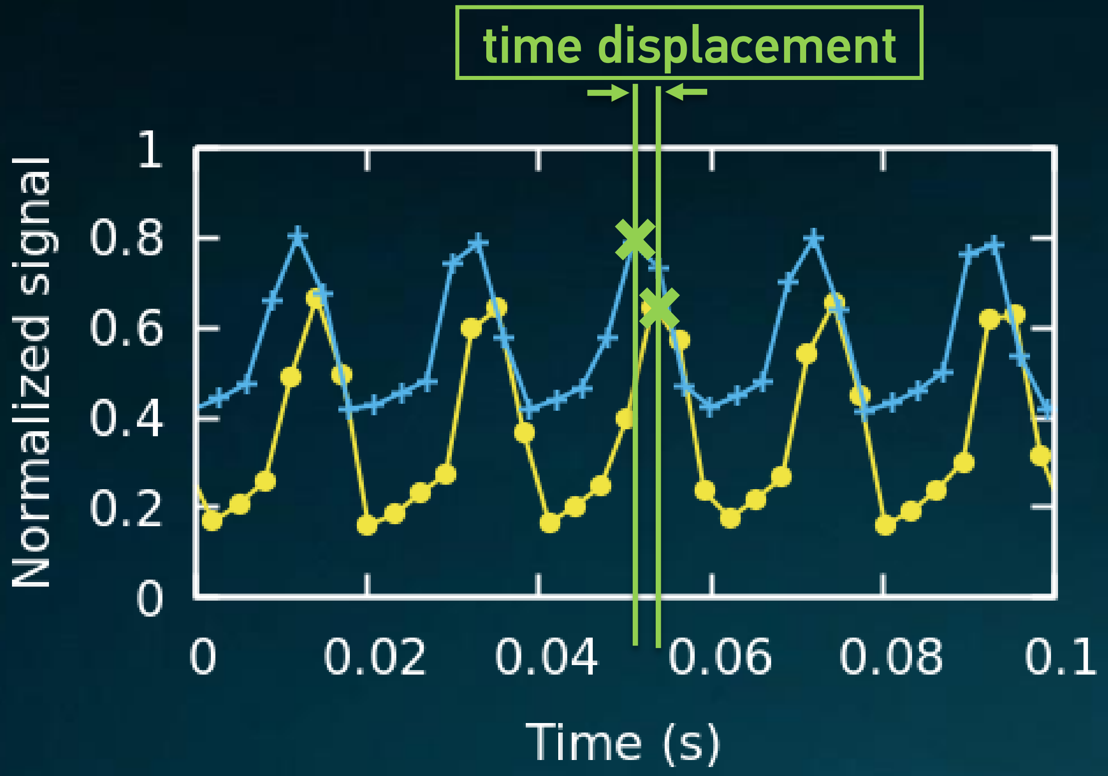
- Same frequency with constant phase difference
- different DC lines

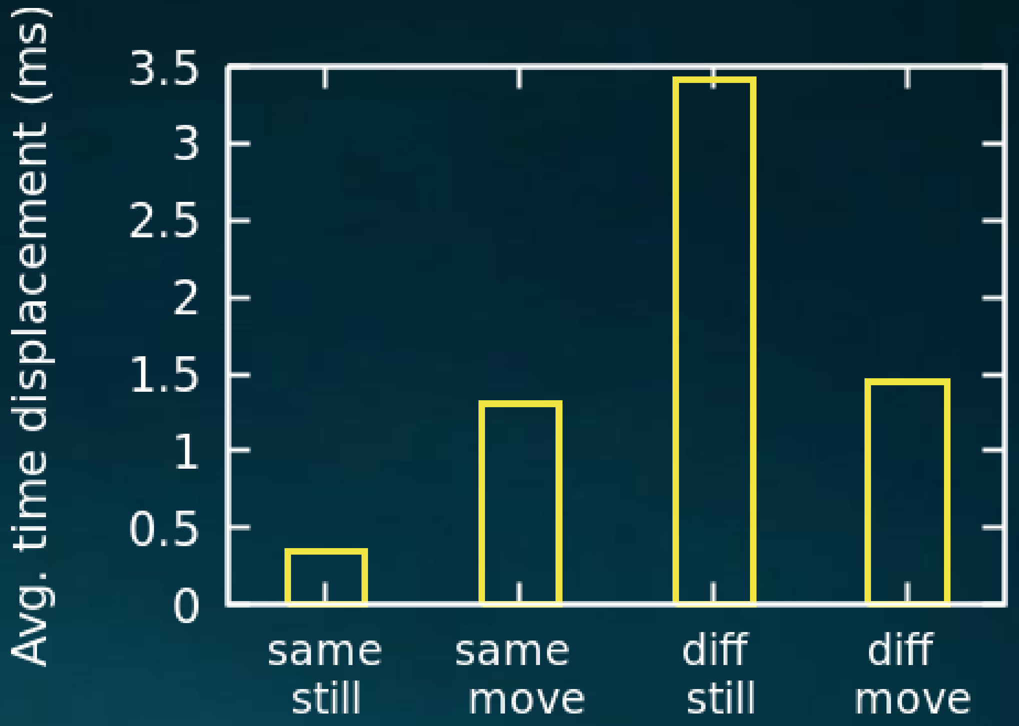
SEPs on Moving Bodies



- changing envelopes
- floating DC lines

SEPs' Synchrony





average time displacement of two SEPs

SEPs at Different Wearing Positions

*the other node keeps on the wrist

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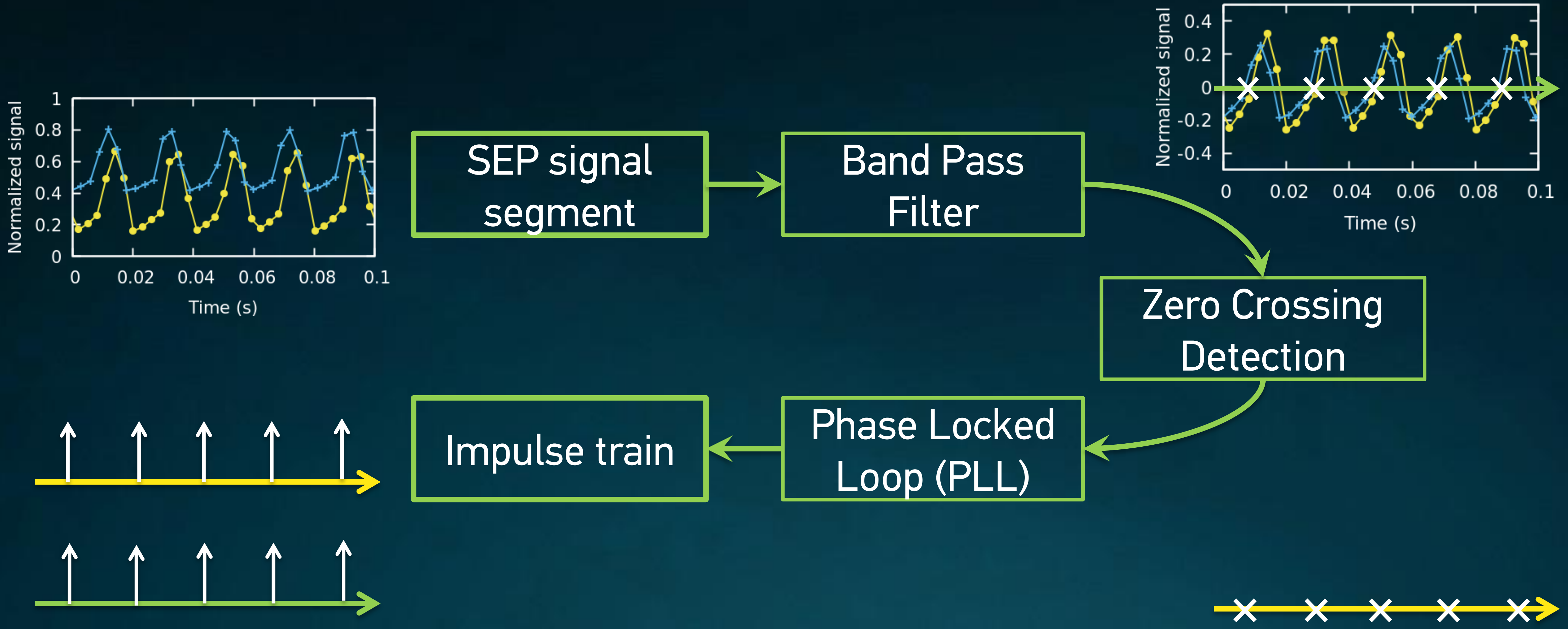
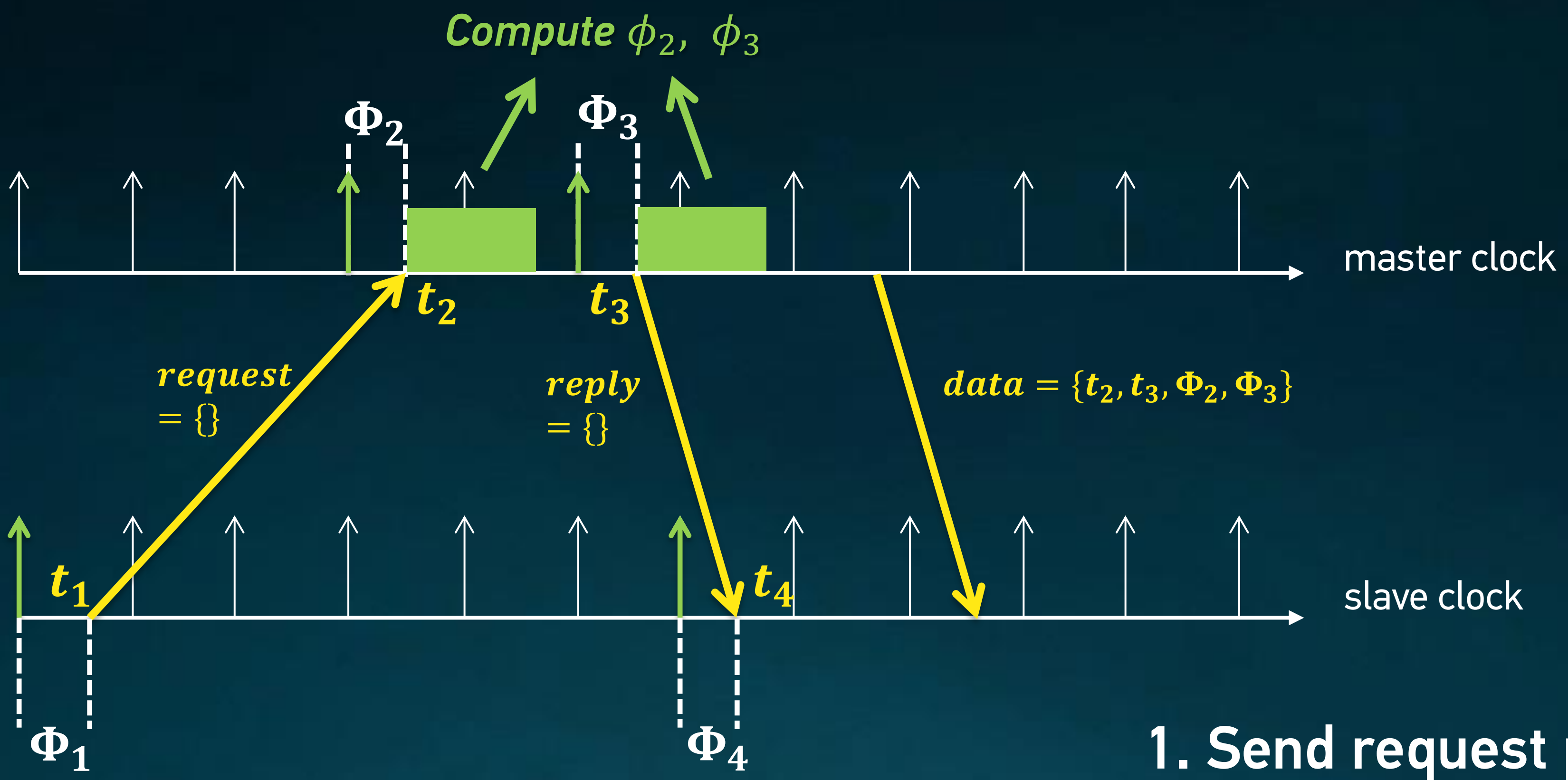
SEP Processing Pipeline

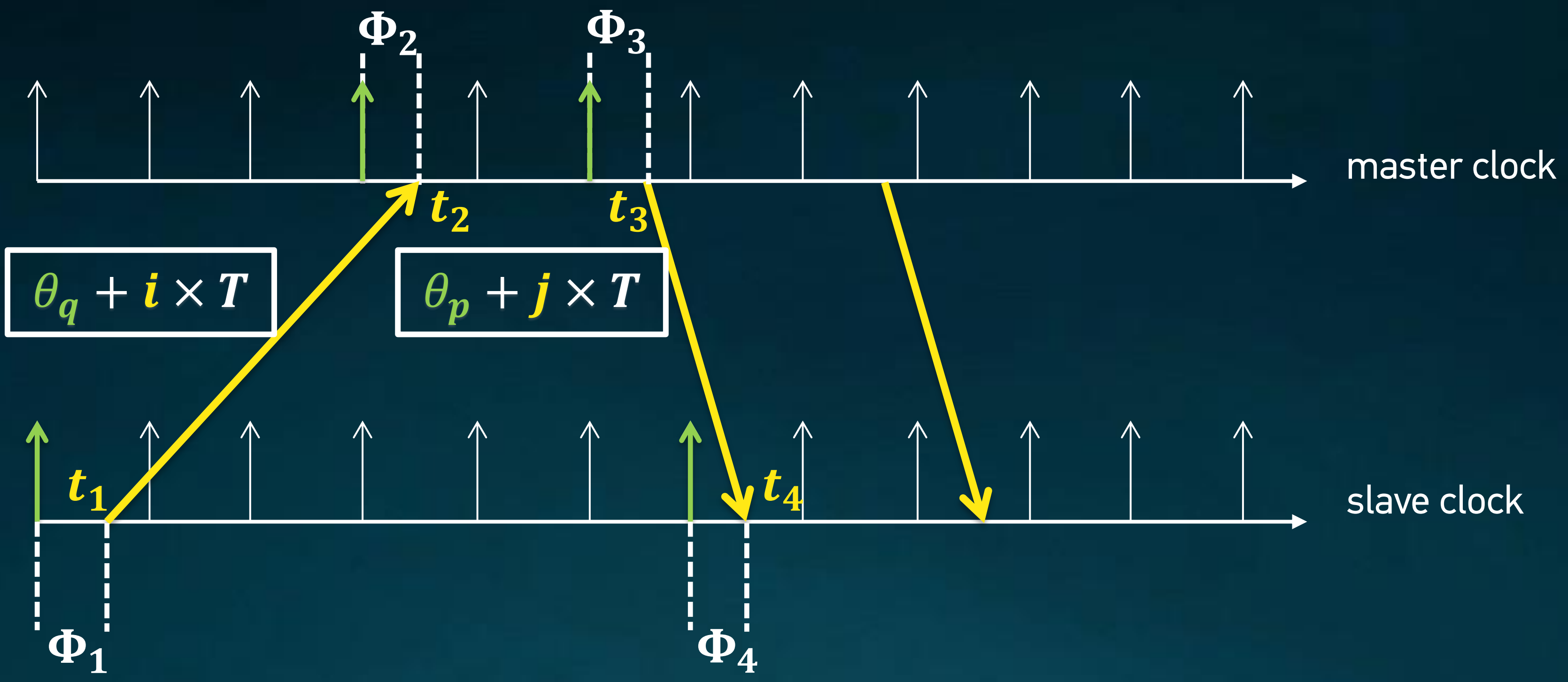


TouchSync Protocol



1. Send request packet
2. Send reply packet
3. Computation of phases
4. Send data packet

Analysis – phase difference

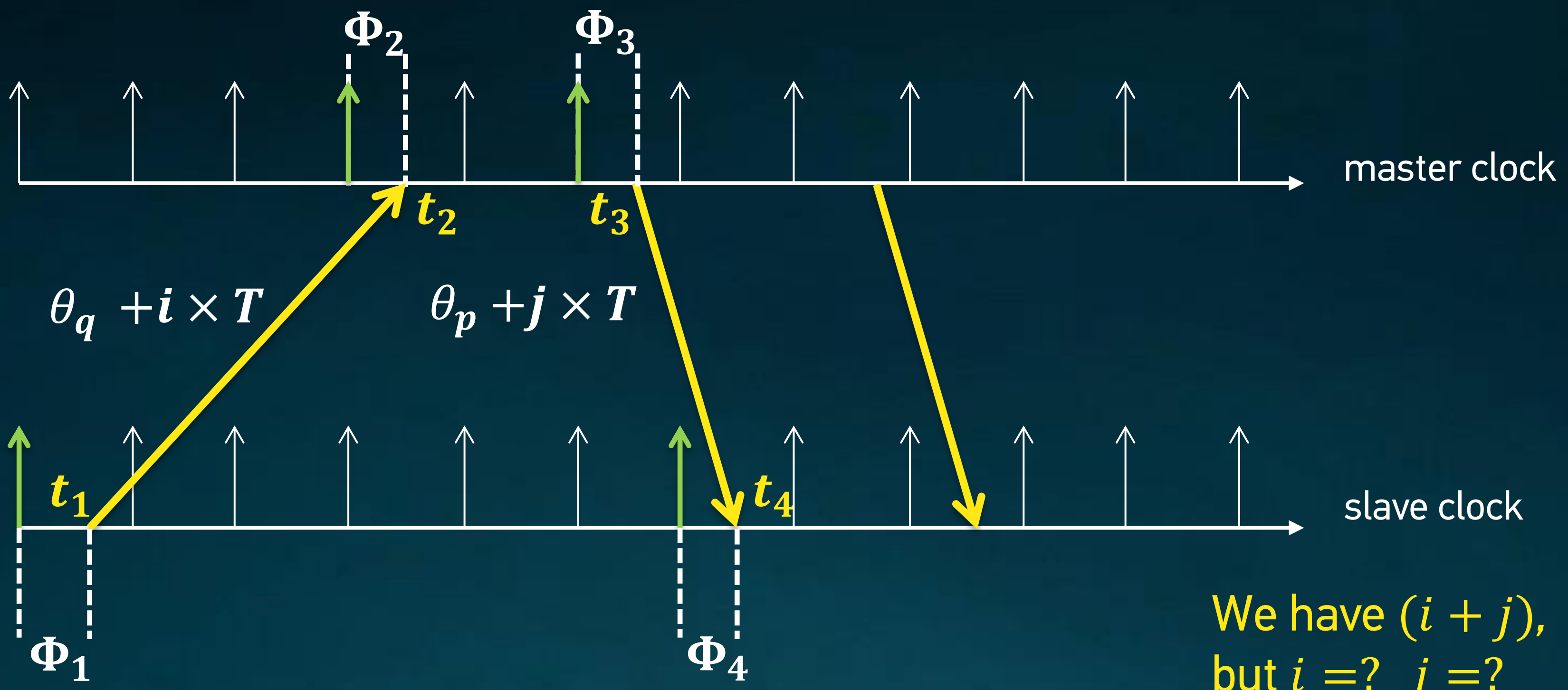


Rounded phase difference during fly:

Request message: $\theta_q = \begin{cases} \Phi_2 - \Phi_1, & if\ \Phi_2 - \Phi_1 \geq 0 \\ \Phi_2 - \Phi_1 + T & otherwise \end{cases}$

Reply message: $\theta_p = \begin{cases} \Phi_4 - \Phi_3, & if\ \Phi_4 - \Phi_3 \geq 0 \\ \Phi_4 - \Phi_3 + T & otherwise \end{cases}$

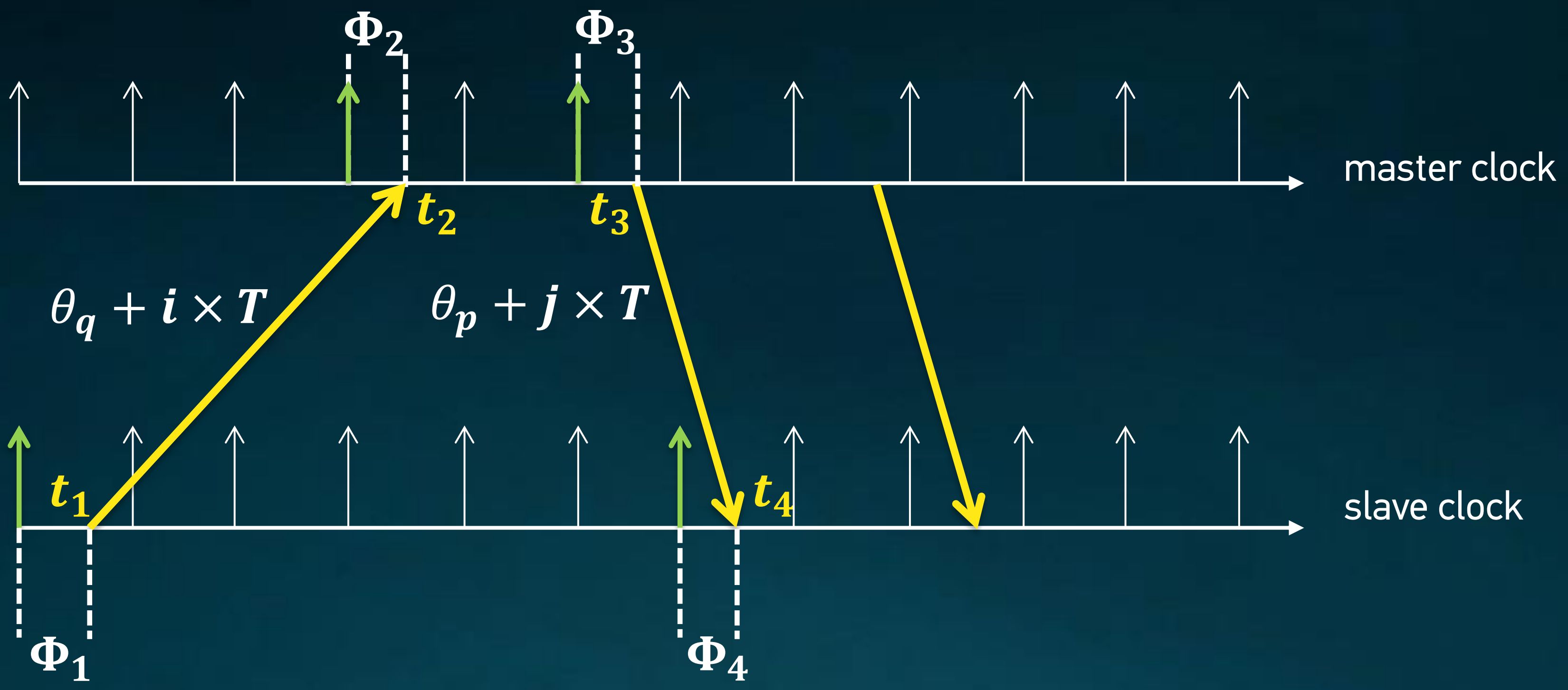
Analysis – round trip time



We have $(i + j)$,
but $i =?\ \ j =?$
(Integer Ambiguity Problem)

Round Trip Time (RTT) $= (\theta_q + \theta_p) + (i + j) \times T = (t_4 - t_1) - (t_3 - t_2)$

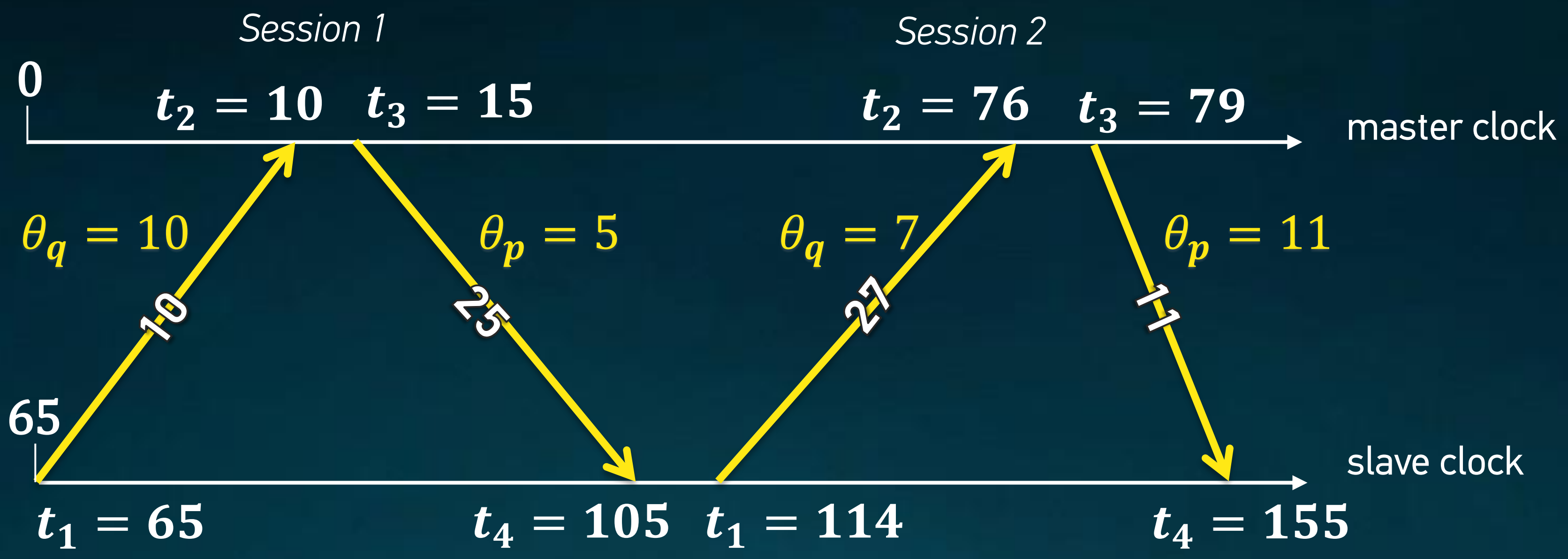
Analysis – clock offset estimation



Estimated clock offset $\delta = t_1 - t_2 + \theta_q + i \times T$

Integer Ambiguity Solver (IAS)

unit: millisecond



For each session:

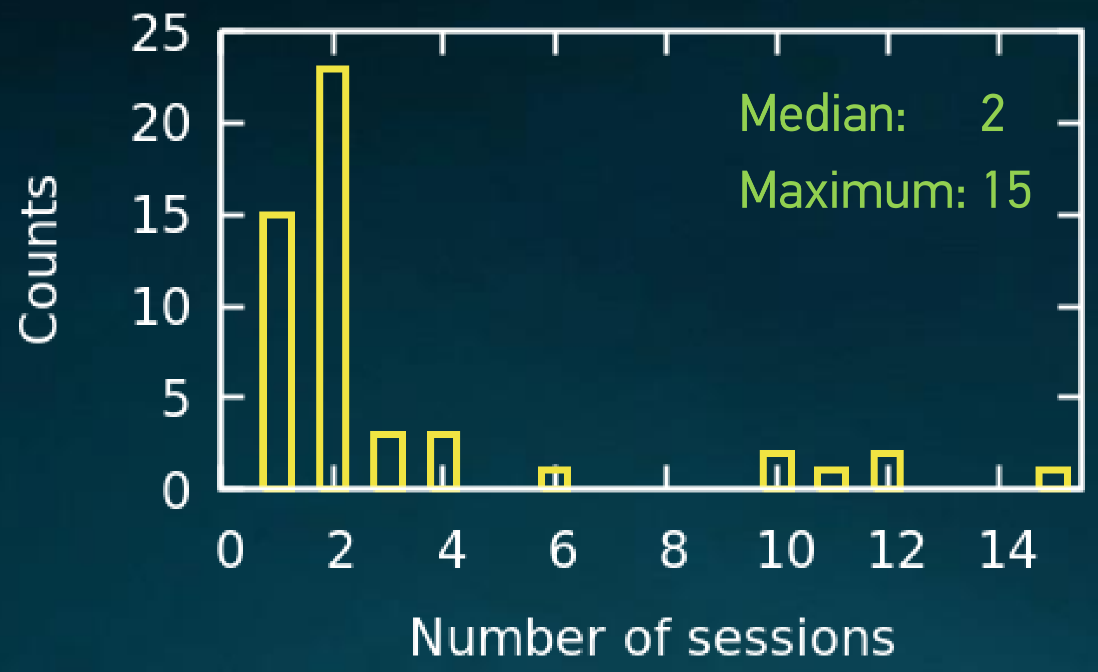
$$\begin{cases} RTT = (t_4 - t_1) - (t_3 - t_2) \\ RTT = (\theta_q + \theta_p) + (i + j) \times T \\ \delta = t_4 - t_3 - \theta_p - j \times T \\ i \geq 0, \ \ j \geq 0 \end{cases}$$

Find the intersection across all candidates:

$$Session\ 1: \{i = 0, j = 1, \boxed{\delta = 65}\}, \{i = 1, j = 0, \delta = 85\}$$

$$Session\ 2: \{i = 0, j = 1, \delta = 45\}, \{i = 1, j = 0, \boxed{\delta = 65}\}$$

Convergence Speed



51 real world experiments

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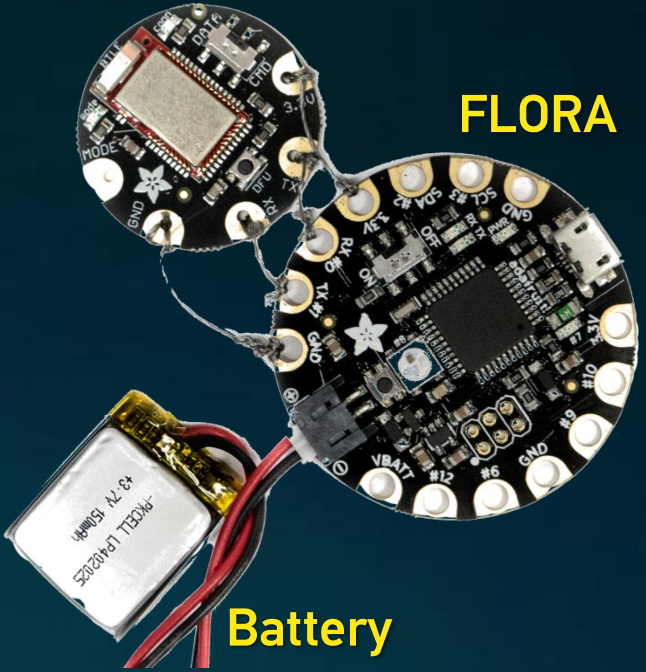
Experiment Setup

Each FLORA node:

- MCU (8 MHz, 2.5 KB RAM)
    - 10-bit ADC
- BLE
- Lithium-ion polymer battery
- SEP sampling rate: 333 Hz

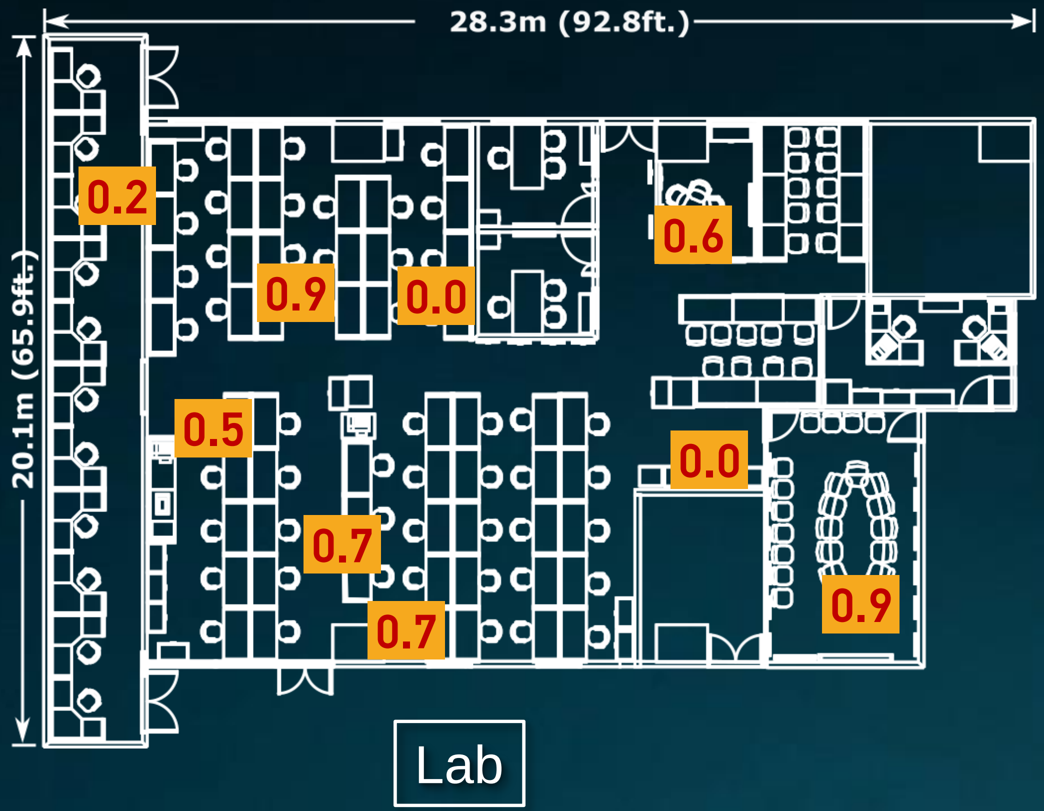
Ground truth:

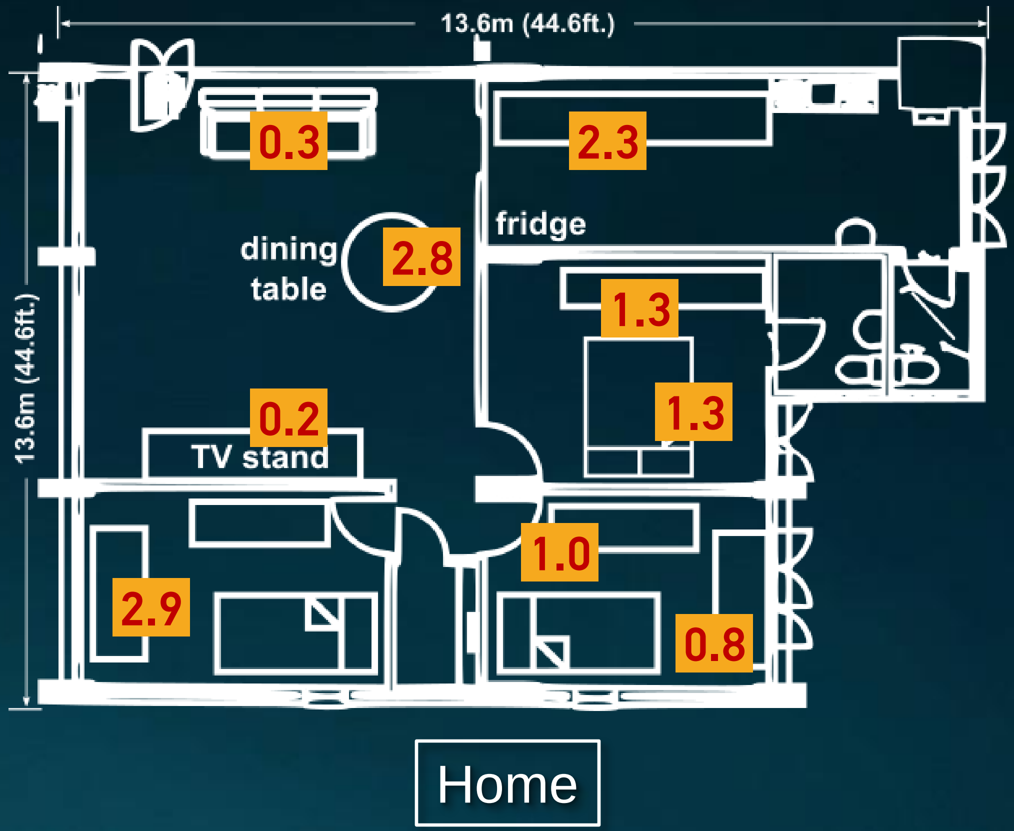
- Raspberry Pi
    - Use GPIO to send a rising edge to FLORAs to get ground-truth offset of two nodes



Experiments

unit: milliseconds



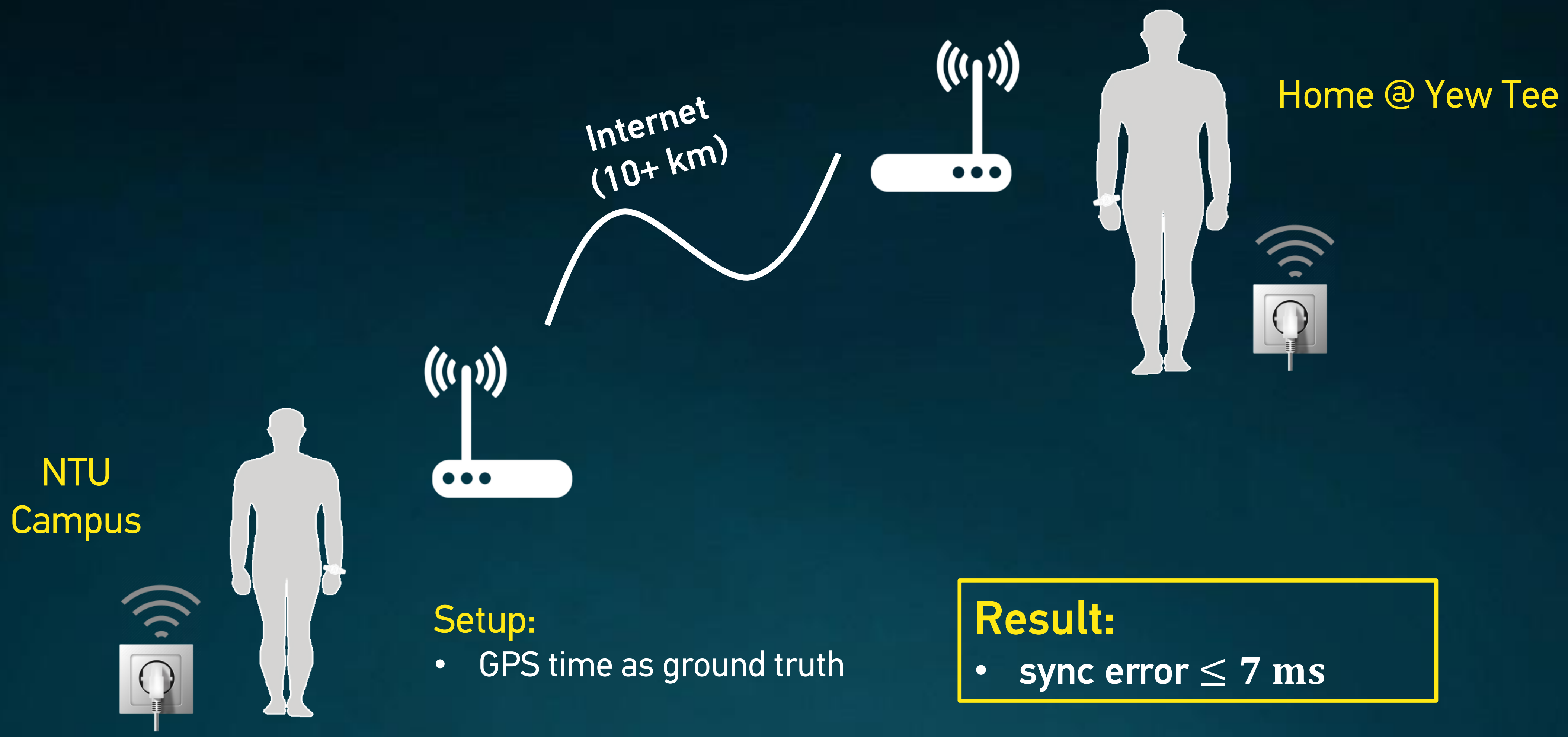


- Four environments: lab, home, office, corridor
- 51 Experiment Locations

Result:

- **Average error: 0.78 ms**

TouchSync-over-Internet



Setup:

- GPS time as ground truth

Result:

- **sync error** $\leq$ **7 ms**

Summary - TouchSync

- Universality
  - standard system APIs to sample ADC and transmit packets
  - runs as a mobile App
- Accuracy
  - milliseconds
  - up to city scale