Network Embedded Systems
Sensor Networks

Time

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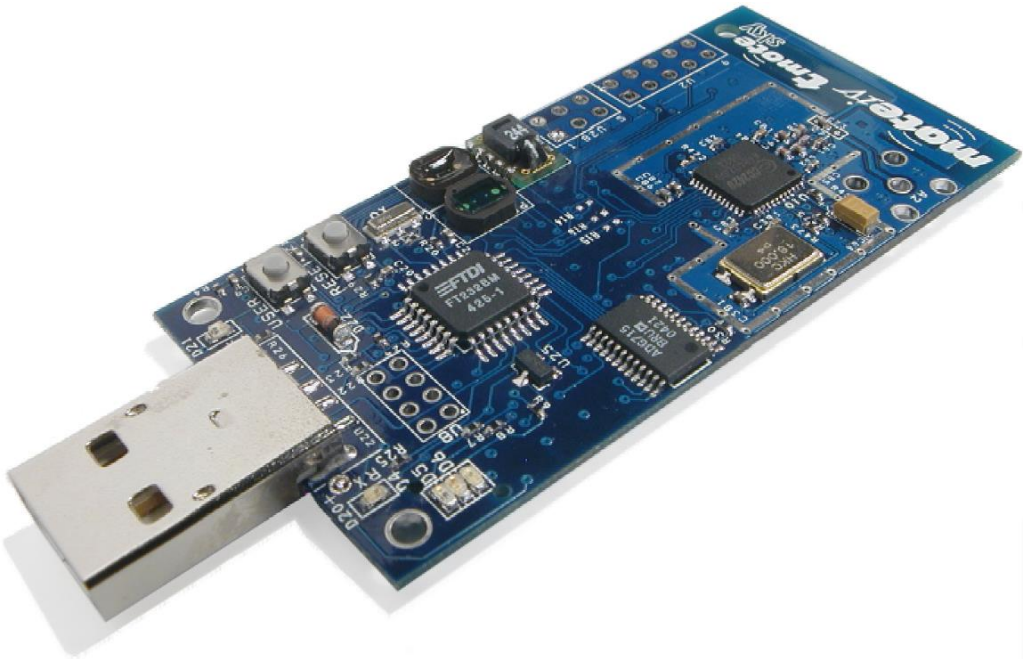
Time

- What we want
  - Agreement
    - Rendezvous: synchronized communication
    - Events: multiple events or same event
  - Measurement
    - Difference , duration
    - Timestamping
- How long?
  - years

Image: S Sepp, Wikipedia

Time

- What we got
  - 16 bit counters
  - 32 kHz, 16 MHz crystals
  - Programmable DCO
- How long?
  - Seconds
- Keep track of overflow!



Problems

- Oscillators have varying frequency
  - Temperature differences
  - Age of component
  - Quality of component
- Clock drift
  - Number of oscillations differs from what the expected
- Clock calibration
  - Measure actual frequency using known reference

TelosB

- MSP430
  - DCO: ±25% @ 2MHz
  - Temp: ±0.1 %/˚C
  - Voltage: 10 %/V
- 32 kHz Crystal
  - 10-20 parts per million (ppm)
  - 0.001 %

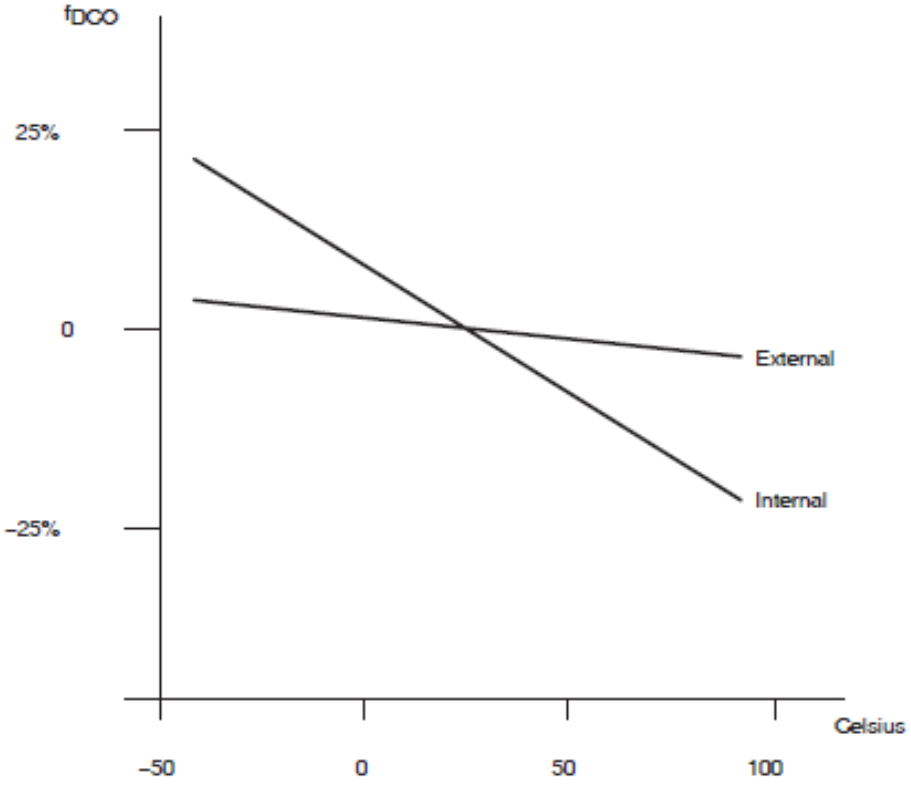


Image: Texas Instruments

Reality

- Beware
  - Accuracy only within specification

- Example:
  - 20 ppm oscillator can drift to 200 ppm at extreme temperatures

- High quality oscillator:
  - Temperature compensated
  - ±2 ppm: 0 ˚C – 40 ˚C
  - ± 3.5 ppm: -40 ˚C – 85 ˚C

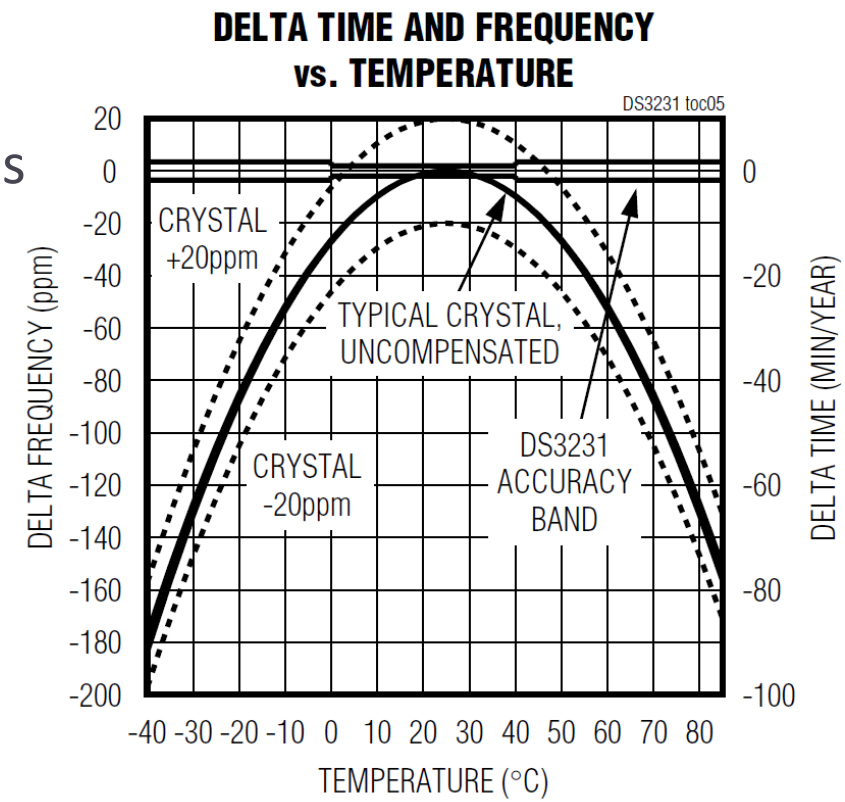


Image: Maxim Integrated

Clock Offset

- Clocks can have different reference points on purpose
  - Daylight Saving Times
  - Time zones
    - Offset from Greenwich Mean Time (GMT)
  - Unix time
    - Midnight, 1st January 1970
  - Gregorian calendar
    - 24th February 1582

- ...or by accident
  - Clocks stop/reset when power cycled

Time Synchronization Degrees

- Clock calibration (level 1)
  - Convert future counts using actual frequency
  - Measure actual number of oscillations using known source
- Local synchronization (level 2)
  - Nodes agree on local event
  - Reset local timer or keep event offset stored
- Global synchronization (level 3)
  - Nodes agree on global event
  - Find formula for converting local timer to human readable one

Time Synchronization Methods

- Online
  - Counters can be converted on the MCU
    - Real-time applications
    - Human interaction
- Offline
  - Counters are recorded and offloaded from the embedded device and converted in a post-processing step
    - Power efficient
    - Data logging

Clock Synchronization: Internet

- Network Time Protocol
  - Client-Server
  - Round-Trip Time
    - Network delay, Server Offset
- Accuracy:
  - 1 ms on local network
  - 10 ms over the Internet
- Sensor Networks?
  - RTT highly variable
  - Individual Node-to-Server RTT not very efficient

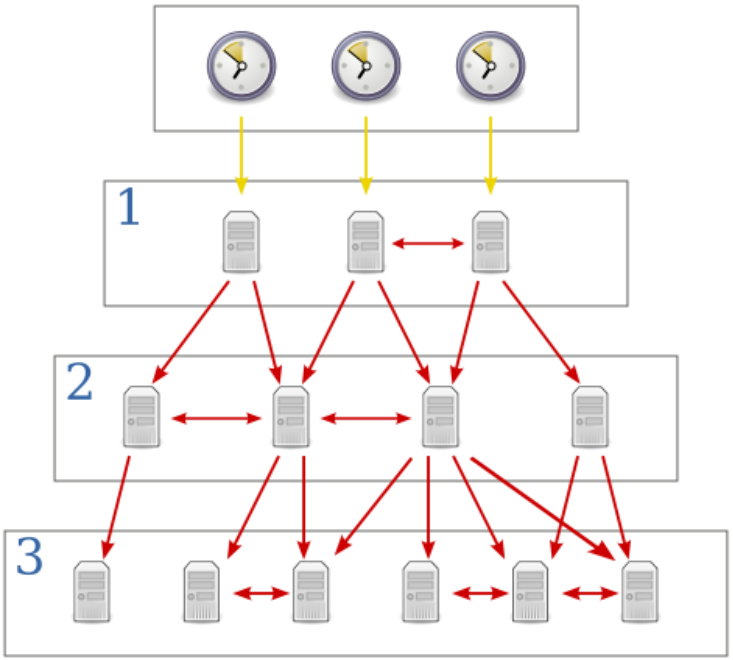


Image: Wikipedia

Wireless Sensor Network

- In-band
  - Use onboard radio to pass messages between nodes and through the network
- Out-of-band
  - Use special hardware to receive messages/events
    - GPS
    - Cell towers
    - Time code signals
    - Light

What Accuracy Do We Need?

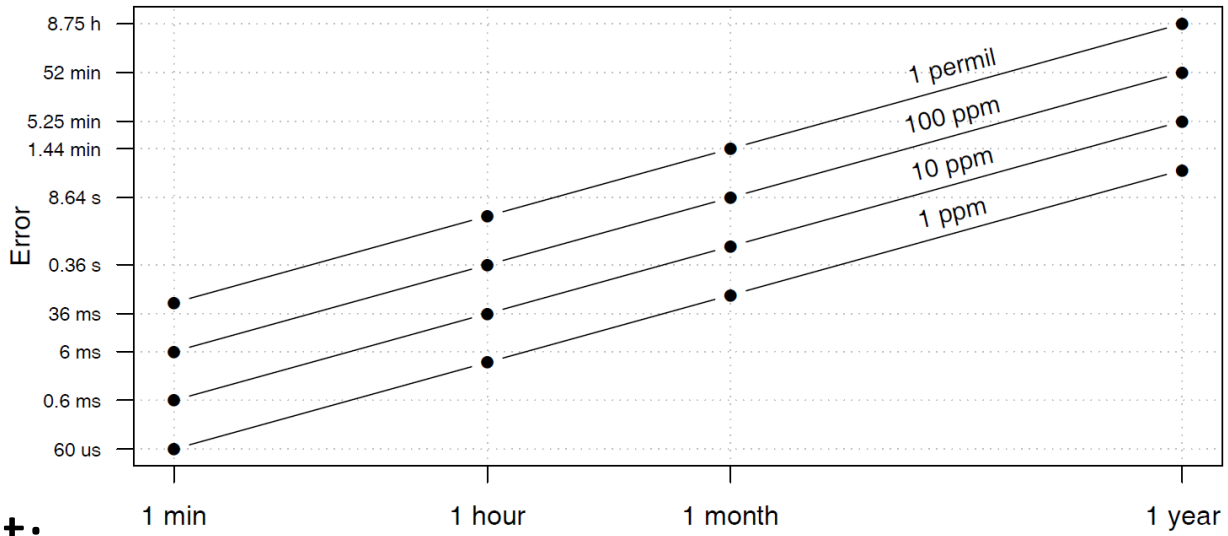
- What are the requirements of your application?
- What clock sources do you have available?

- Localization, Time-of-Flight/Arrival
  - Sound: milliseconds → meters, microseconds → millimeters
  - Light: nanoseconds → meters

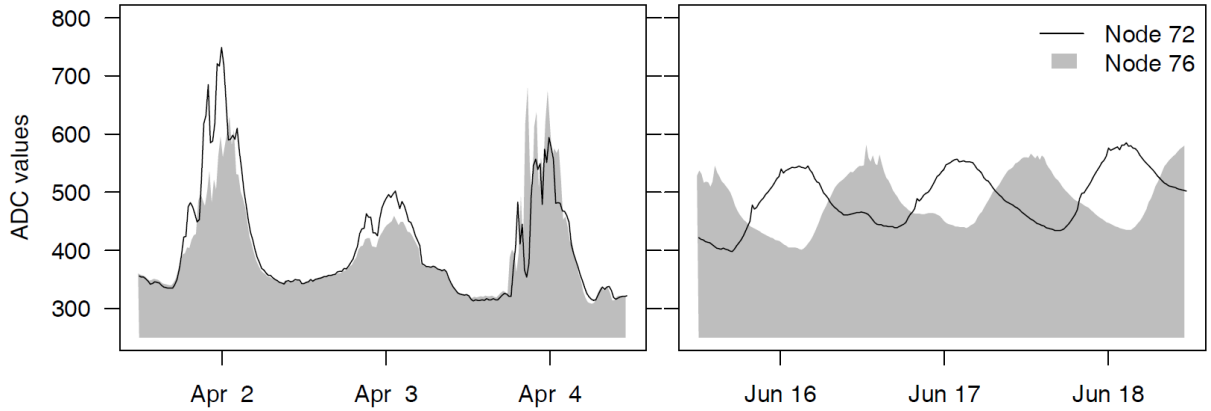
- MAC TDMA
  - Microseconds – radio actuation time scale
- Environmental Monitoring
  - seconds, minutes, hours – weather time scale

Challenges In Reality

- Clocks drift over time:

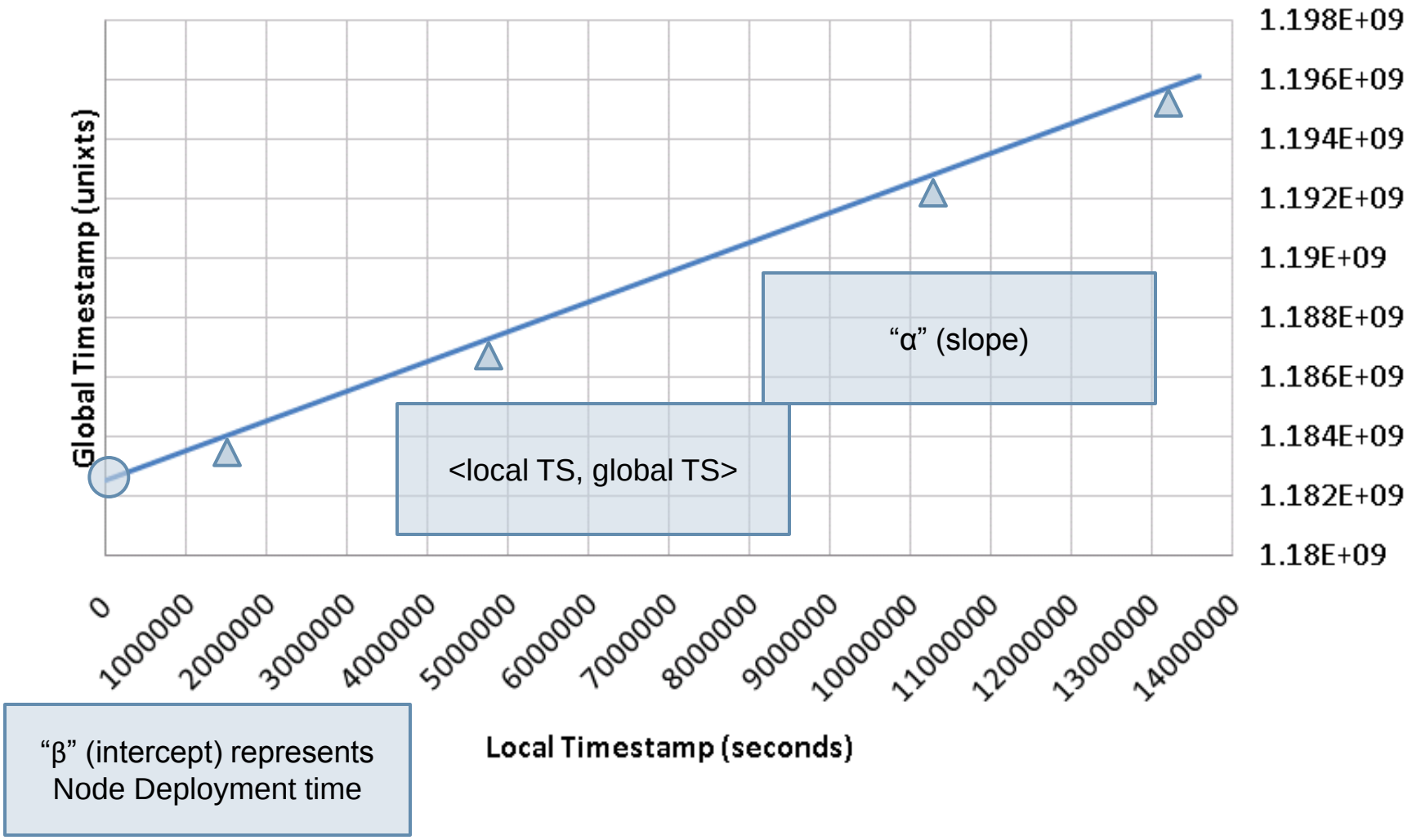


- Clocks reset:



Source: Jayant Gupchup

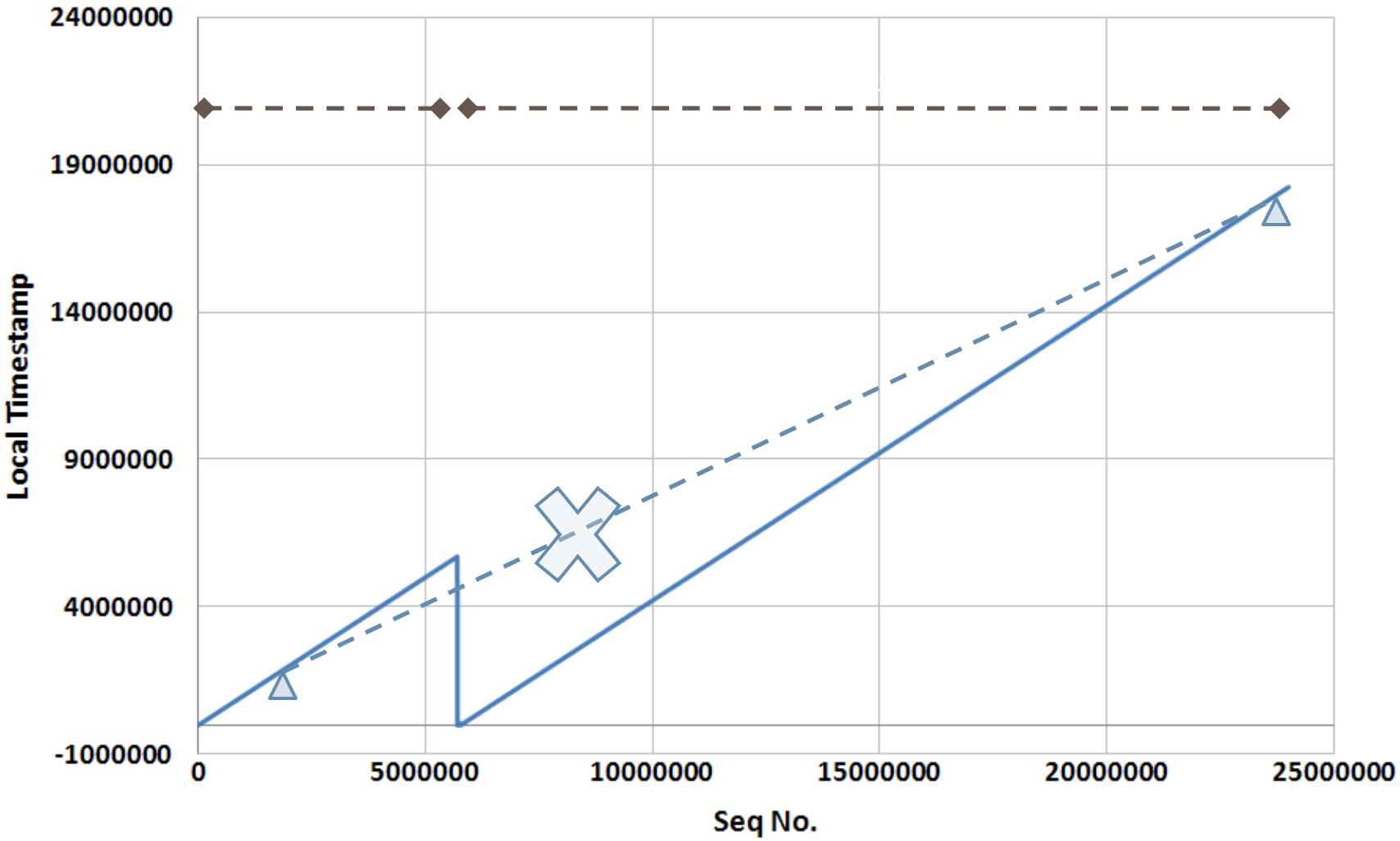
Ideal Time Synchronization



“β” (intercept) represents Node Deployment time

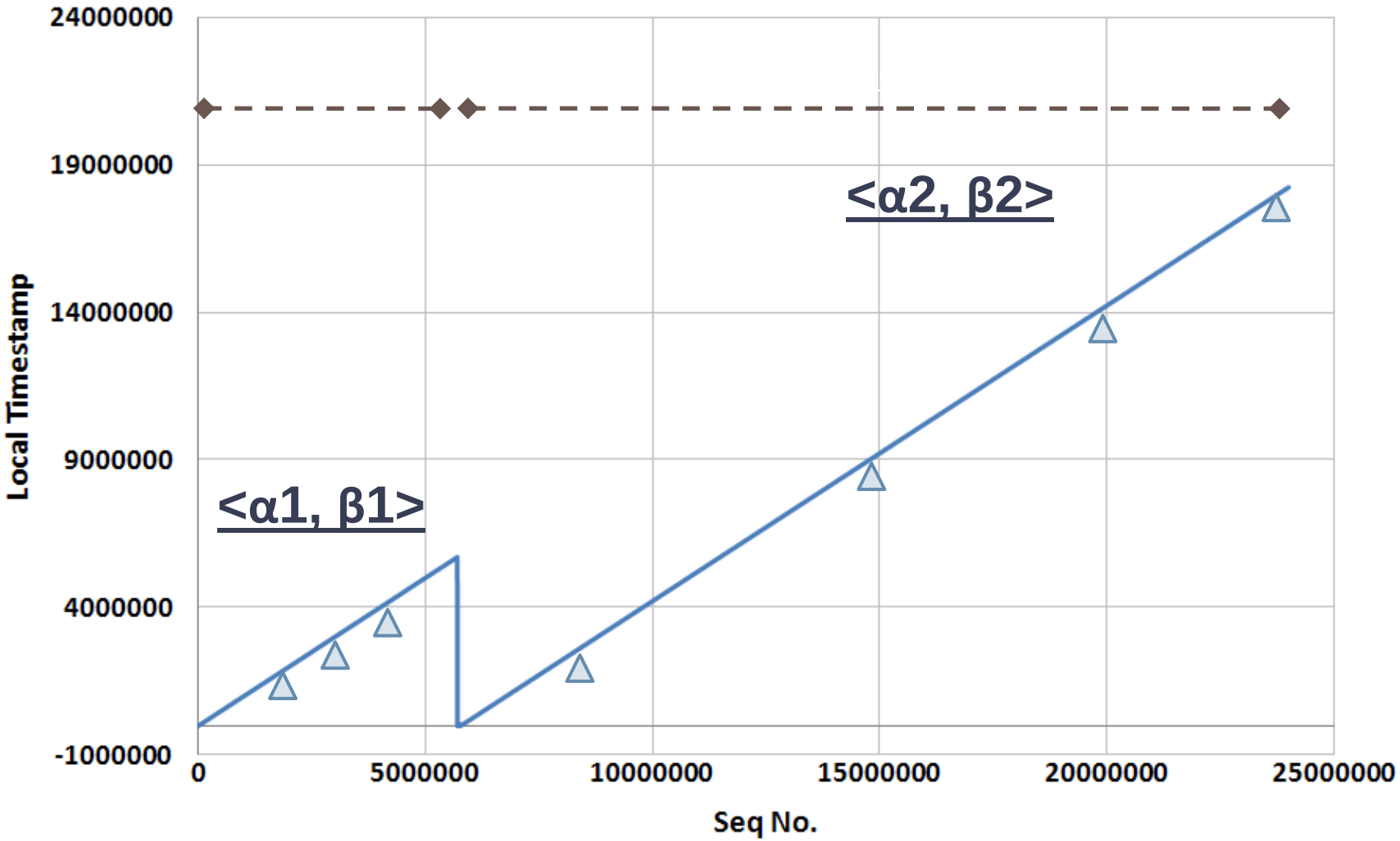
Source: Jayant Gupchup

In Reality Reboots Occur



Source: Jayant Gupchup

In Reality Reboots Occur



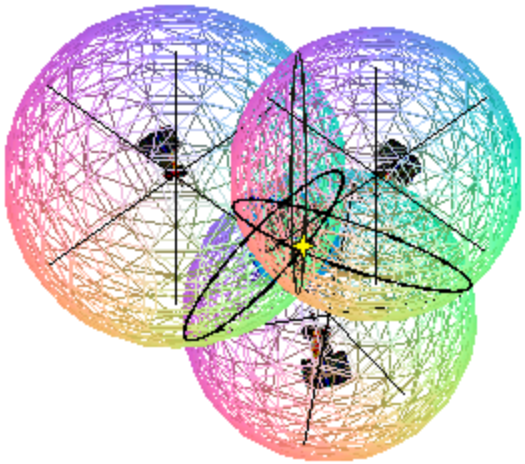
Source: Jayant Gupchup

Out-of-band Time Synchronization

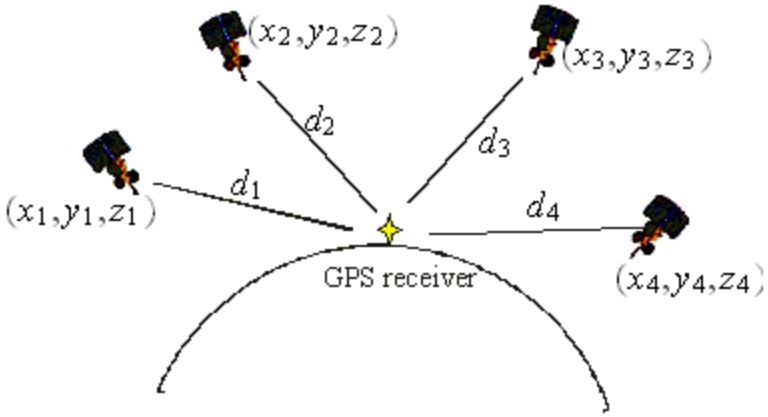
GPS

GPS (Simplified)

- Location based on time-of-flight from (at least) 4 known satellite location
  - Satellite transmissions include very accurate timestamp
  - Solve for unknown (x,y,z,t)



Three spheres



t_B: receiver clock offset

$$\sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2}+ct_B=d_1$$

$$\sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2}+ct_B=d_2$$

$$\sqrt{(x-x_3)^2+(y-y_3)^2+(z-z_3)^2}+ct_B=d_3$$

$$\sqrt{(x-x_4)^2+(y-y_4)^2+(z-z_4)^2}+ct_B=d_4$$

Souce: http://www.math.tamu.edu/~dallen/physics/gps/gps.htm

GPS

- Pros
  - Globally available
  - Nanosecond accuracy
  - Global time

- Cons
  - Online processing is power consuming
  - GPS radio can be expensive to add
  - Problematic to use indoors

Ultra-Low Power Time Synchronization Using Passive Radio Receivers

Yin Chen, Qiang Wang, Marcus Chang, and Andreas Terzis

Appeared in IPSN 2011

Time Code Signals

- Radio Controlled Clock

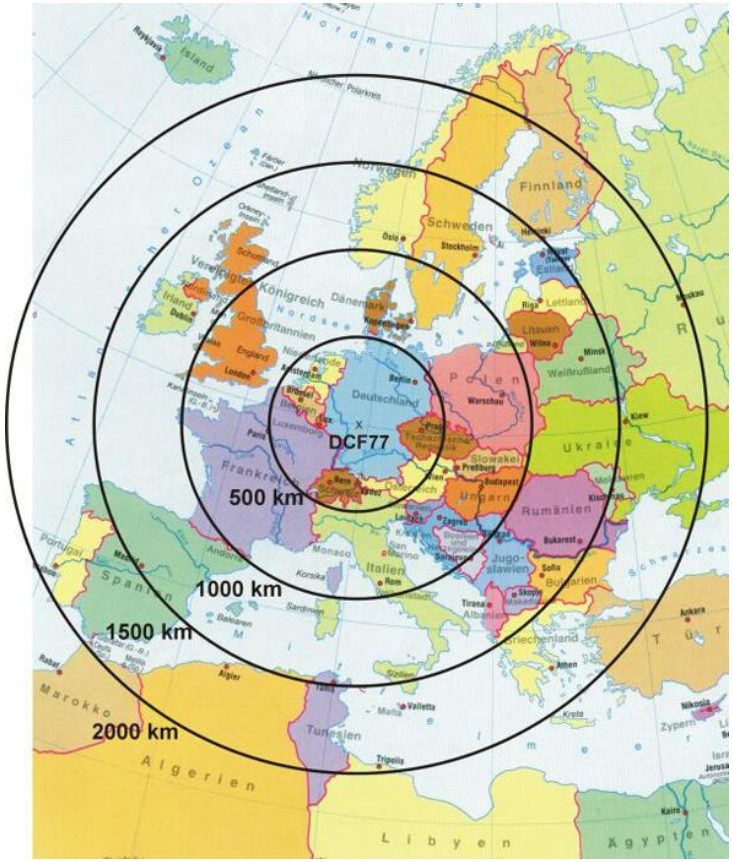


Image: C-MAX Time Solutions

Image: PTB - Physikalisch-Technischen Bundesanstalt

Signal Format

- WWVB (DCF77 is similar)
  - 60 kHz AM carrier signal

- 60 bit frame format
  - On the top of every second the amplitude is decreased
    - 0/1 are encoded with different durations, i.e., 1 bit per second
  - On the top of every minute a special duration is used
  - Time and date can be decoded after full frame is received

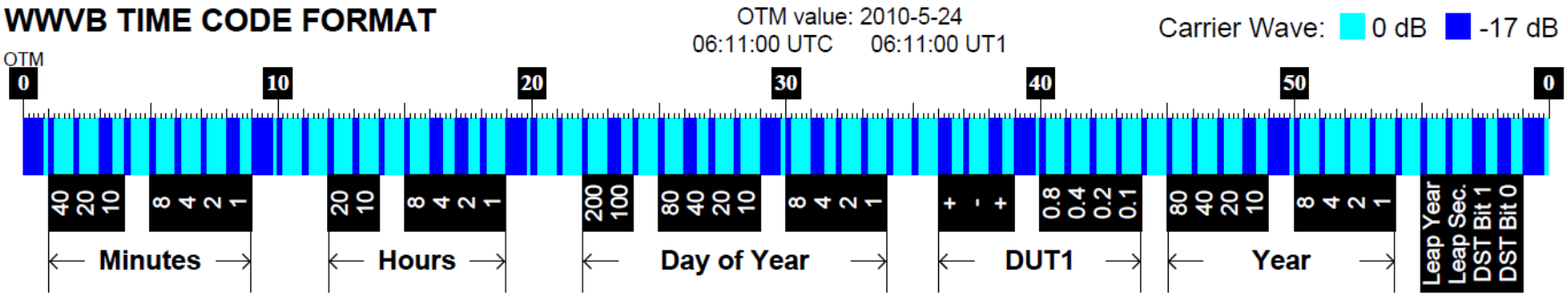
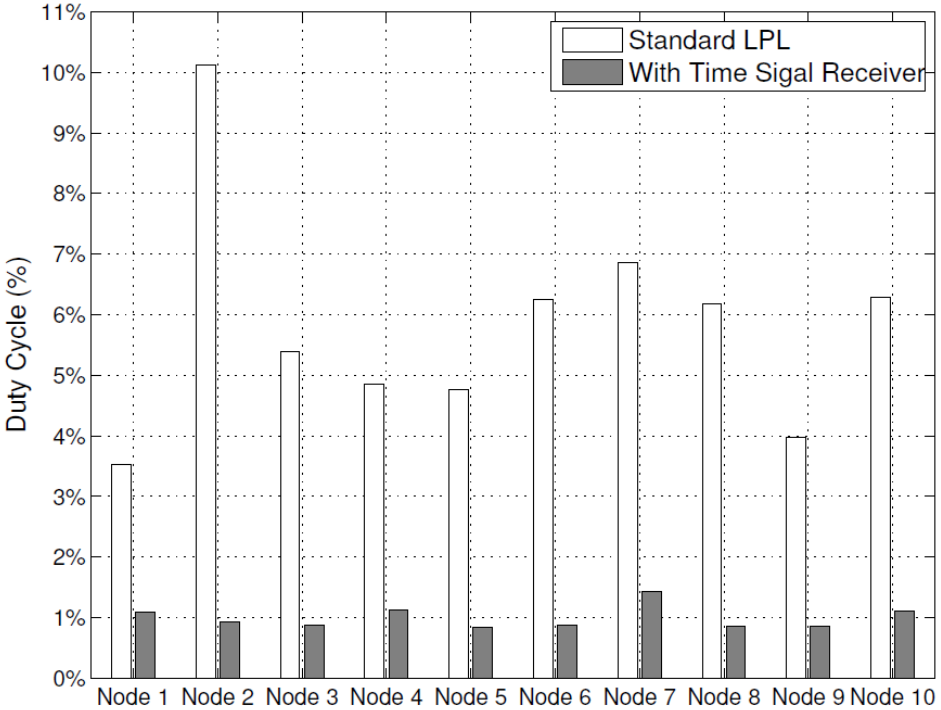


Image: Denelson83, Wikipedia

Benefits

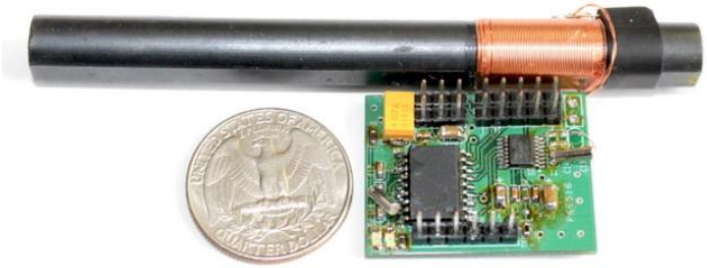
- Pros
  - Radio is very cheap
  - Power consumption is three orders of magnitude lower than the TelosB radio
  - Nodes receive the same signal
  - Global synchronization

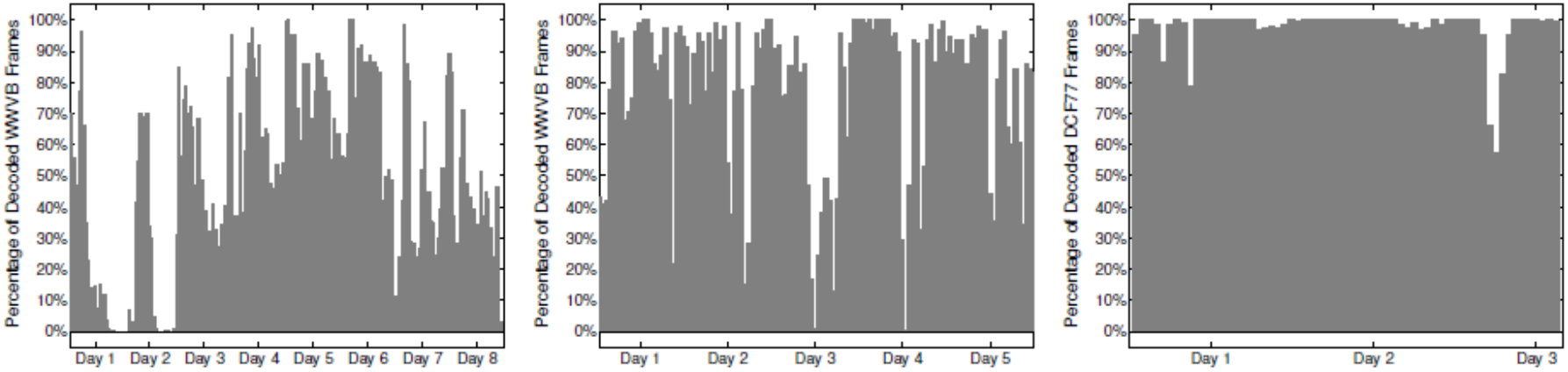


- Example
  - CTP with scheduled communication

Limitations

- Cons
  - Availability degrades with distance
  - Susceptible to interference from power lines and atmospheric conditions
  - Millisecond accuracy
  - Bulky antenna





(a) Indoor WWVB, 2400 km. (b) Outdoor WWVB, 2400 km. (c) Indoor DCF77, 700 km.

Exploiting FM Radio Data System for Adaptive Clock Calibration in Sensor Networks

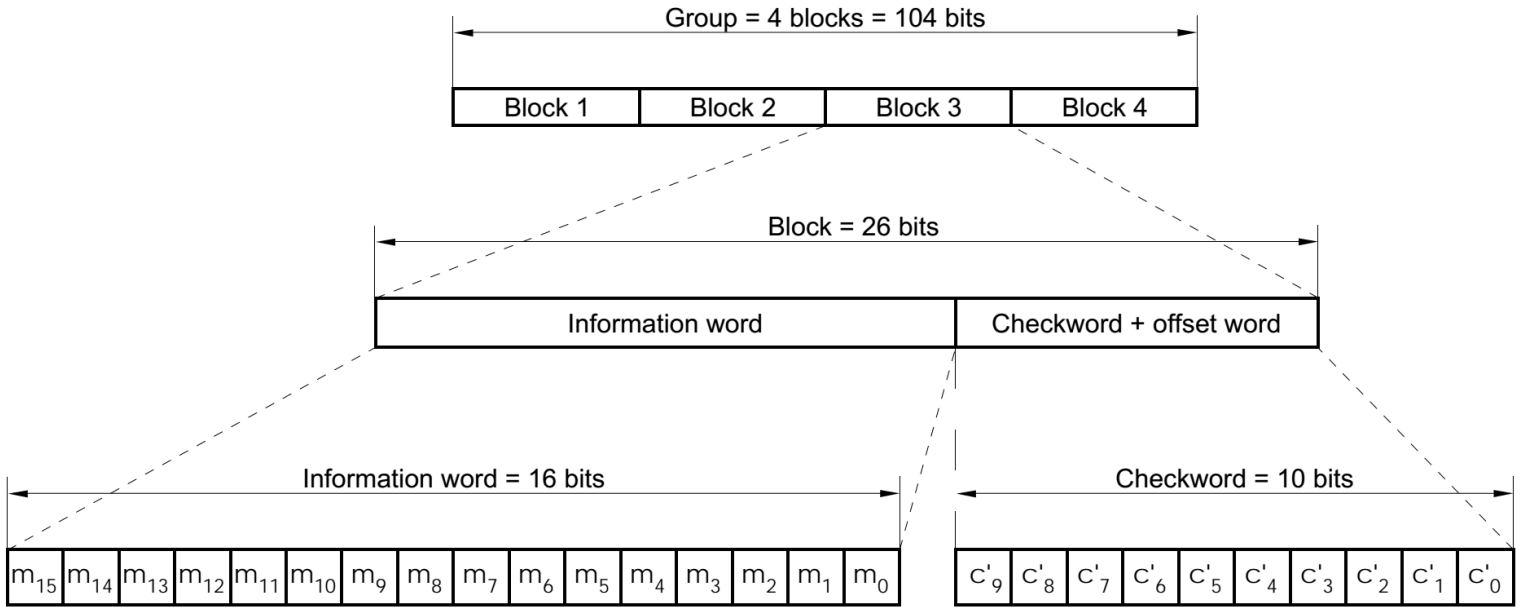
Liqun Li, Guoliang Xing, Limin Sun, Wei Huangfu,
Ruogu Zhou, Hongsong Zhu
Appeared in MobiSys 2011

Idea

- Radio Broadcast Data System (RBDS, RDS)
  - Digital information embedded in FM radio signals
    - Program type (PTY)
    - Station ID/name (PI, PS)
    - Traffic information (TA, TP, TMC, used by car GPS)
    - Clock (CT)

Signal Format

- 57 kHz sub-carrier
  - 1187.5 bits per second
  - Groups transmitted continuously
  - Date and time is transmitted at the top of every minute



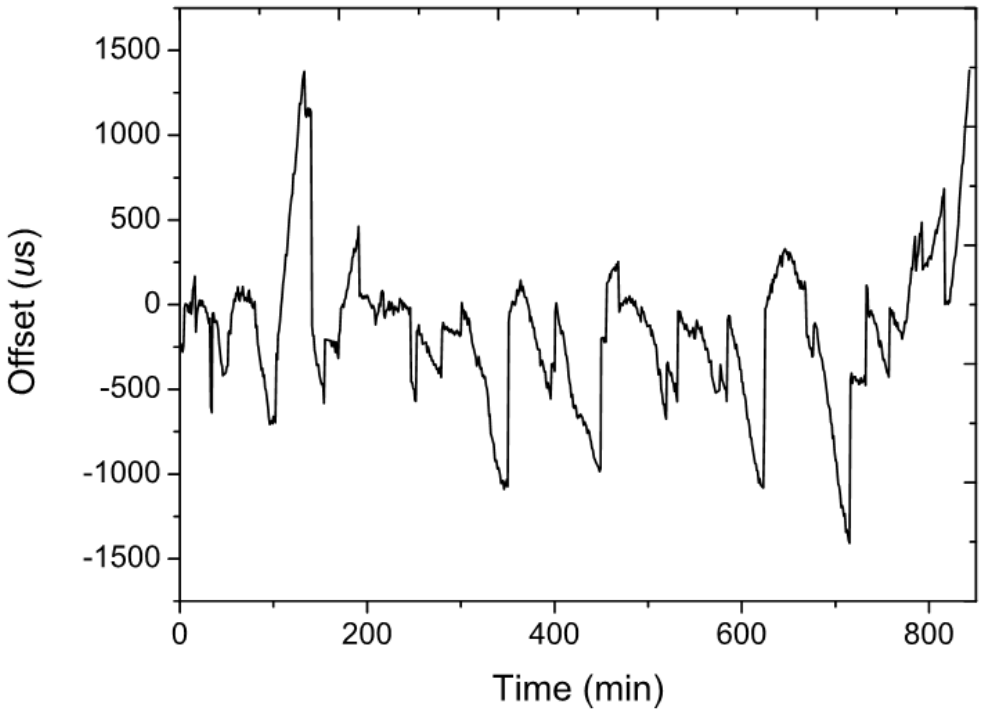
- Pros
  - Radio towers can cover a large area (100 km radius)
  - FM radio with RDS is widely available in populated areas
  - FM receivers are cheap and found in many consumer devices
  - Works well indoor

- Cons
  - Millisecond accuracy
    - 1187.5 bps equals 685.0961… groups per minute
      - i.e., Groups drift over time
  - FM receivers have non-deterministic interrupts

Clock Calibration

- Tell FM radio to generate interrupt on every Group start
  - Use Group frequency 11.42 Hz to calibrate internal clock

- Clock offset between two nodes:



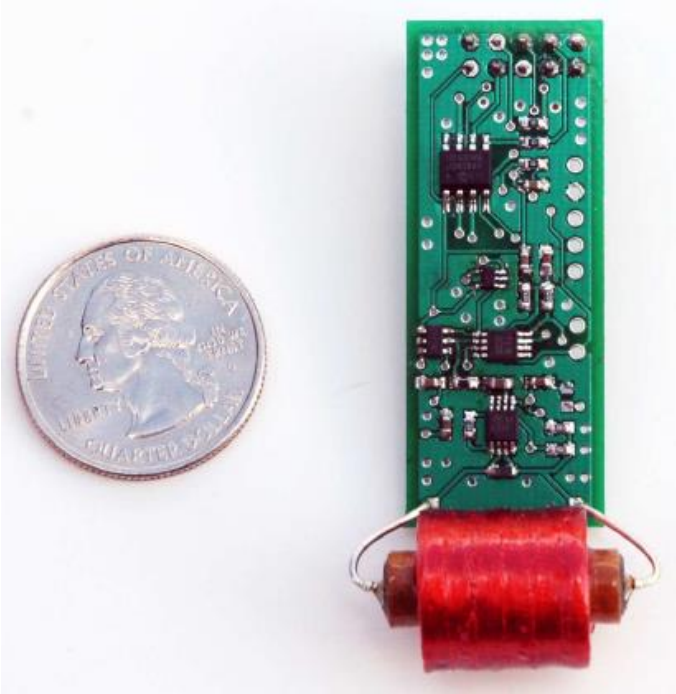
Low-power Clock Synchronization using Electromagnetic Energy Radiating from AC Power Lines

Anthony Rowe, Vikram Gupta, and Ragunathan (Raj) Rajkumar

Appeared in SenSys 2009

Syntonization

- Hybrid scheme
  - Message passing and special hardware
- Power lines oscillate at 60 Hz
  - Frequency lock motes
  - → Drift
- Message passing (once)
  - → Offset

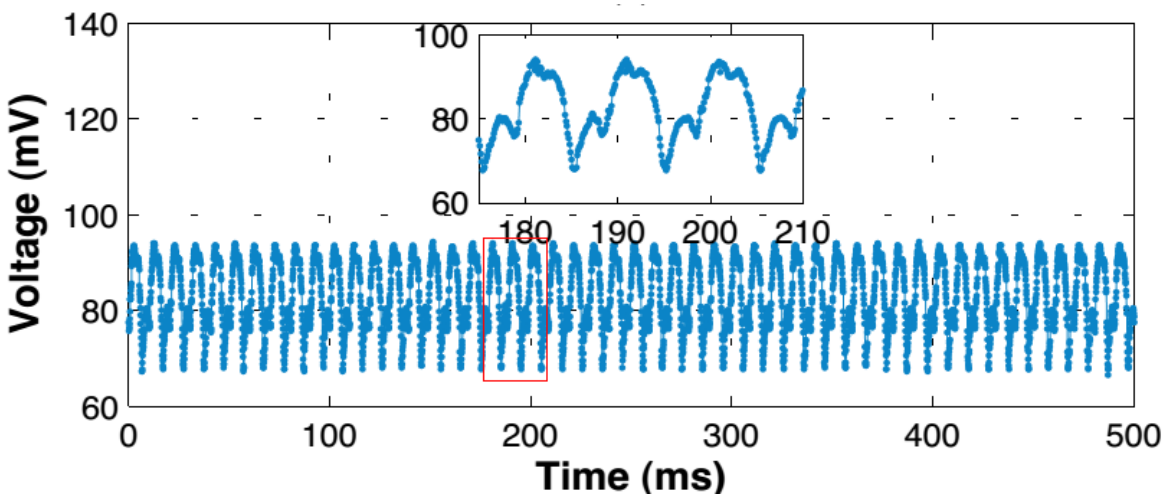


FLIGHT: Clock Calibration Using Fluorescent Lighting

Zhenjiang Li, Wenwei Chen, Cheng Li, Mo Li,
Xiang-yang Li, and Yunhao Liu
Appeared in MobiCom 2012

FLIGHT

- Fluorescent light
  - Intensity fluctuates with half the frequency of the AC
- Sample light sensor fast enough to detect changes
- Millisecond accuracy



In-band Time Synchronization

The Flooding Time Synchronization Protocol

Miklós Maróti, Branislav Kusy, Gyula Simon, and Ákos Lédeczi

Appeared in SenSys 2004

FTSP

- In-band message passing
- Target: microsecond, TelosB class devices
- Radio is a broadcast medium (one-to-many)
- One-hop radio propagation time is negligible (ns vs. µs)

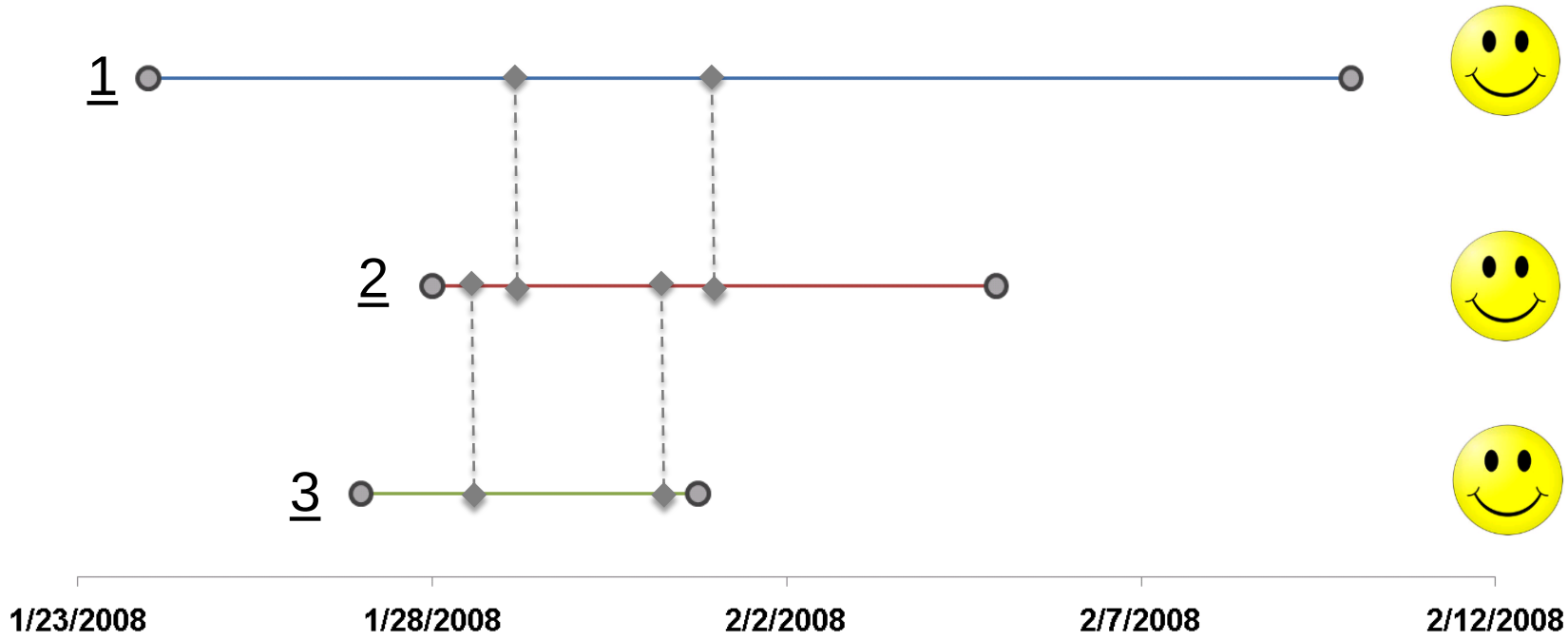
- Hierarchical network structure
  - Nodes synchronizes to node with lowest ID within range
  - Local time: distributed election of master
  - Global time: use node with global time as master

Phoenix: An Epidemic Approach to Time Reconstruction

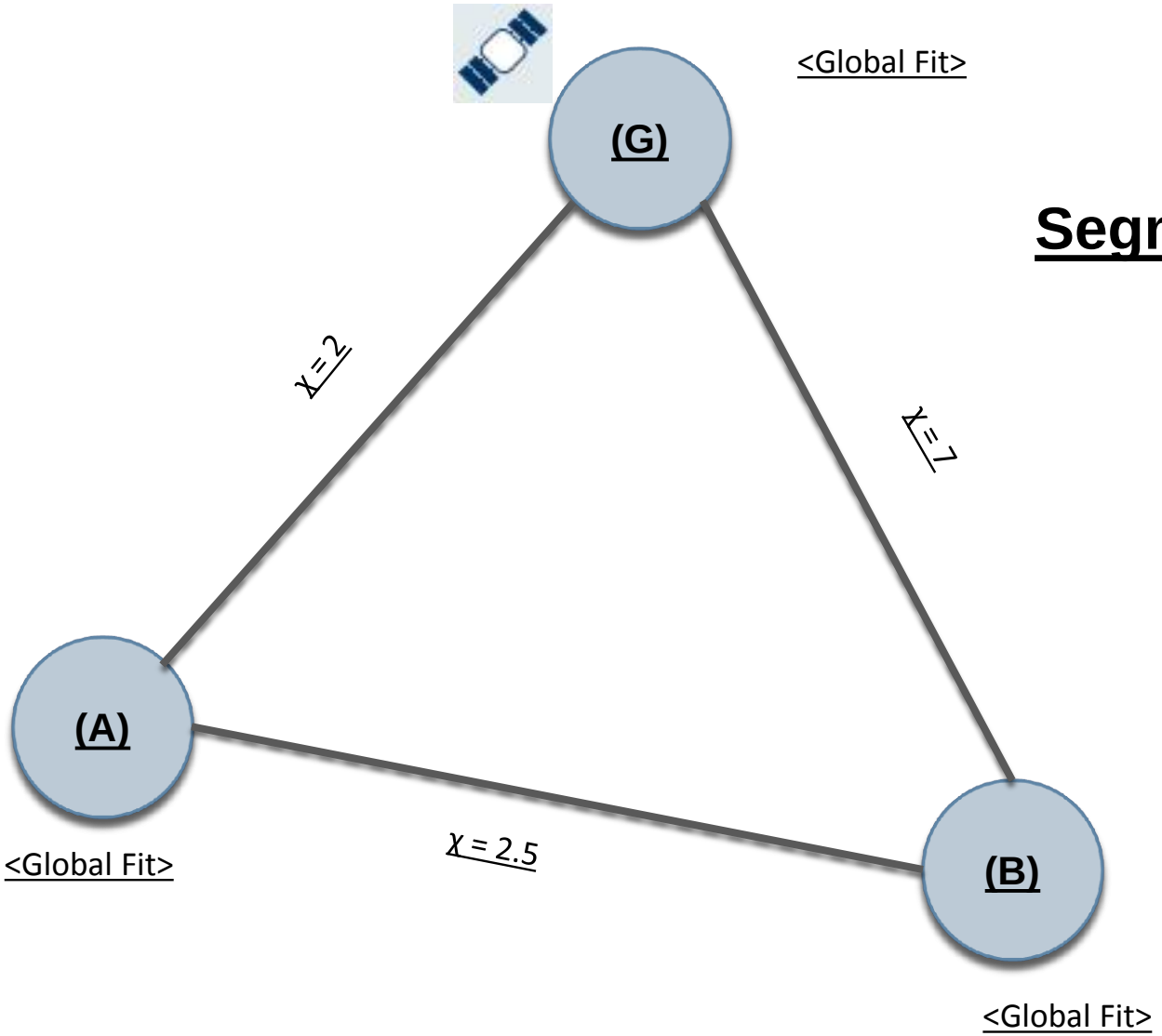
Jayant Gupchup, Doug Carlson, Razvan Musaloiu-E., Alex Szalayz, and Andreas Terzis Appeared in EWSN 2009

Idea

- Phoenix
  - Establish pair-wise calibration curves between nodes
  - Traverse segment graph based on calibration goodness

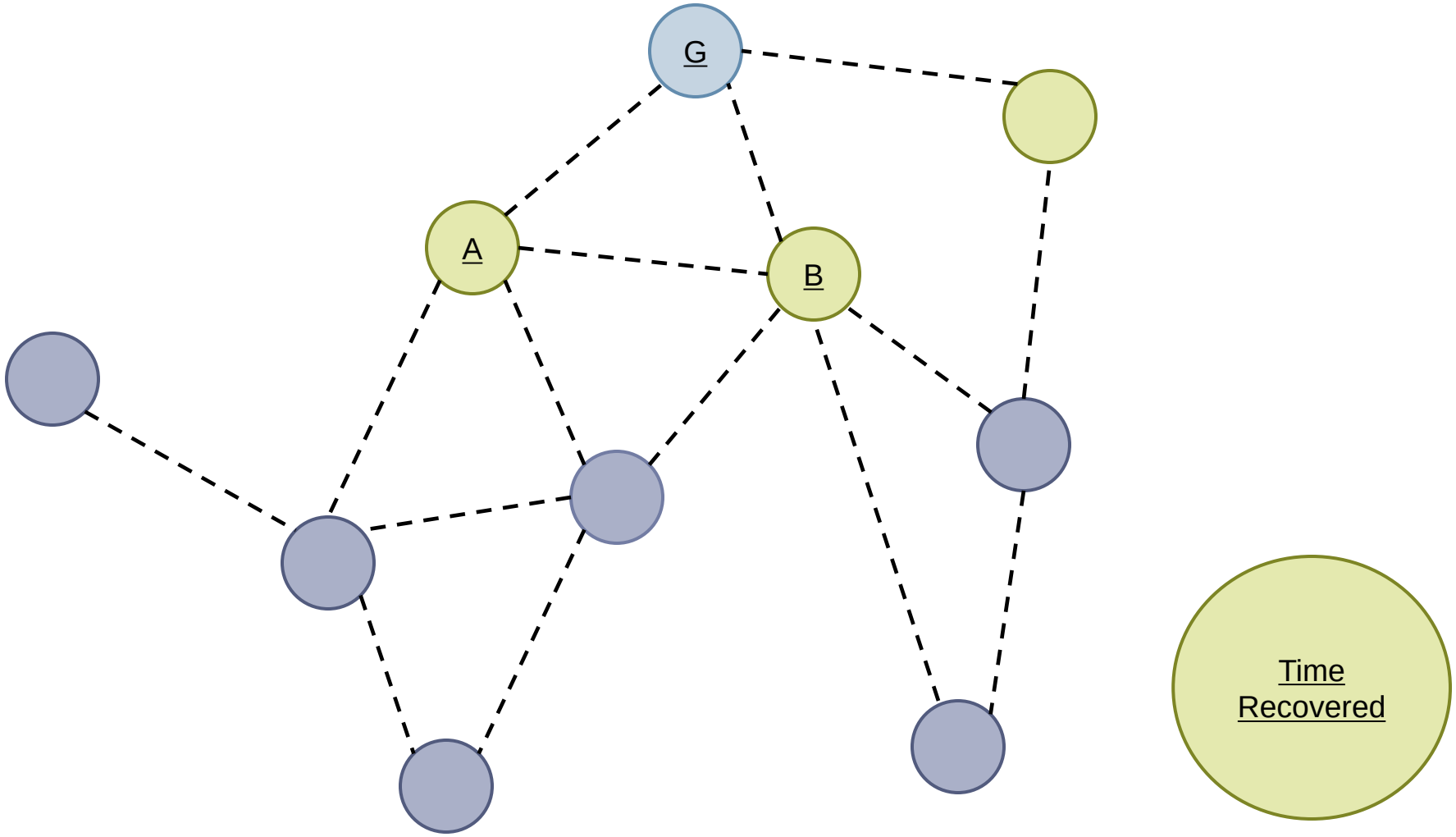


Pair-wise Node Calibration

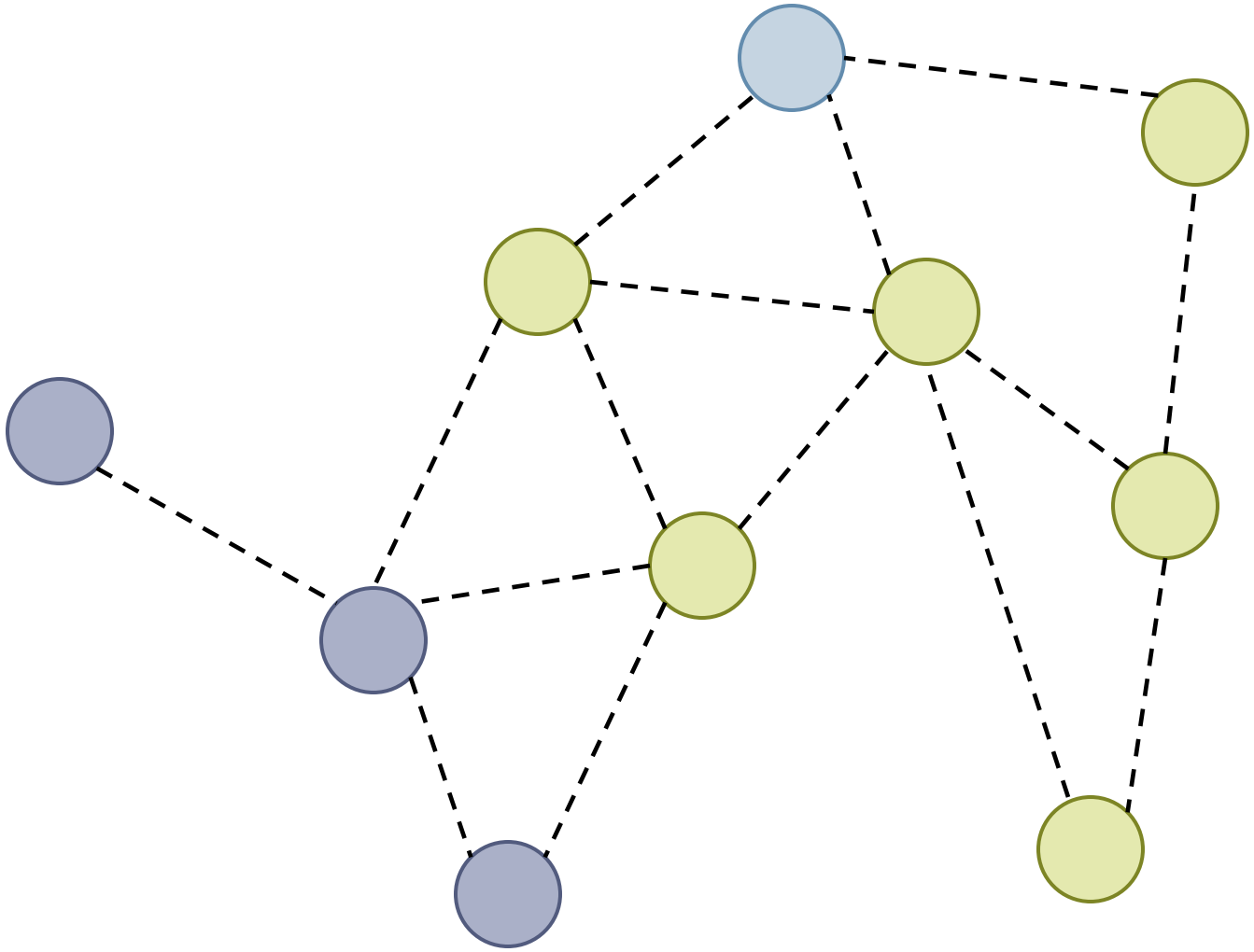


Segment Graph

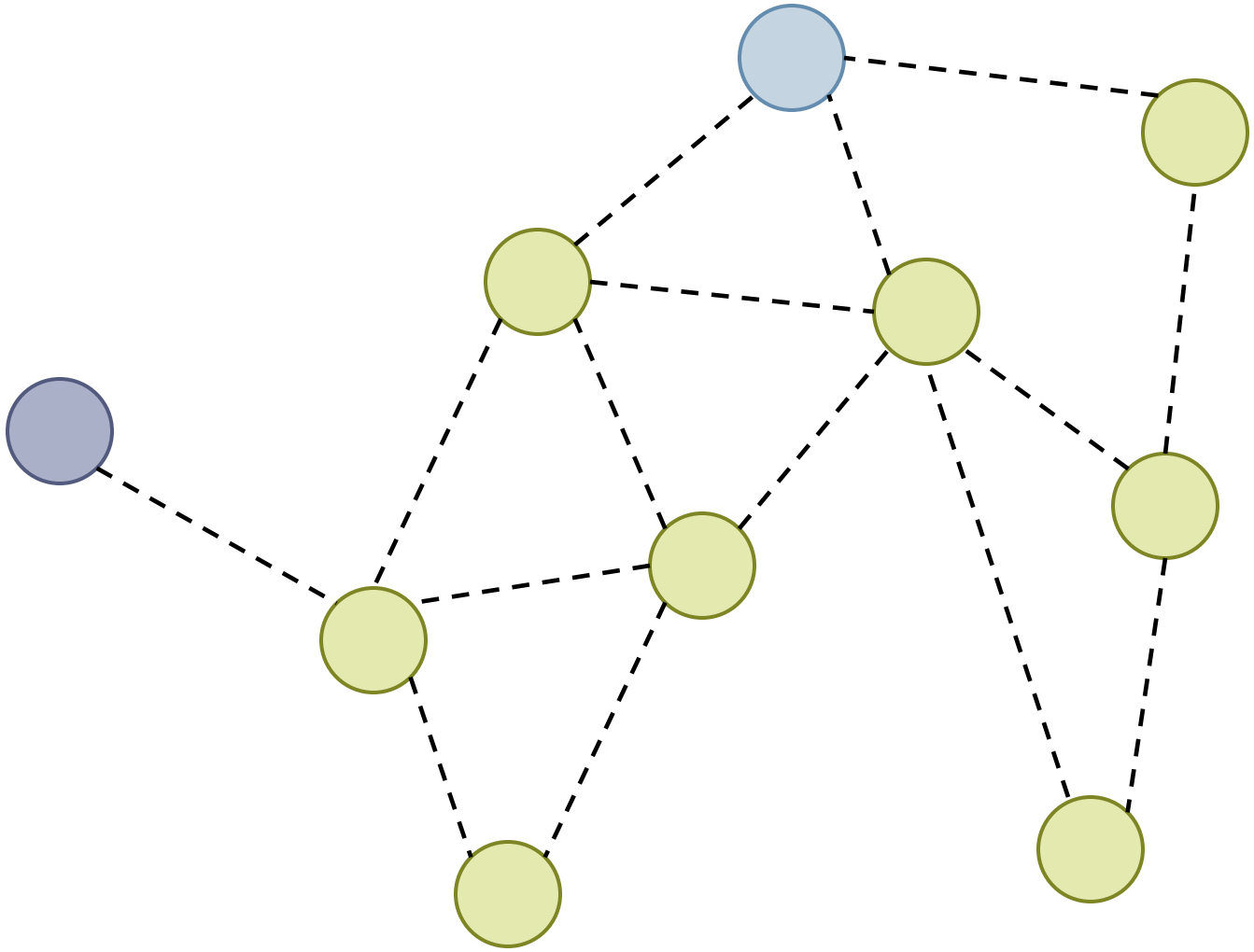
Example



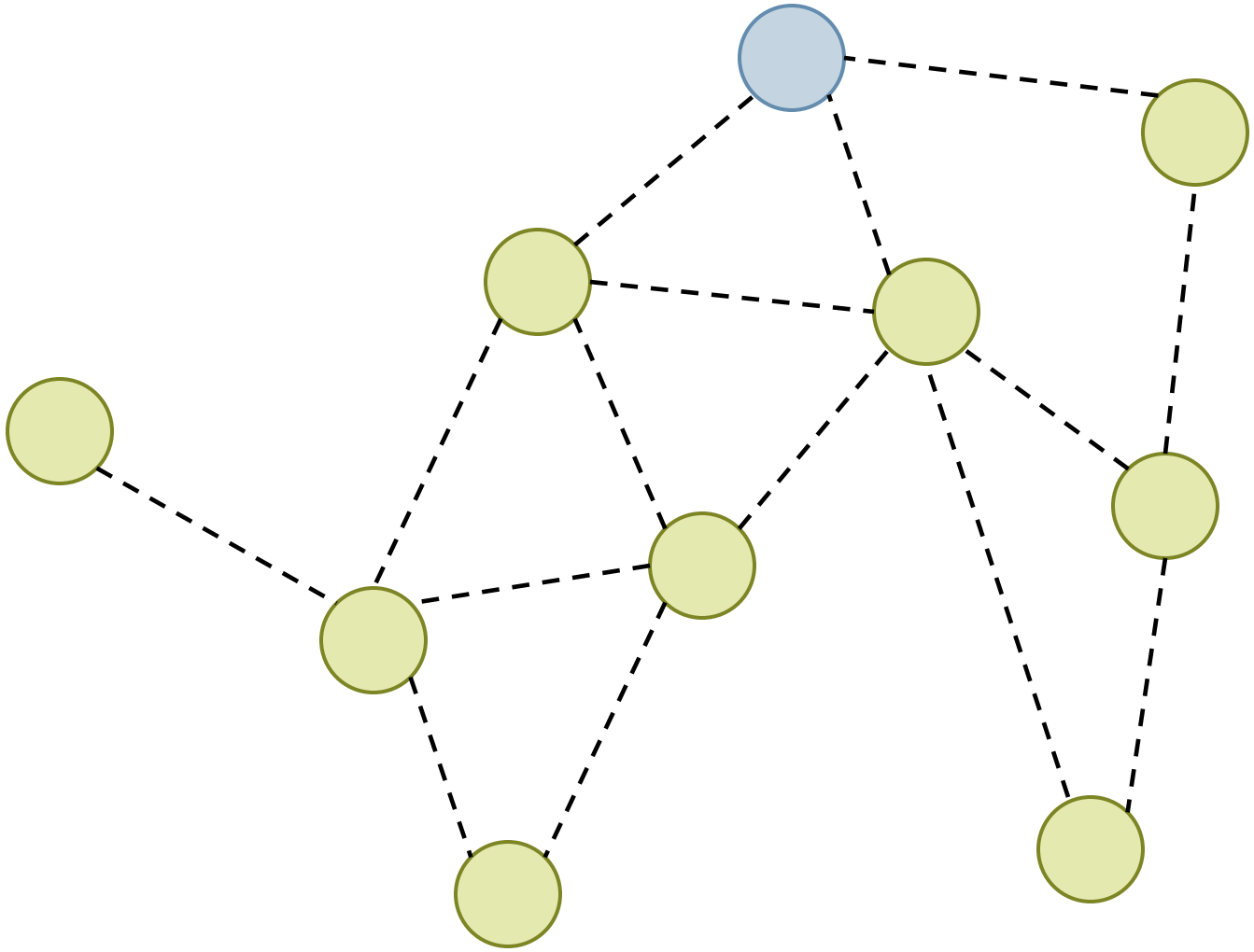
Example



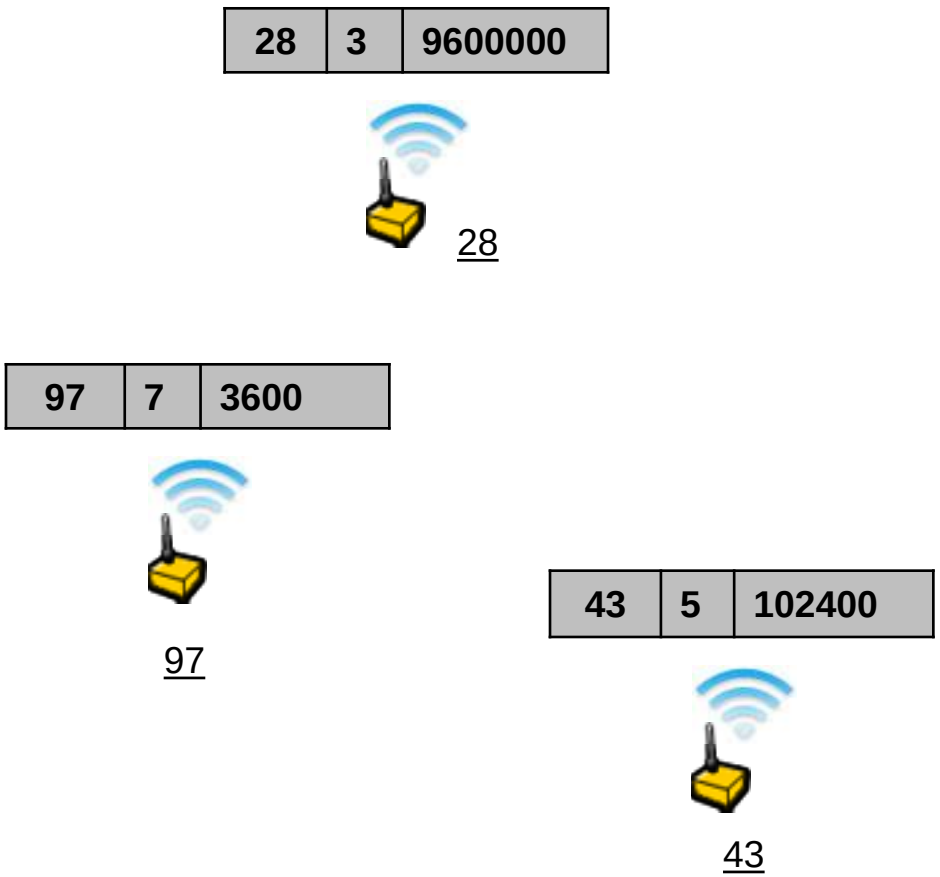
Example



Example



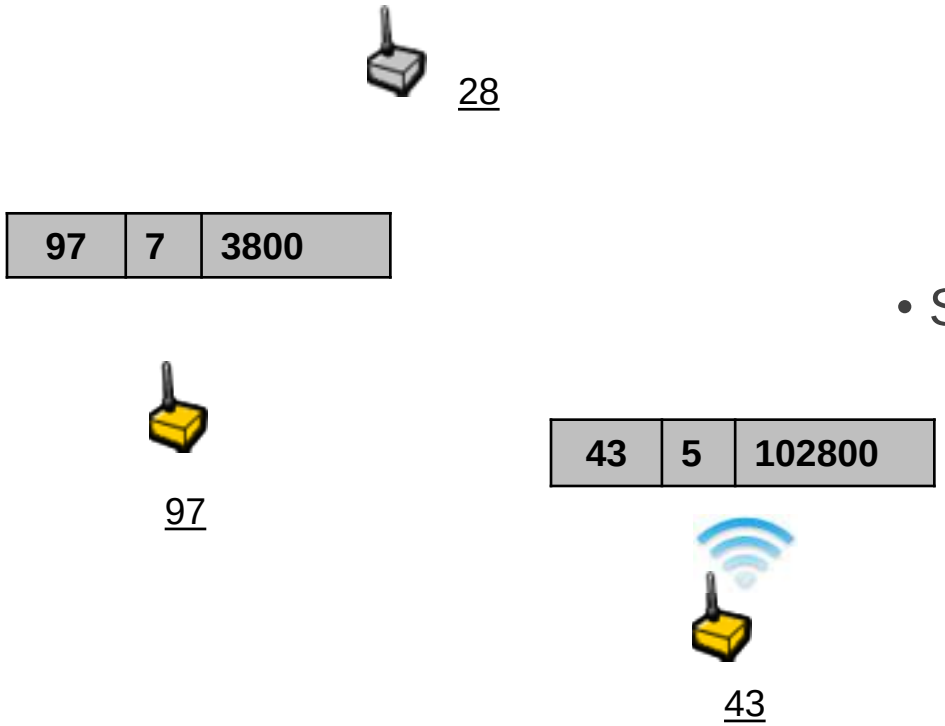
Anchor Collection



Each Mote:

- Beacons time-state periodically
  - <moteid, RC #, LC>
  - Beacon interval~ 30s
  - Duty-cycle overhead: 0.075%

Anchor Collection



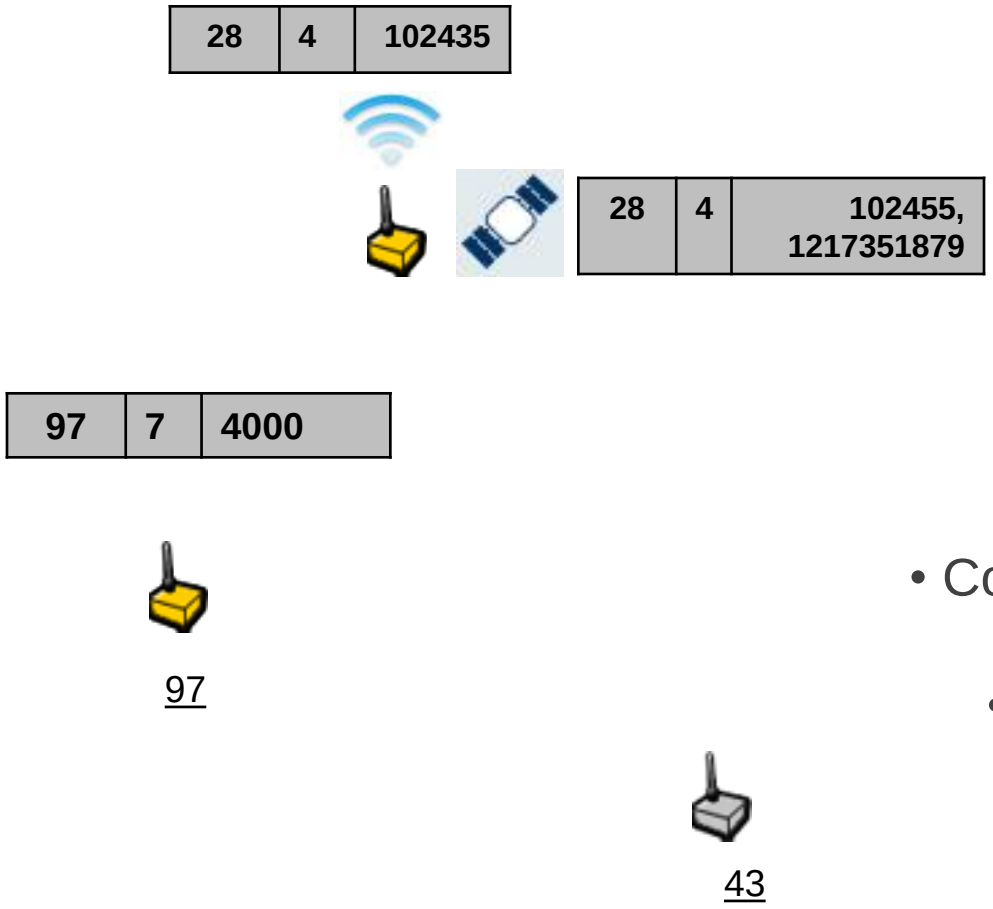
Each Mote:

- Stays up (30s) after reboot
- Listens for announcements
- Wakes up periodically (~ 6 hrs)
- Stays up (30s)
- Listens for announcements

- Stores <local, neighbor> anchors

- Duty-Cycle : 0.14%

Anchor Collection



G-Mote:

- Connected to a global clock source
- Beacon its time-state (30s)
- Store Global References (6 hrs)
- Global clock source (GPS, Basestation etc)

Benefits and Limitations

- Pros
  - Power efficient, scalable
  - Robust to
    - Node reboots and failures
    - Absence of global time for long periods
  - 6 ppm accuracy

- Cons
  - Offline, post-processing
  - Anchors need to be stored and offloaded
  - Time synchronization accuracy: seconds

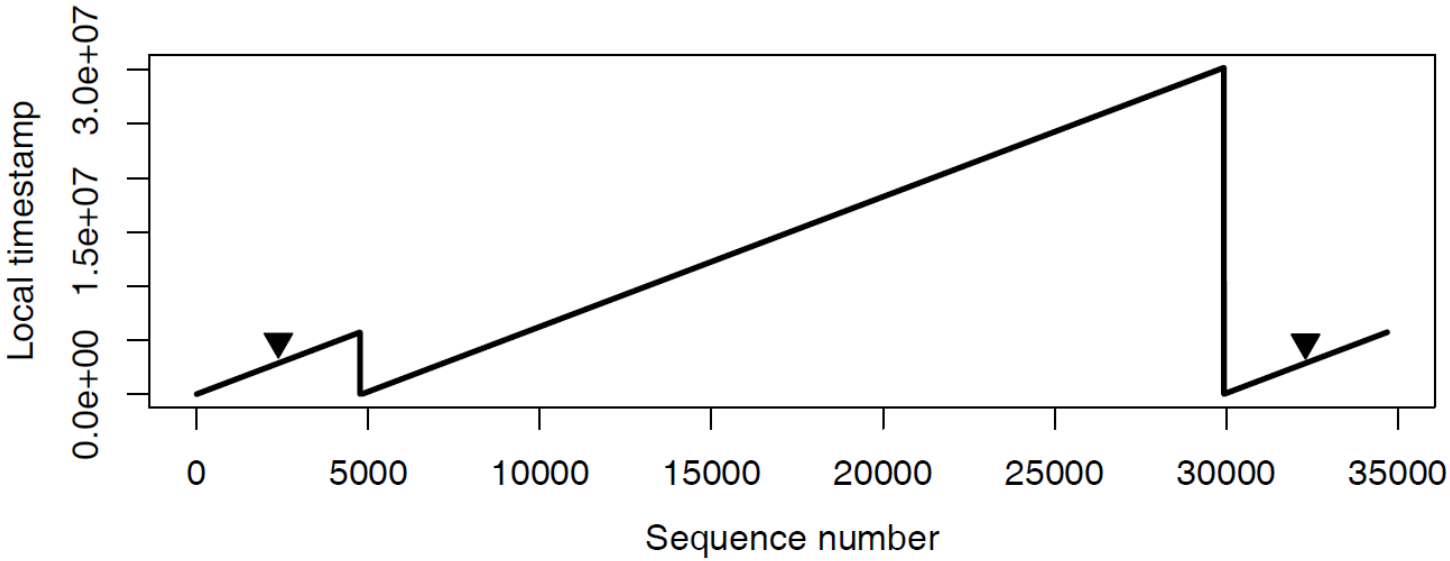
Sundial: Using Sunlight to Reconstruct Global Timestamps

Jayant Gupchup, Razvan Musaloiu-E., Alex Szalayz, and Andreas Terzis

Appeared in EWSN 2010

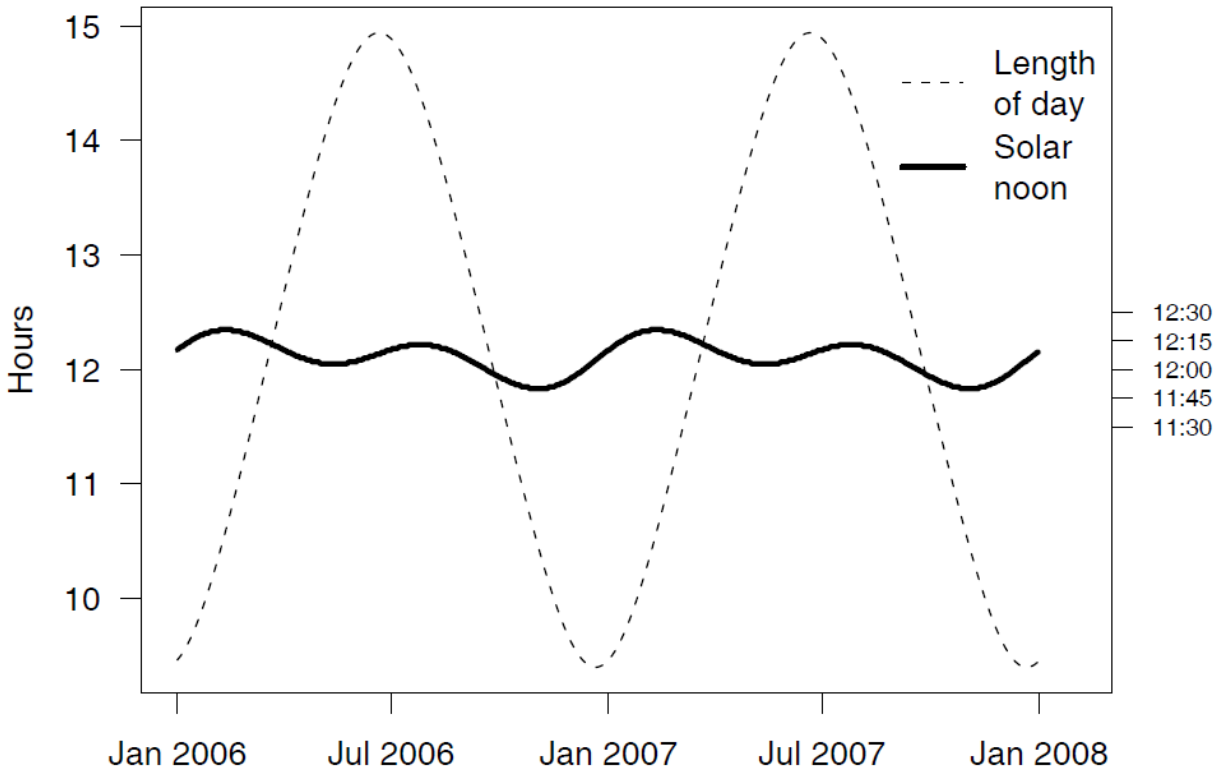
Damage Control

- Offline scheme
- What do you do if your time synchronization fails?
  - Node reboots and resets counter
  - No local-time-global-time pairs

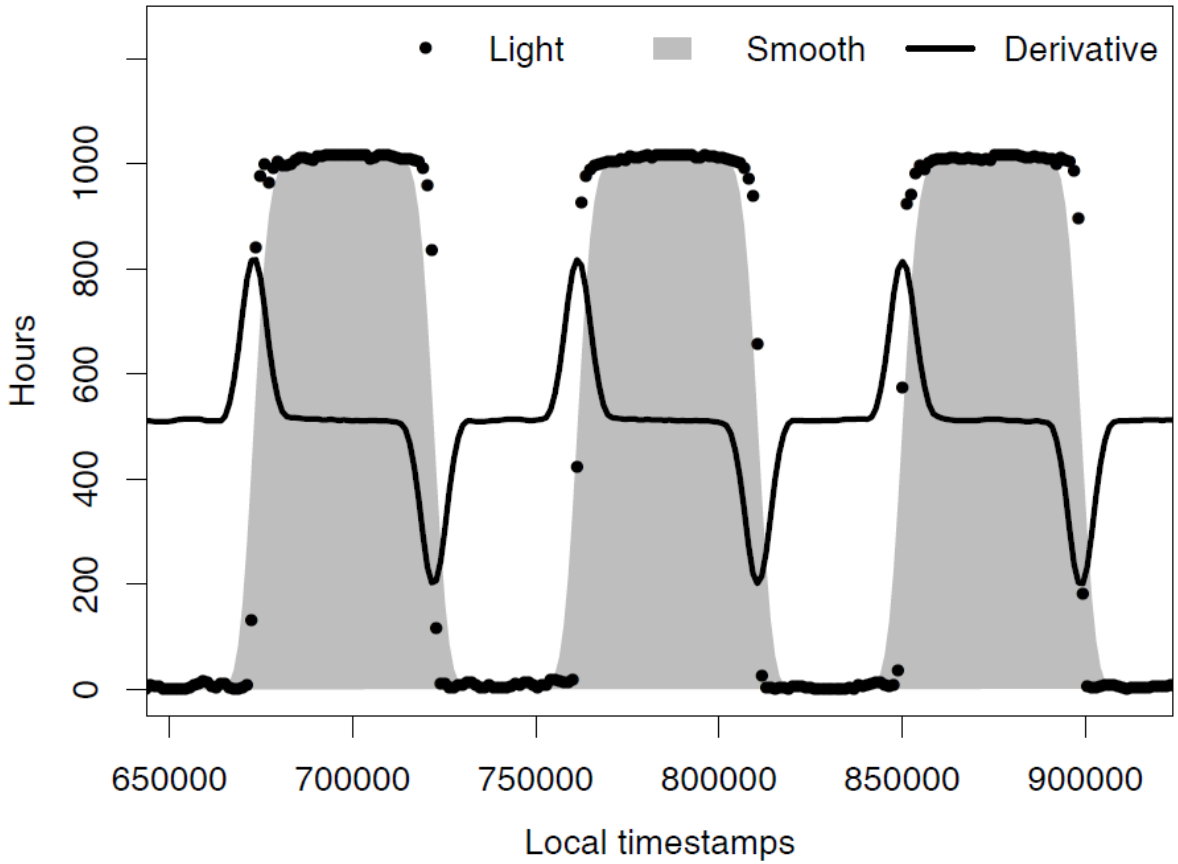


Back to Basics

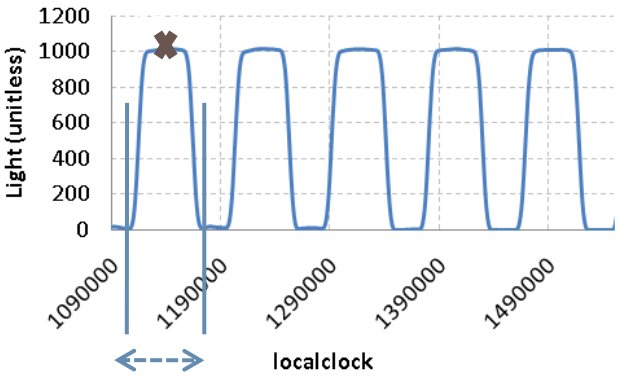
- Annual Solar Pattern (given the lattitude)
  - Solar Noon
  - Length of Day

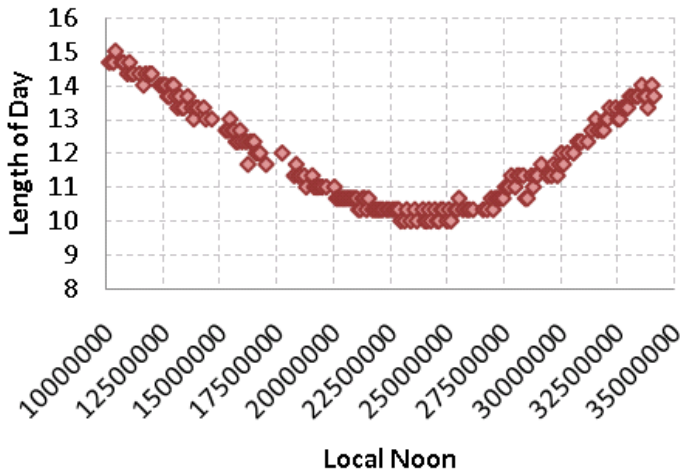


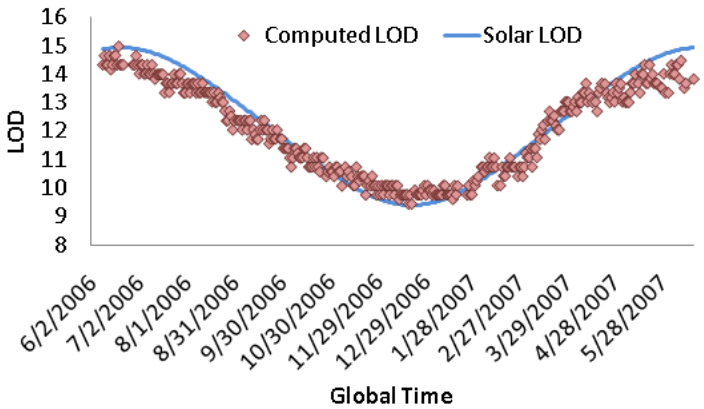
- Light measurements



“Sundial”

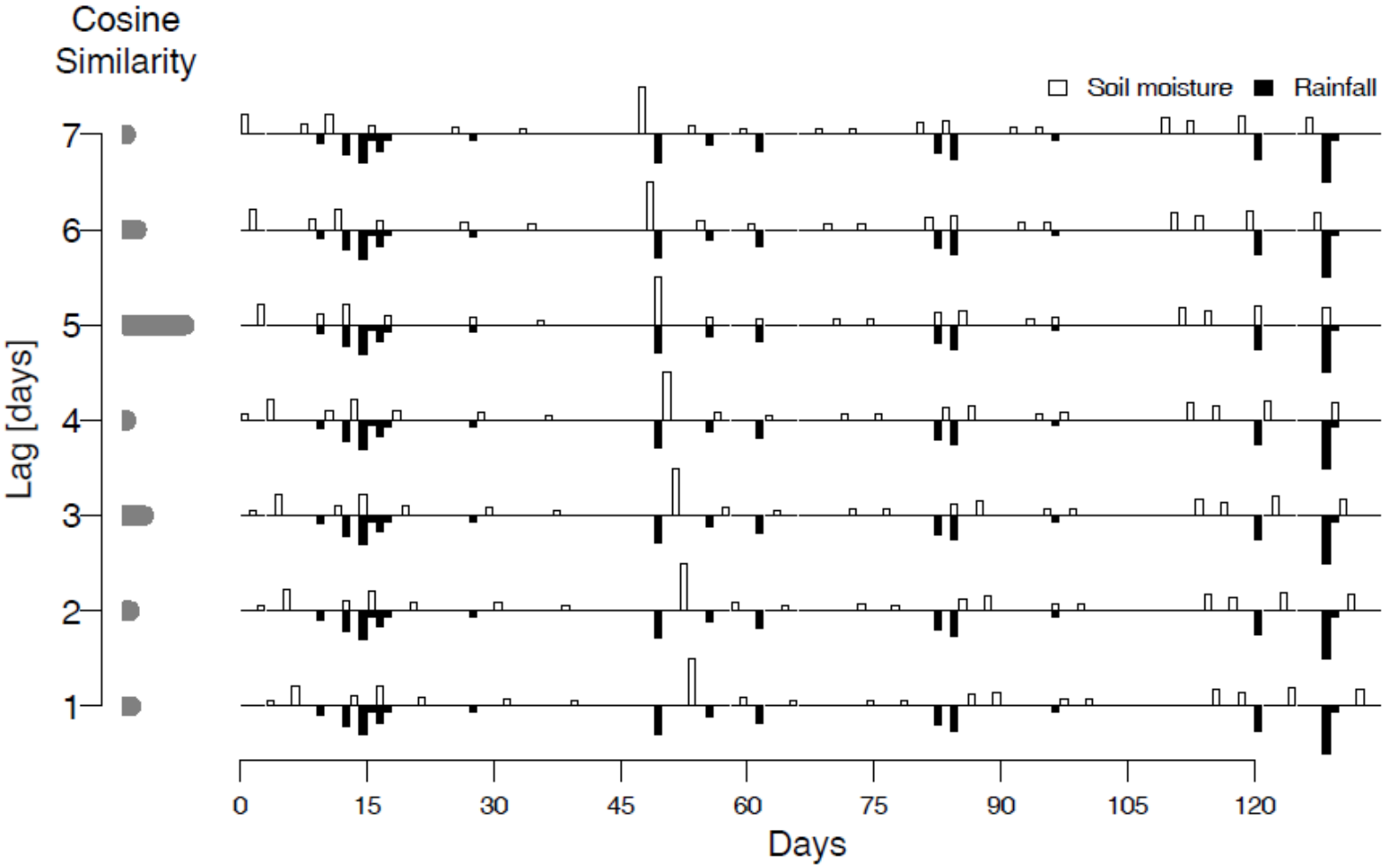






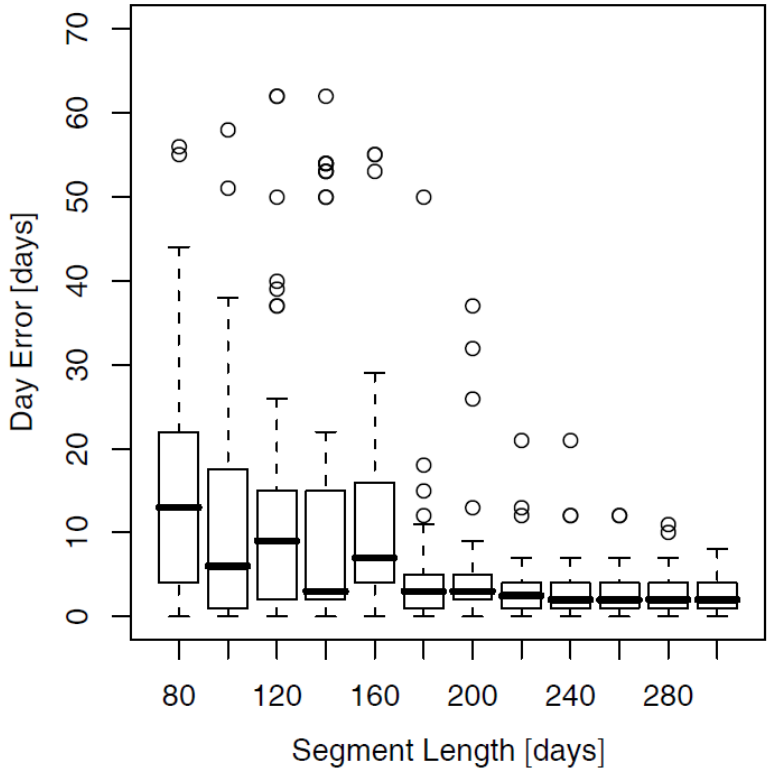
Local Noon	Global Noon
Lts $_1$	Gts $_1$
Lts $_2$	Gts $_2$
…	…
…	…
Lts $_n$	Gts $_n$

Moisture and Rainfall Correlation

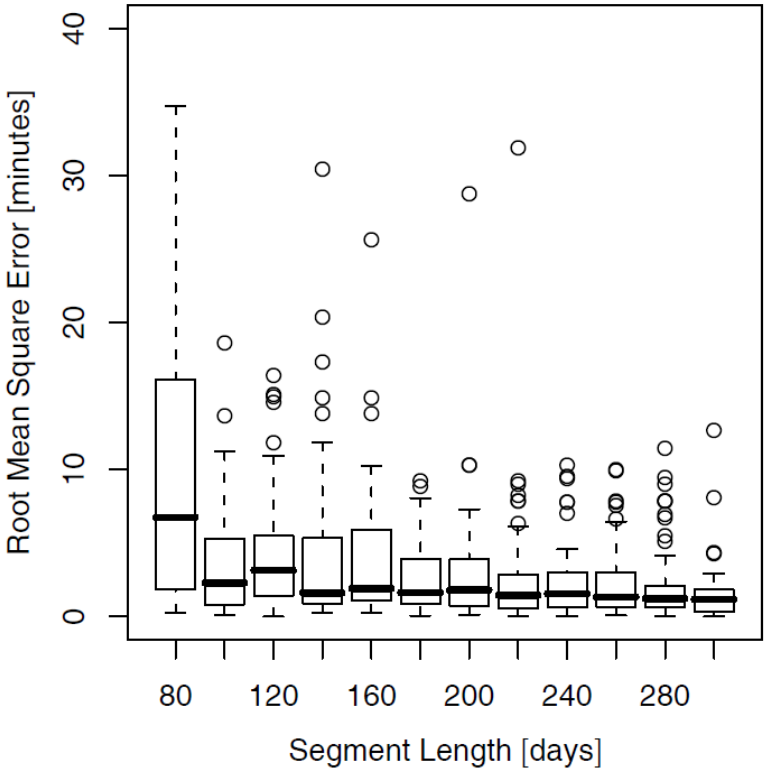


Evaluation

Sunlight



Rain



Schedule

- Week 1: Introduction and Hardware
- Week 2: Embedded Programming
- Week 3: Medium Access Control
- Week 4: Link Estimation and Tree Routing
- Week 5: IP Networking
- Week 6: JHU Special feat. Doug Carlson
- Week 7: (seminar, no lecture)
- Week 8: Energy Management and Harvesting
- Week 9: Review and Midterm
- Week 10: Time Synchronization
- Week 11: **Localization**
- Week 12: TBD
- Week 13: (seminar, no lecture)
- Week 14: TBD