Network Embedded Systems/Sensor Networks
Week 8: Time Synchronization

Marcus Chang @ CS JHU
Time

- Agreement
  - Rendezvous: synchronized communication
  - Events: multiple events or same event

- Measurement
  - Difference: Duration, Time-of-flight
  - Timestamping
Clock Offset

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

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

- SI Second: 9,192,631,770 oscillations of caesium 133 @ 0K

- Normal clocks:
  - kHz to MHz

- Drift
  - Number of oscillations differs from what the expected
    - Temperature variations
    - Crystal aging

Image: Maxim IC, DS3231 Datasheet
Long Term Drift

1 permil
100 ppm
10 ppm
1 ppm

- Error
- Time: 1 min, 1 hour, 1 month, 1 year

ADC values
- Node 72
- Node 76

Dates:
- Apr 2, Apr 3, Apr 4
- Jun 16, Jun 17, Jun 18
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
Clock Synchronization: Sensor Networks

- What are the requirements of your application?
- What clock 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; weather time scale
Time Synchronization Methods

- **In-band**
  - Use onboard radio to pass messages

- **Out-of-band**
  - Use special hardware to receive messages/events
    - GPS
    - Time code signals
    - Light!

- **Online vs. Offline processing**
  - Real-time application
  - Power efficiency
The Flooding Time Synchronization Protocol

Miklós Maróti, Branislav Kusy, Gyula Simon, and Ákos Lédeczi
Appeared in SenSys 2004
## Uncertainty Sources in Message Passing

<table>
<thead>
<tr>
<th>Time</th>
<th>Magnitude</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Send and Receive</td>
<td>0 – 100 ms</td>
<td>nondeterministic, processor load</td>
</tr>
<tr>
<td>Access</td>
<td>10 – 500 ms</td>
<td>nondeterministic, channel contention</td>
</tr>
<tr>
<td>Transmission / Reception</td>
<td>10 – 20 ms</td>
<td>deterministic, message length</td>
</tr>
<tr>
<td>Propagation</td>
<td>&lt; 1μs for distances up to 300 meters</td>
<td>deterministic, distance between sender and receiver</td>
</tr>
<tr>
<td>Interrupt Handling</td>
<td>&lt; 5μs in most cases, but can be as high as 30μs</td>
<td>nondeterministic, interrupts being disabled</td>
</tr>
<tr>
<td>Encoding plus Decoding</td>
<td>100 – 200μs, &lt; 2μs variance</td>
<td>deterministic, radio chipset and settings</td>
</tr>
<tr>
<td>Byte Alignment</td>
<td>0 – 400μs</td>
<td>deterministic, can be calculated</td>
</tr>
</tbody>
</table>
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
FTSP – Main Ideas

- Avoid nondeterministic uncertainty by using MAC layer timestamping, i.e.,
  - write timestamp to packet while it is being sent
  - capture receive time while radio receives packet
  - → Offset

- Keep history of master-slave timestamp pairs and use linear regression to estimate clock skew
  - → Drift
Pairwise Accuracy

The diagram illustrates the pairwise accuracy over time, with measurements in microseconds and percentages. The x-axis represents time in hours and minutes, while the y-axes represent microseconds and percentages, respectively. The graph shows the evolution of average pairwise error (black dots), maximum pairwise error (red dots), and synchronized motes (blue dots) over time.
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
WWVB

- 60 kHz AM
- 1 bit per second
- Millisecond range
Comparison: FTSP and CTP

<table>
<thead>
<tr>
<th>Interval (s)</th>
<th>$I$ (mA)</th>
<th>$I_{ts}$ (mA)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.126</td>
<td>3.5e-4</td>
<td>361:1</td>
</tr>
<tr>
<td>3,600</td>
<td>0.067</td>
<td>9.72e-5</td>
<td>686:1</td>
</tr>
<tr>
<td>7,200</td>
<td>0.047</td>
<td>4.86e-5</td>
<td>970:1</td>
</tr>
<tr>
<td>10,800</td>
<td>0.038</td>
<td>3.24e-5</td>
<td>1188:1</td>
</tr>
</tbody>
</table>

[Graph showing duty cycle (%) for different nodes with and without time signal reception.]
Limitations

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

- **Raw:**

  ![Histogram of raw data]

- **PLL:**

  ![Histogram of PLL data]
Evaluation
GPS
GPS (Simplified)

- Ephemeris: date and time
- Almanac: satellite location
- Online: 18 seconds to minutes
- Offline: 200 ms

\[
\begin{align*}
\sqrt{(x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2 + c t_B} &= d_1 \\
\sqrt{(x-x_2)^2 + (y-y_2)^2 + (z-z_2)^2 + c t_B} &= d_2 \\
\sqrt{(x-x_3)^2 + (y-y_3)^2 + (z-z_3)^2 + c t_B} &= d_3 \\
\sqrt{(x-x_4)^2 + (y-y_4)^2 + (z-z_4)^2 + c t_B} &= d_4
\end{align*}
\]

Source: http://www.math.tamu.edu/~dallen/physics/gps/gps.htm
Sundial: Using Sunlight to Reconstruct Global Timestamps

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

Graphs showing data over a period of years, with axes labeled 'Hours', 'Length of day', 'Solar noon', 'Local timestamps', and 'Hours'.
Evaluation

Sunlight

Rain

Day Error [days]

Segment Length [days]

Root Mean Square Error [minutes]

Segment Length [days]
Summary

- Time synchronization
  - Message passing
  - Special signals and hardware
  - Offline time reconstruction

- Next week:
  - Review and midterm!
Schedule

- Week 1: Introduction and Applications
- Week 2: Mote Hardware
- Week 3: Embedded Programming
- Week 4: Medium Access Control
- Week 5: Link Estimation and Tree Routing
- Week 6: IP Networking
- Week 7: Energy Management
- Week 8: Time Synchronization
- **Week 9: Review and Midterm**
- Week 10: Operating Systems and Programming Languages
- Week 11: Advanced Networking Topics
- Week 12: Localization
- Week 13: Energy Harvesting
- Week 14: TBD