Chapter 5

Clock Synchronization

Distributed Systems

SS 2015

Fabian Kuhn

Clock Synchronization

Overview

- For a change, a more practical chapter ☺
- After considering logical time, let's care how to actually approximate and deal with real time ...
  - How to get synchronized clocks...
- Topics:
  1. General introduction to time and time synchronization
  2. Clock synchronization in computer systems / distributed systems
  3. Theory of clock synchronization

- **Slides (slightly adapted) by Roger Wattenhofer (ETH Zurich)**

  Thanks a lot!

Motivation

- Logical Time ("happens-before")
  - Determine the order of events in a distributed system
  - Synchronize resources

- Physical Time
  - Timestamp events (email, sensor data, file access times etc.)
  - Synchronize audio and video streams
  - Measure signal propagation delays (Localization)
  - Wireless (TDMA, duty cycling)
  - Digital control systems (ESP, airplane autopilot etc.)


Properties of Clock Synch. Algorithms

- External vs. internal synchronization
  - External sync: Nodes synchronize with an external clock source (UTC)
  - Internal sync: Nodes synchronize to a common time
    - to a leader, to an averaged time, ...

- One-shot vs. continuous synchronization
  - Periodic synchronization required to compensate clock drift

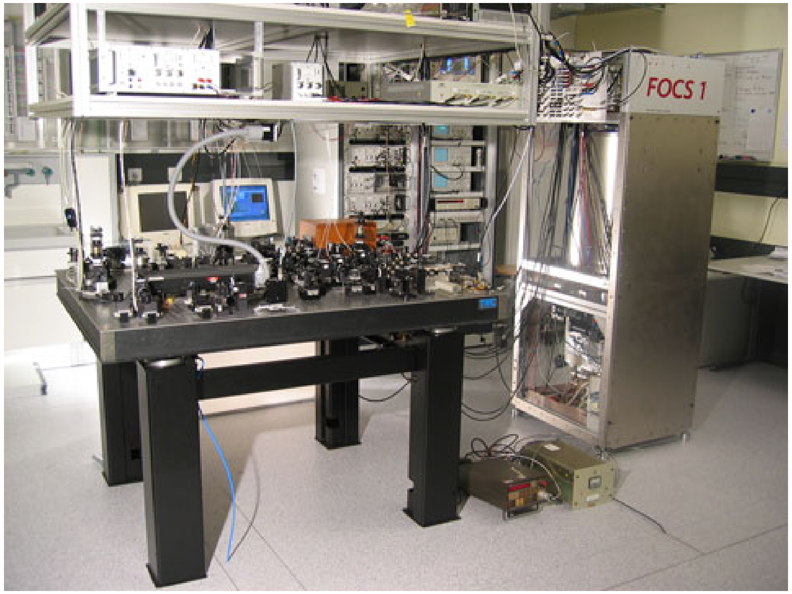
- Online vs. offline time information
  - Offline: Can reconstruct time of an event when needed

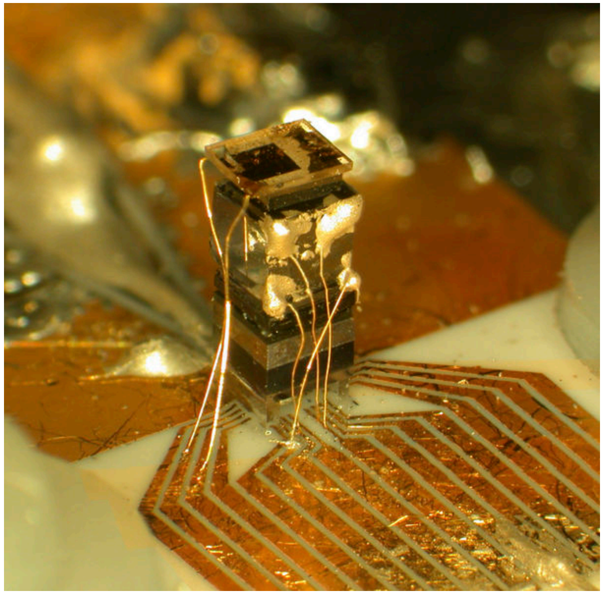
- Global vs. local synchronization (explained later)

- Accuracy vs. convergence time, Byzantine nodes, …

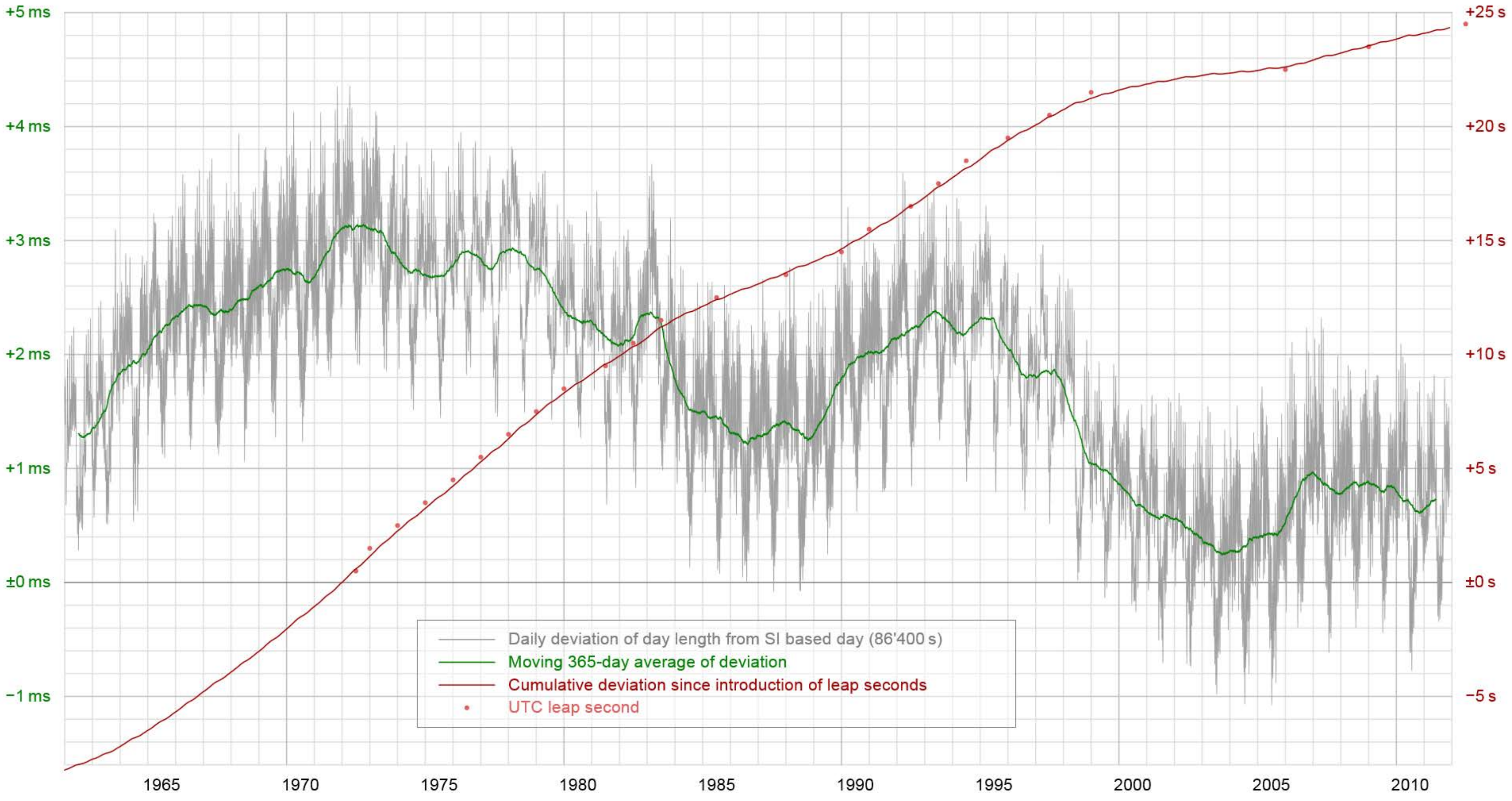
World Time (UTC)

- Atomic Clock
  - UTC: Coordinated Universal Time
  - SI definition 1s := 9192631770 oscillation cycles of the caesium-133 atom
  - Atoms are excited to oscillate at their resonance frequency and cycles can be counted.
  - Almost no drift (about 1s in 10 Million years)
  - Getting smaller and more energy efficient!





Atomic Clocks vs. Length of a Day



Access to UTC

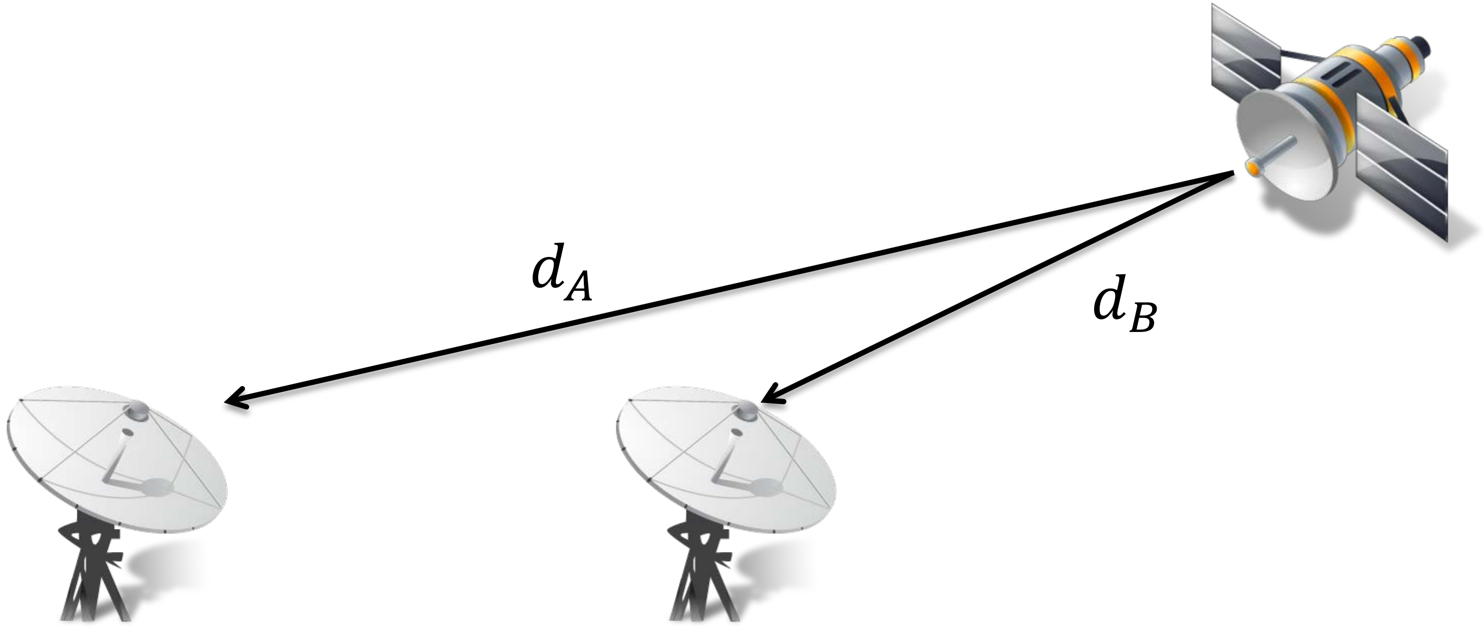
- Radio Clock Signal
  - Clock signal from a reference source (atomic clock) is transmitted over a long wave radio signal
  - DCF77 station near Frankfurt, Germany transmits at 77.5 kHz with a transmission range of up to 2000 km
  - Accuracy limited by the propagation delay of the signal, Frankfurt-Freiburg is about 0.8 ms
  - Special antenna/receiver hardware required

What is UTC, really?

- International Atomic Time (TAI)
  - About 200 atomic clocks
  - About 50 national laboratories
  - Reduce clock skew by comparing and averaging
  - UTC = TAI + UTC leap seconds (irregular rotation of earth)

- GPS
  - USNO Time
  - USNO vs. TAI difference is a few nanoseconds

Comparing (and Averaging)



Station A

$$t_{\Delta A} = t_A - (t_{SV} + d_A)$$

Station B

$$t_{\Delta B} = t_B - (t_{SV} + d_B)$$

$$\begin{aligned} t_\Delta &= t_{\Delta B} - t_{\Delta A} = t_B - (t_{SV} + d_B) - t_A + (t_{SV} + d_A) \\ &= t_B - t_A + d_A - d_B \end{aligned}$$

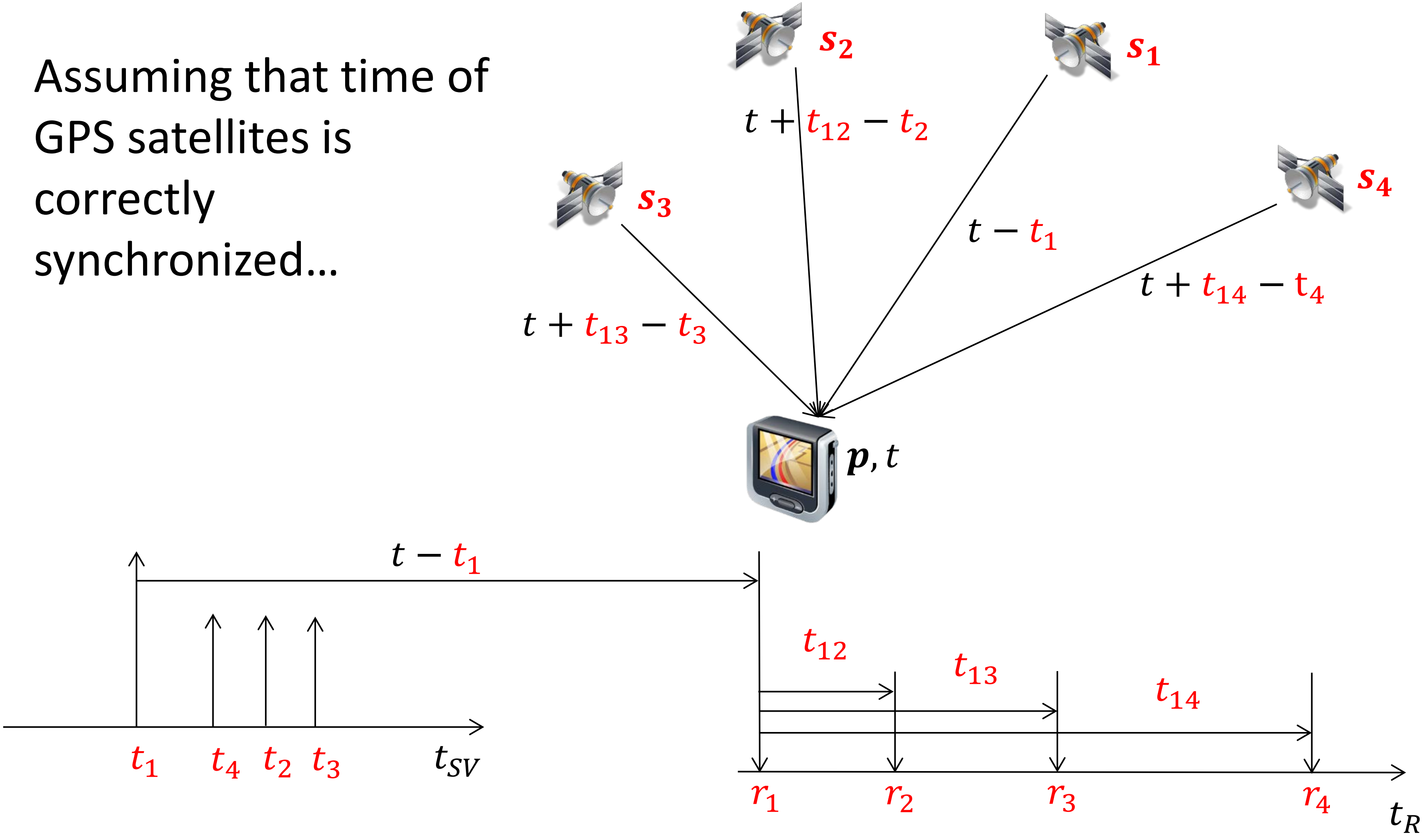
Global Positioning System (GPS)

- Satellites continuously transmit own position and time code
- Line of sight between satellite and receiver required
- Special antenna/receiver hardware required
- Time of flight of GPS signals varies between 64 and 89ms
- Positioning in space and time!

- Which is more accurate,
  GPS or Radio Clock Signal?

GPS Localization

Assuming that time of GPS satellites is correctly synchronized…



GPS Localization

$$\left\|\frac{\boldsymbol{s}_1-\boldsymbol{p}}{c}\right\| = t - t_1$$

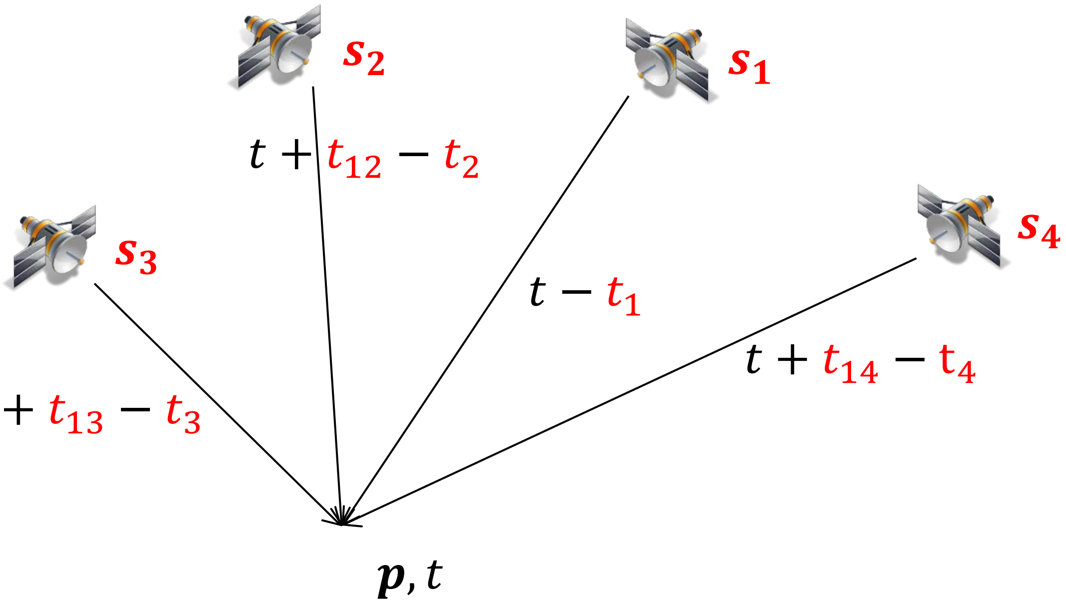
$$\left\|\frac{\boldsymbol{s}_2-\boldsymbol{p}}{c}\right\| = t + t_{12} - t_2$$

$$\left\|\frac{\boldsymbol{s}_3-\boldsymbol{p}}{c}\right\| = t + t_{13} - t_3$$

$$\vdots$$

$$\vdots$$

$$\left\|\frac{\boldsymbol{s}_n-\boldsymbol{p}}{c}\right\| = t + t_{1n} - t_n$$



c = speed of light

Find least squares solution in t and $\boldsymbol{p}$

Keeping GPS Satellites synchronized