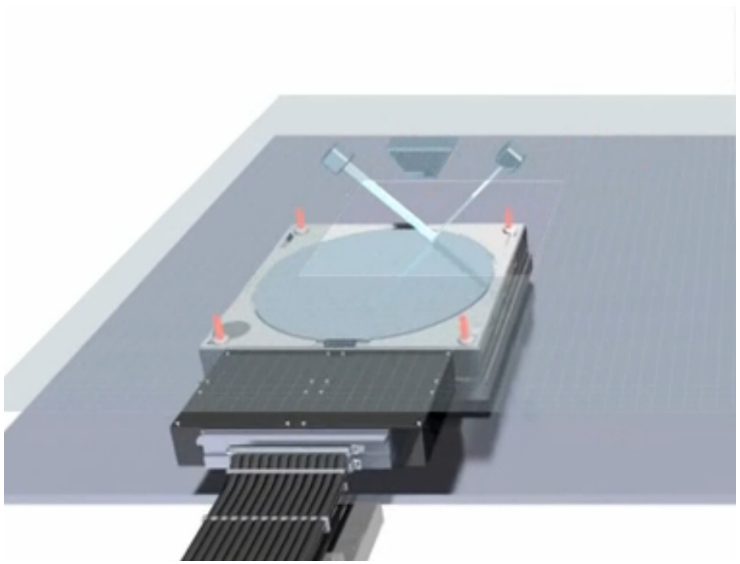
Autonomous Wireless Sensors Inside a Lithography Machine

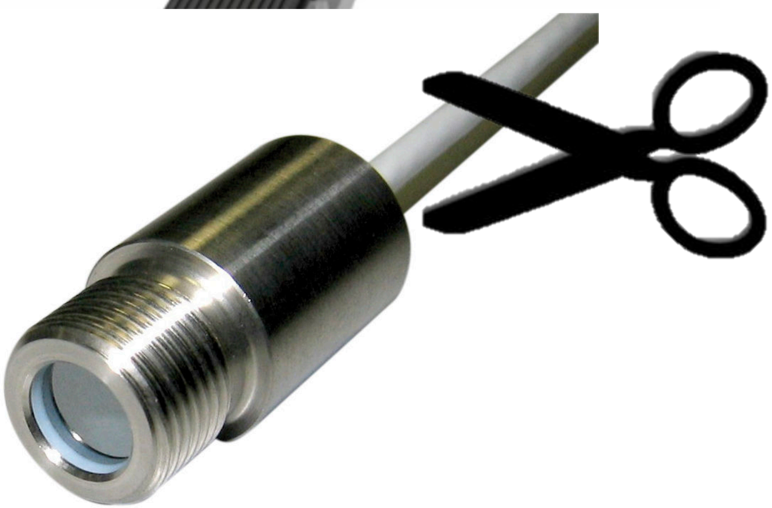
Alle-Jan van der Veen

Based on results of the STW FASTCOM and OLFAR projects by

Sundeep Prabhakar Chepuri, Raj Thilak Rajan, Geert Leus
Circuits and Signals group, TU Delft

Introduction





Current situation

- Sensors connected to communication unit
- Communication unit connected via flatcable to fixed world

Connectors are unreliable, flatcable modifies motion dynamics

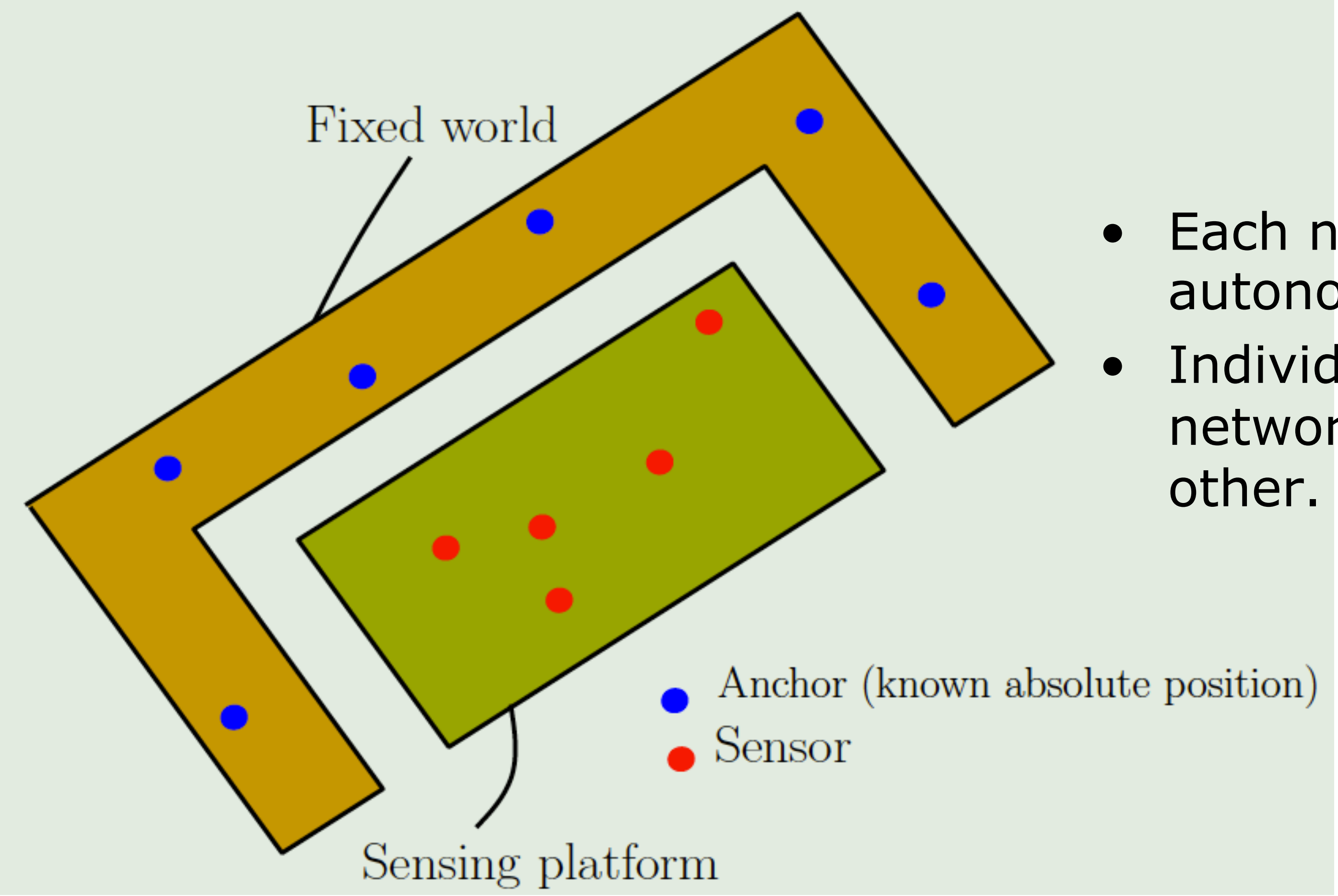
Proposed

Autonomous sensor unit with wireless communication link to fixed world

Challenges

- Synchronization (all sensors to sample at same clock instant)
- High-speed wireless communication in a highly reflective environment

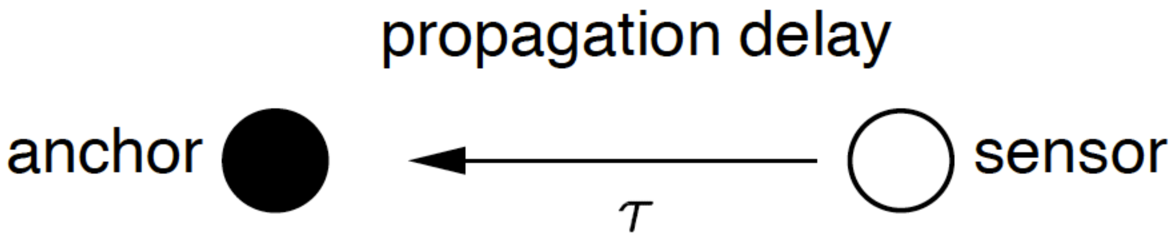
Introduction



- Each node has an autonomous clock.
- Individual clocks in a network drift from each other.

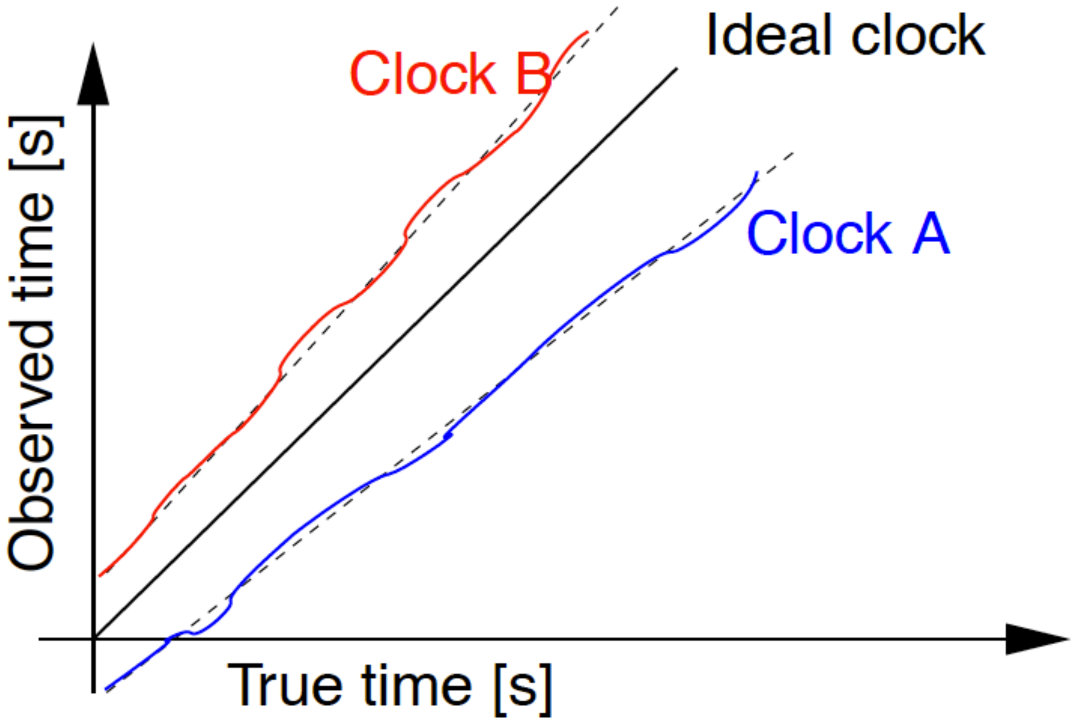
Required: accurate clock synchronization over a wireless network

Wireless synchronization



- For estimating clock offset, we need also to know distance (propagation delay)
- To synchronize clocks, we need two-way communication

Clock model

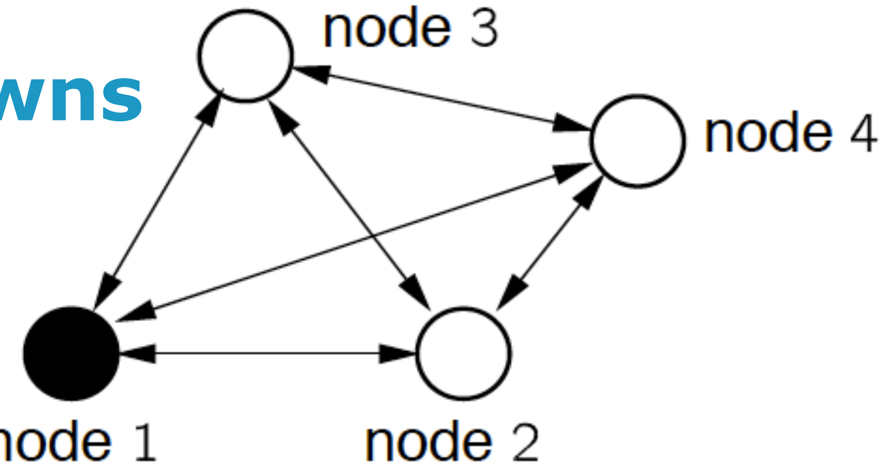


$$t_i = \omega_i t + \phi_i \Leftrightarrow t = \alpha_i t_i + \beta_i$$

skew **offset**

For a reference clock: $\alpha = 1, \beta = 0$

Equations and unknowns



Assume *N* nodes

Unknowns:

- $2N$ clock parameters of all the N nodes
- $2N$ or $3N$ location coordinates for N nodes

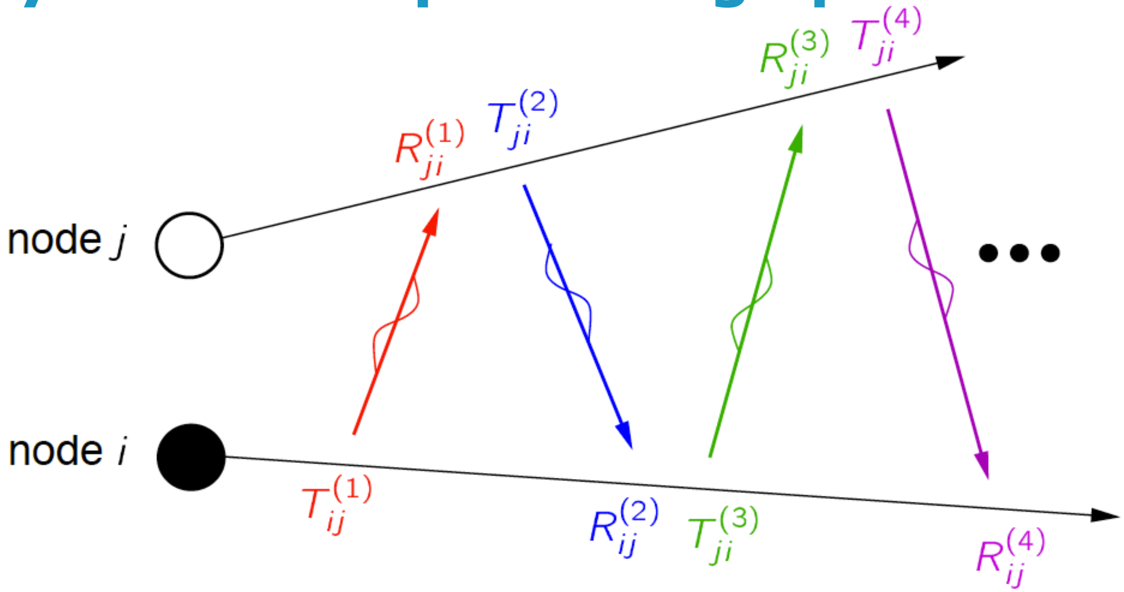
Distance measurements:

- $\binom{N}{2} = \frac{N(N-1)}{2}$ delays $\tau_{i,j}$ over all links
- Repeat K times

Exploiting the network, we can estimate all parameters

The distance equations are nonlinear, but can be linearized by introducing redundant parametrization (2-step approach)

Two-way time-stamp exchange protocol



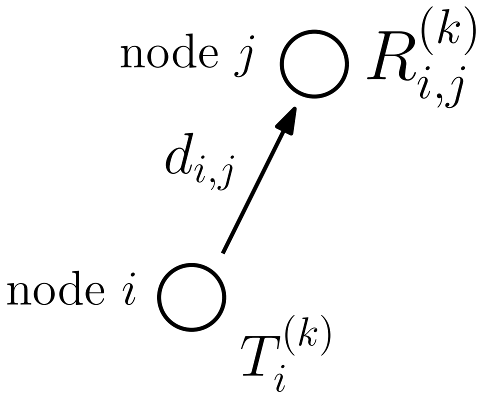
Two-way ranging

- Transmitter time stamp: $T_{ij}^{(k)}$, where k is the message index

  Receiver time stamp: $R_{ji}^{(k)}$

- Traditionally, the time stamps are incorporated in the message and propagated until one node collects them all.

Time stamping



i^{th} node transmits a message and
j^{th} node receives;
both record a time stamp

$$\tau_{i,j} = \frac{d_{i,j}}{c} = (\alpha_j R_{i,j}^{(k)} + \beta_j) - (\alpha_i T_i^{(k)} + \beta_i) + n_{i,j}^{(k)}$$

- *K* such messages (or measurements) can be collected.
- Every link *(i,j)* results in one equation.

- For the transmission from node i to node j:

$$
\begin{aligned}
t^{RX(j)} &= t^{TX(i)} + \tau_{ij} \quad (+\text{noise}) \\
\beta_j R_{ji} + \alpha_j &= \beta_i T_{ij} + \alpha_i + \tau_{ij}
\end{aligned}
$$

- Similarly, for the transmission back from node j to node i:

$$\beta_i R_{ij} + \alpha_i = \beta_j T_{ji} + \alpha_j + \tau_{ji}$$

$$
\begin{bmatrix} T_{ij} & -R_{ji} & 1 & -1 & 1 \\ -R_{ij} & T_{ji} & -1 & 1 & 1 \end{bmatrix}
\begin{bmatrix} \beta_i \\ \beta_j \\ \alpha_i \\ \alpha_j \\ \tau_{ij} \end{bmatrix}
= \begin{bmatrix} 0 \\ 0 \end{bmatrix}
$$

We have 2 equations with 5 unknowns (using $\tau_{ij} = \tau_{ji}$).

Solution: repeat transmissions K times, and use all pairs (i, j).

- E.g., for 3 nodes and 1 transmission per link:

$$
\left[\begin{array}{ccc|ccc|ccc}
T_{12} & -R_{21} & & 1 & -1 & & 1 & & \\
-R_{12} & T_{21} & & -1 & 1 & & 1 & & \\
T_{13} & & -R_{31} & 1 & & -1 & & 1 & \\
-R_{13} & & T_{31} & -1 & & 1 & & 1 & \\
& T_{23} & -R_{32} & & 1 & -1 & & & 1 \\
& -R_{23} & T_{32} & & -1 & 1 & & & 1
\end{array}\right]
\left[\begin{array}{c}
\beta_1 \\ \beta_2 \\ \beta_3 \\ \hline \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \hline \tau_{12} \\ \tau_{13} \\ \tau_{23}
\end{array}\right]
=
\left[\begin{array}{c}
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0
\end{array}\right]
$$

- With K pairwise transmissions, this becomes a $6K \times 9$ matrix equation. Unfortunately it is singular $\cdots$.

To solve it, choose an anchor (node 1): $\beta_1 = 1$, $\alpha_1 = 0$.

Solution for all pairs, K messages

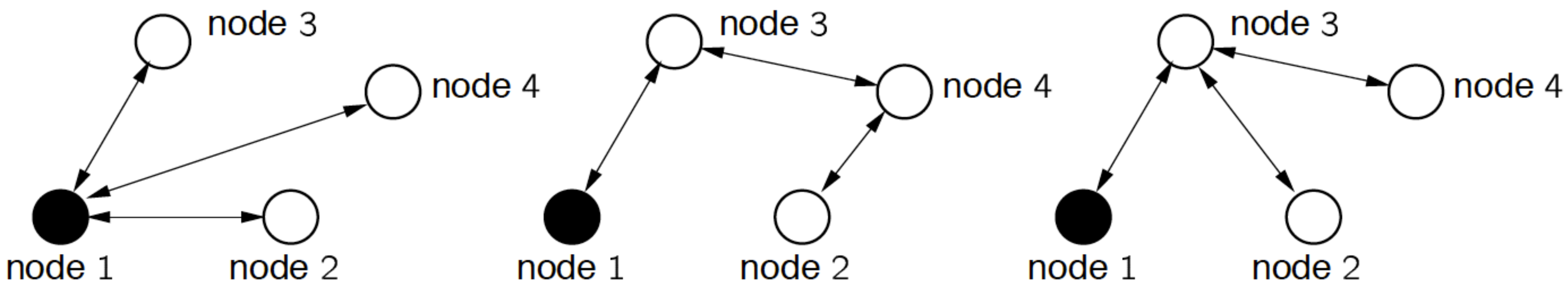
- K pairwise transmissions, all pairs:

$$\left[\begin{array}{cc|cc|ccc} -R_{21} & & -1 & & 1 & & \\ T_{21} & & 1 & & 1 & & \\ & -R_{31} & & -1 & & 1 & \\ & T_{31} & & 1 & & 1 & \\ T_{23} & -R_{32} & 1 & -1 & & & 1 \\ -R_{23} & T_{32} & -1 & 1 & & & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & & \vdots \end{array}\right] \left[\begin{array}{c} \beta_2 \\ \beta_3 \\ \hline \alpha_2 \\ \alpha_3 \\ \hline \tau_{12} \\ \tau_{13} \\ \tau_{23} \end{array}\right] = \left[\begin{array}{c} -T_{12} \\ R_{12} \\ -T_{13} \\ R_{13} \\ 0 \\ 0 \\ \vdots \end{array}\right]$$

- Global Least Squares (GLS) estimate:

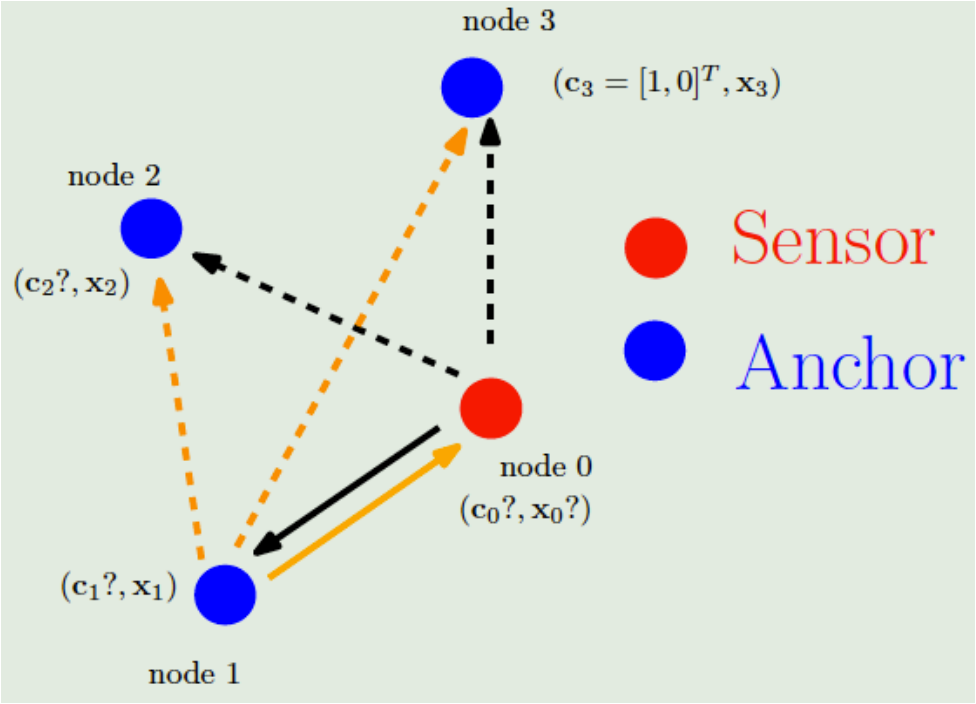
$$\mathbf{A}\theta = \mathbf{t} \qquad \Rightarrow \qquad \hat{\theta} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{t}$$

Missing links



- If certain links are missing, the corresponding rows in **A** are dropped.
- Many links can be dropped before **A** becomes singular!
- Some links could be only one-directional.

Extension 1: Broadcasting (passive listening)

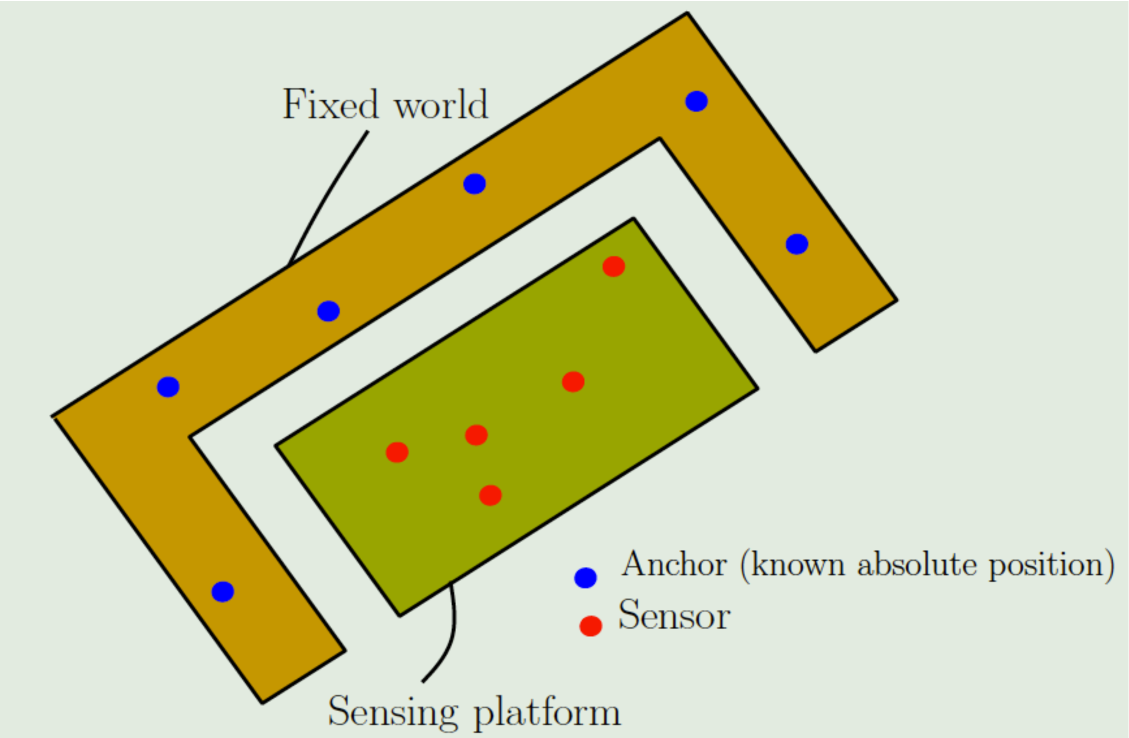


Node 0 transmits to node 1, and node 1 replies back

Other nodes also record the messages with time stamps

This increases the number of equations without sending more messages (order N faster convergence)

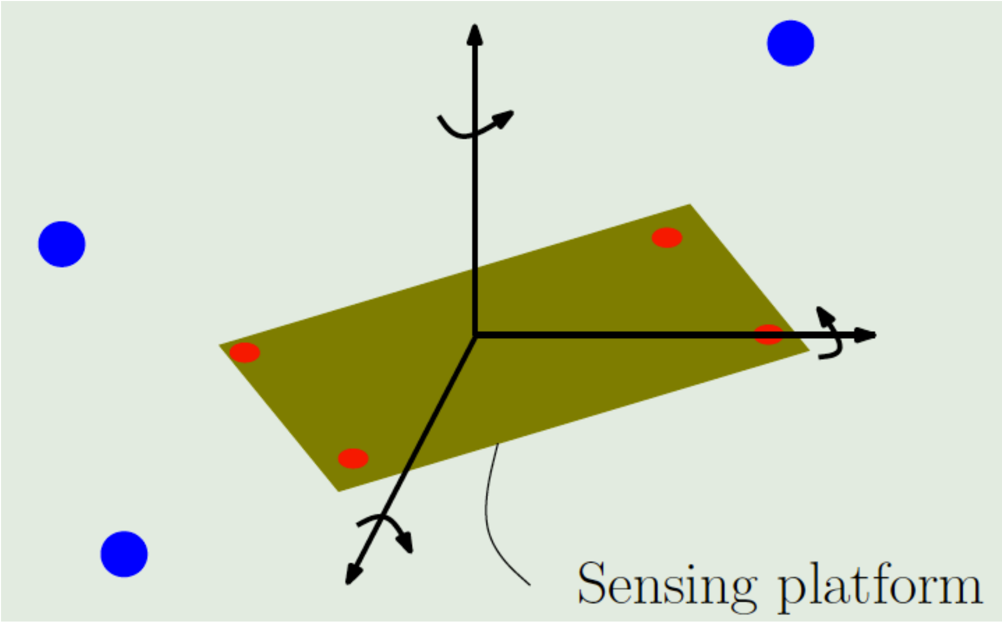
Extension 2: Platform and fixed world



Nodes on the platform have known distances
Nodes in the fixed world also have a common clock

This reduces the number of unknowns

Extension 3: Rigid body parametrization



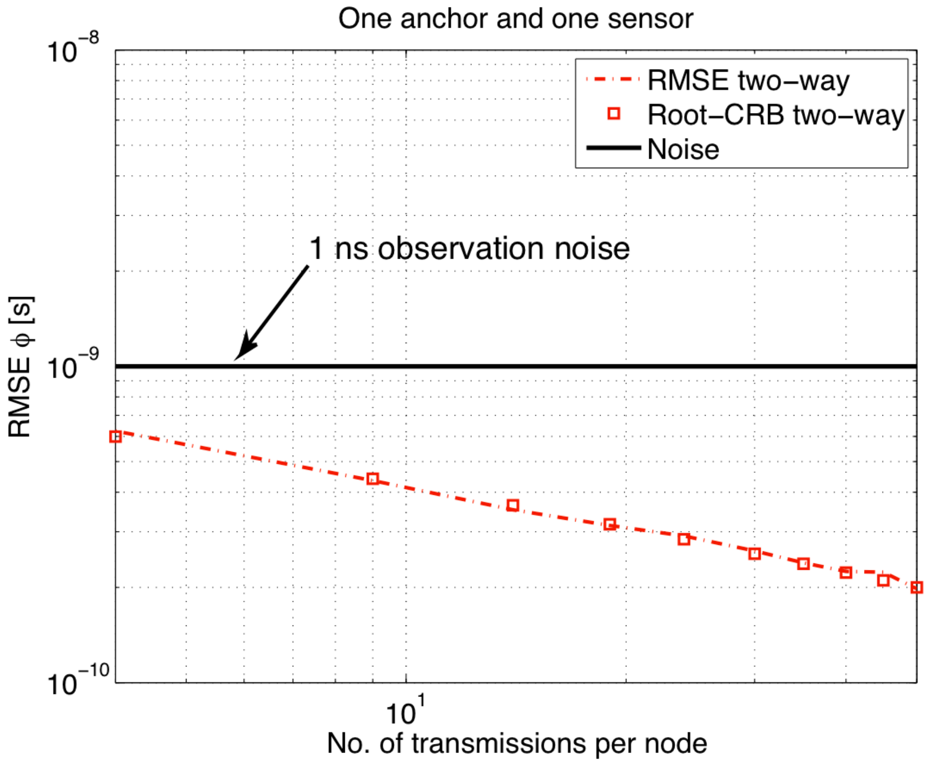
The distances between nodes on the platform and nodes in the fixed world is parametrized by a rotation and translation (position and orientation)

This further reduces the number of unknowns, but the equations become nonlinear. They can be linearized by squaring and introducing some redundancy.

Simulation results (1)

Two nodes (1 sensor, 1 anchor)

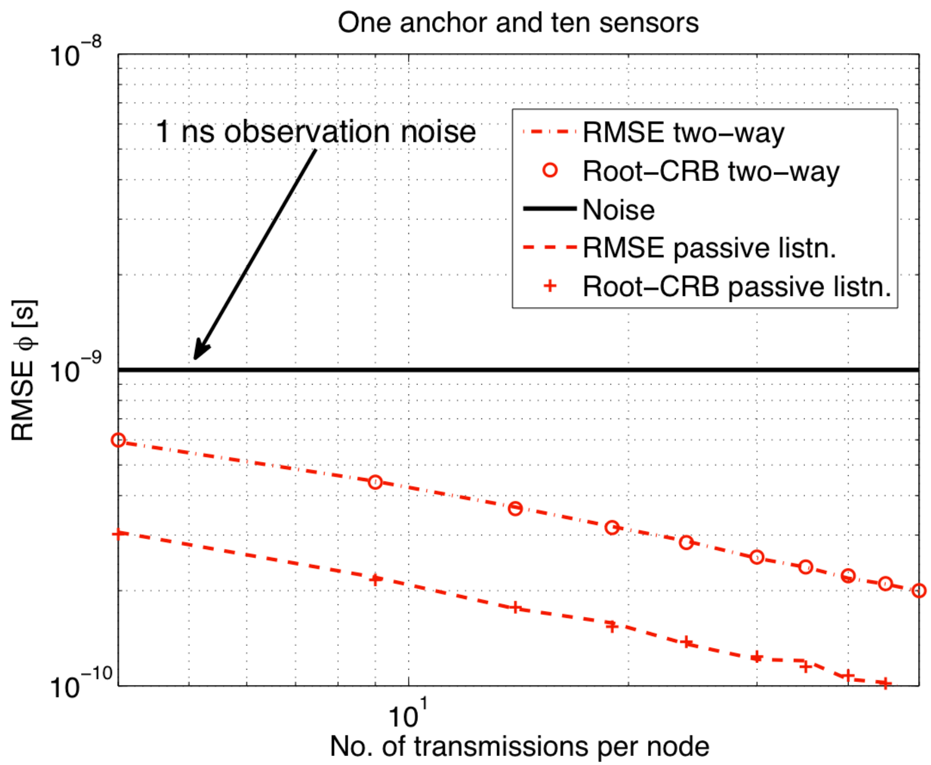
- Time-stamps corrupted by noise with standard deviation 1 ns
- Max range 300 cm
- Observation interval 100 s



Simulation results (2)

Nodes on a platform (10 sensors, 1 anchor)

- Platform 50 * 50 cm; max range 300 cm
- Time-stamp noise has standard deviation of 1 ns.
- Passive listening; known distances on platform



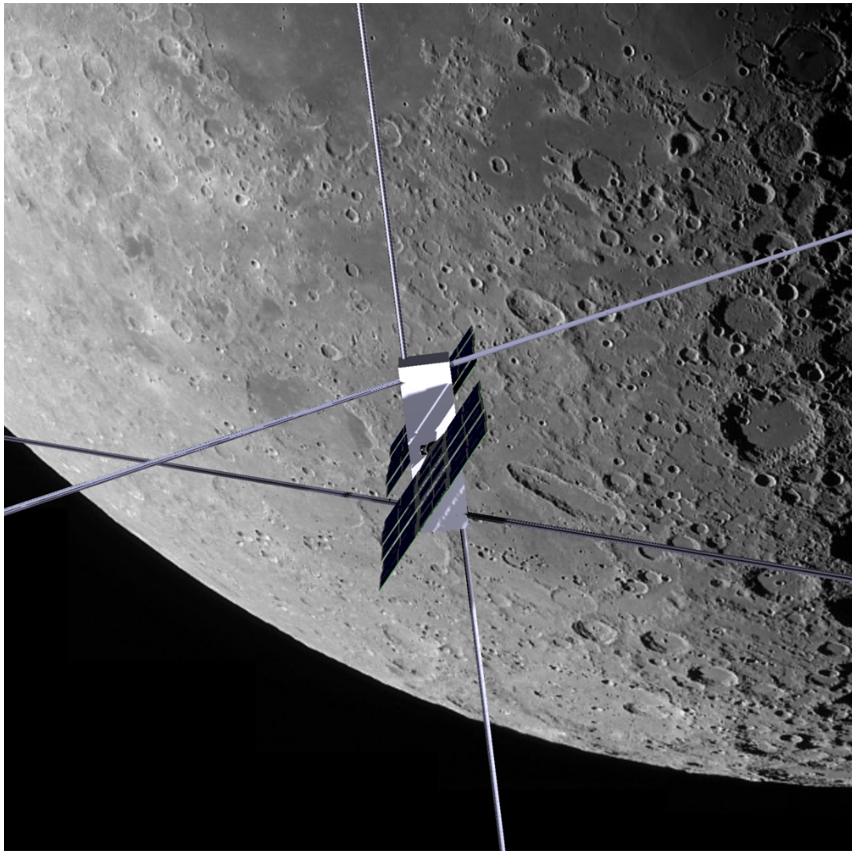
No broadcast

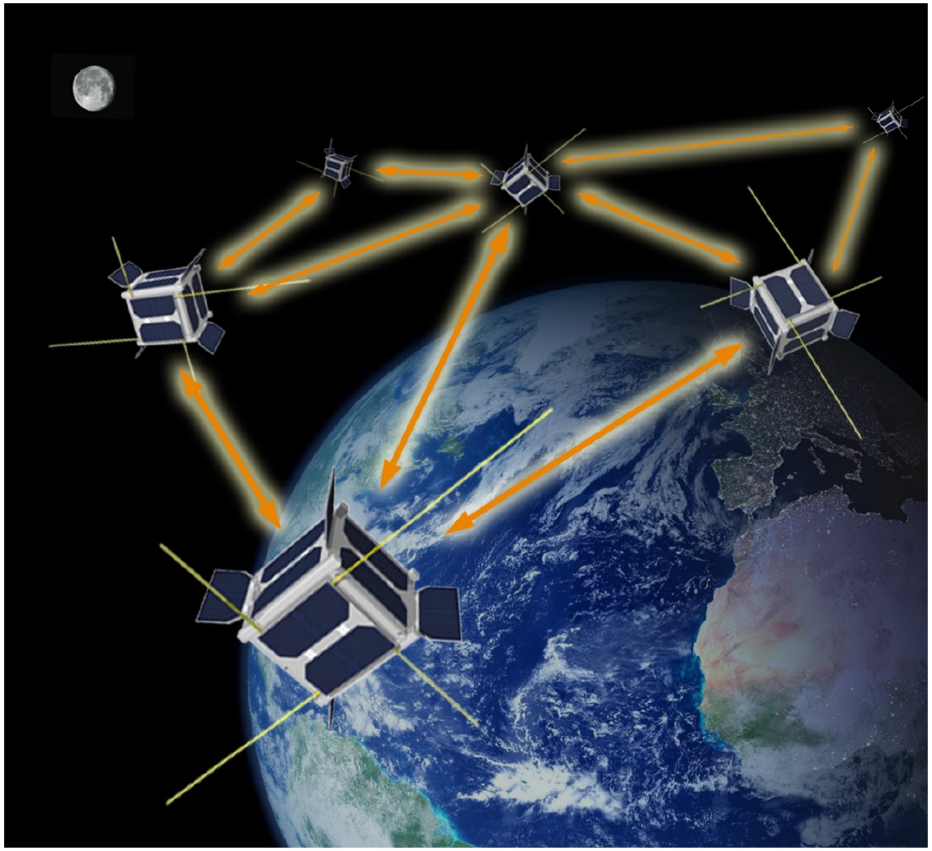
Broadcast

Further extensions

- Introduce a higher-order clock model (e.g. drift)
- Introduce specialized hardware for accurate time-stamping
- Use chip-scale atomic clock (8 ps accuracy; 120 mW)
- Introduce tracking (equations of motion)

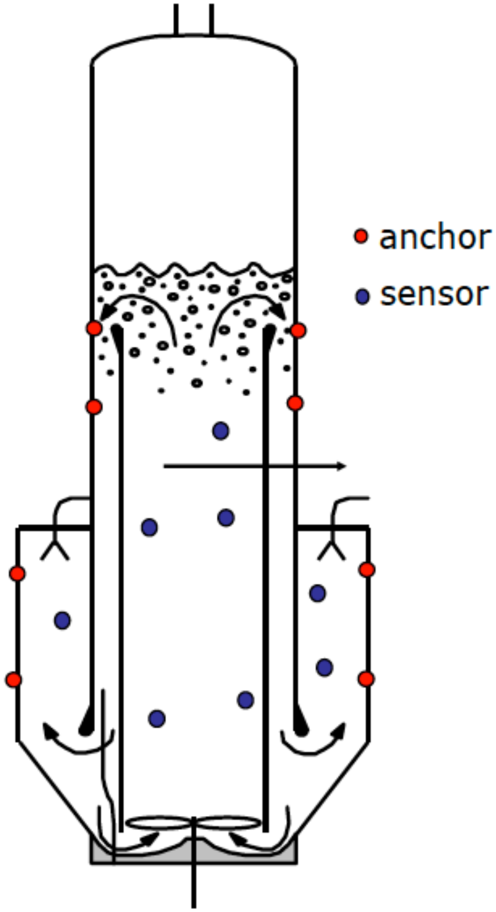
Other applications (1)





(OLFAR) Radio telescope in space

Other applications (2)

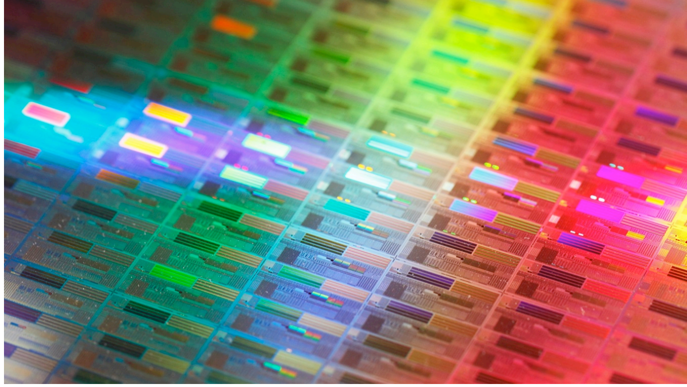


(SmartPEAS) Sensor network for the process industry

Other applications (3)

(HERE) Indoor localization

Conclusions



Joint localization and synchronization is feasible using linear least squares:

- Based on two-way communication
- Accurate with reasonable numerical complexity
- Extensions for tracking
- Extensions for distributed processing

Autonomous sensor nodes function better in a network:

- Exploiting redundancy offered by the links
- Individual clock accuracy improved by order of magnitude (10 nodes, 10 messages/node)