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Low-Power, Sub-Microsecond, Multi-Hop Time Synchronization with COTS Components

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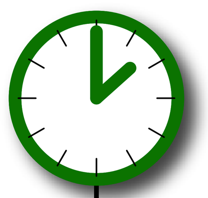
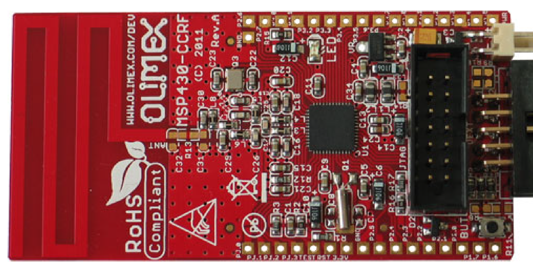
Motivation

Tight time synchronization is needed for applications such as localization or accurate control in distributed systems.

Sub-microsecond time synchronization for a distributed system can be achieved using GPS receivers. For many applications this is not a feasible approach because
(1) GPS receivers are costly, both economically and power-wise, and
(2) they do not work in places without satellite reception, e.g. indoors.

To provide an ***economic solution***, we aim to push the limits of ***state-of-the-art* (> 2 μs)** time synchronization using a ***wireless multi-hop network built of cheap commercial of the shelf (COTS) components***.



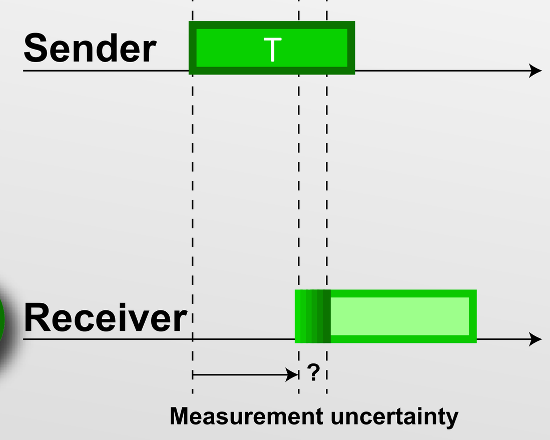


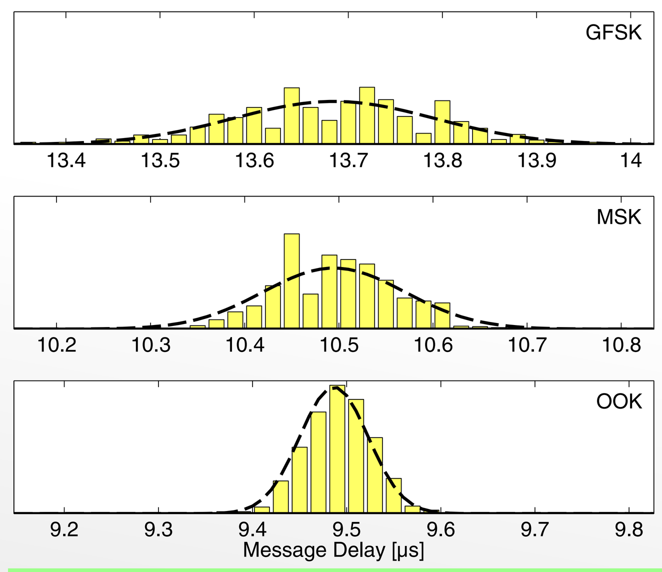
MSP430-CCRF module, providing a CC430 system-on-chip, 13MHz clock, GFSK/MSK/OOK modulation, price ~ 15€

① Impact of Radio Modulation

Errors in time information exchange due to ***measurement errors*** and ***varying channel characteristics***.

Measurement accuracy and packet delay is different for ***different radio modulation techniques***.





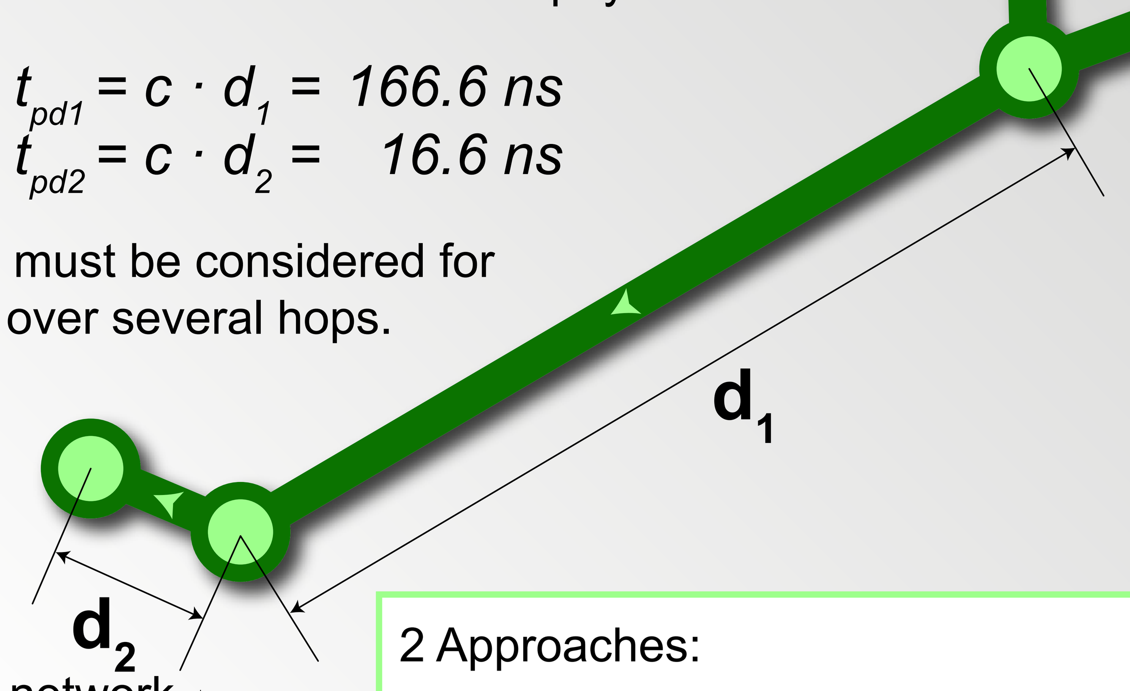
On-off keying (***OOK***) results in smallest measurement uncertainty.
Minimum-shift keying (***MSK***) is beneficial when using concurrent transmissions.

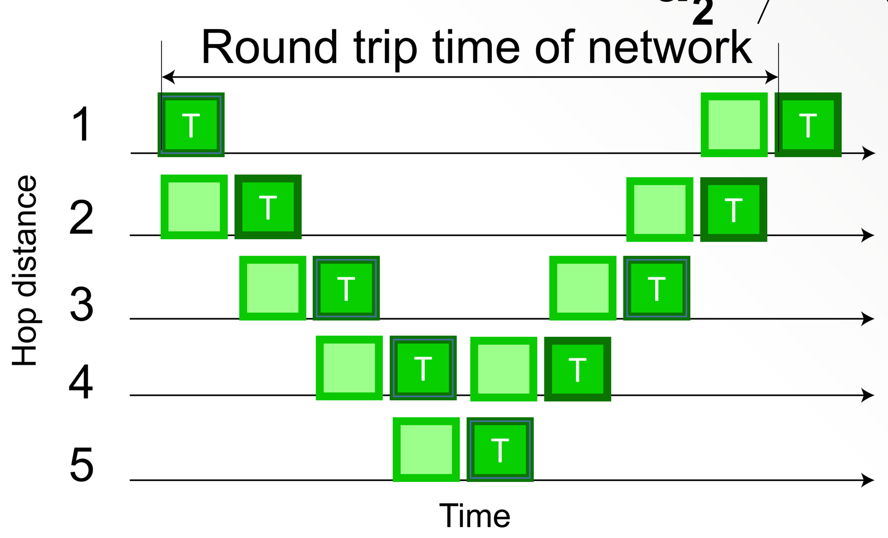
② Impact of Propagation Delay

Electromagnetic waves travel at speed of light. This leads to ***different propagation delays*** t_{pd} between nodes with different physical distances.
Example:

$$d_1 = 50\ m \quad t_{pd1} = c \cdot d_1 = 166.6\ ns$$
$$d_2 = 5\ m \quad t_{pd2} = c \cdot d_2 = 16.6\ ns$$

Varying propagation delays must be considered for sub-microsecond accuracy over several hops.





2 Approaches:

1) Estimate an average propagation delay based on the ***round-trip time of the whole network***.

2) Let nodes learn the propagation delay to neighboring nodes using ***local round-trip measurements***.

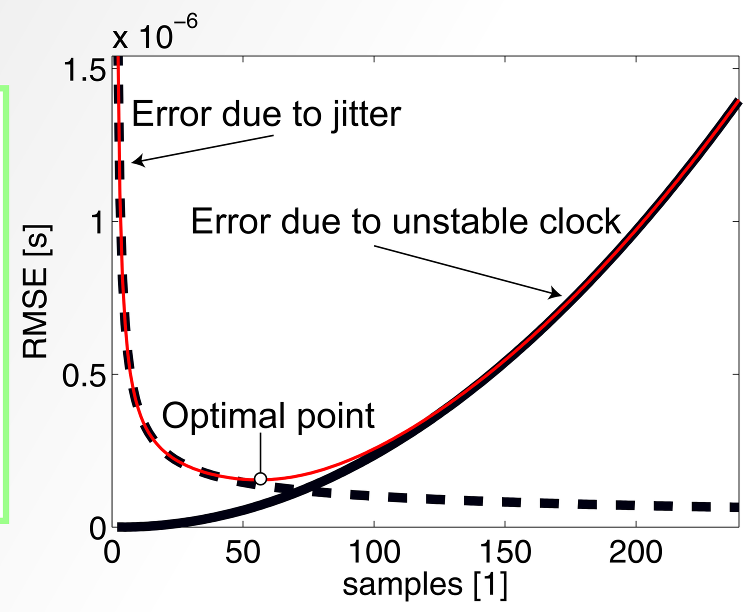
③ Impact of Clock Drift

Different individual clock speeds due to temperature, aging, manufacturing or supply voltages.

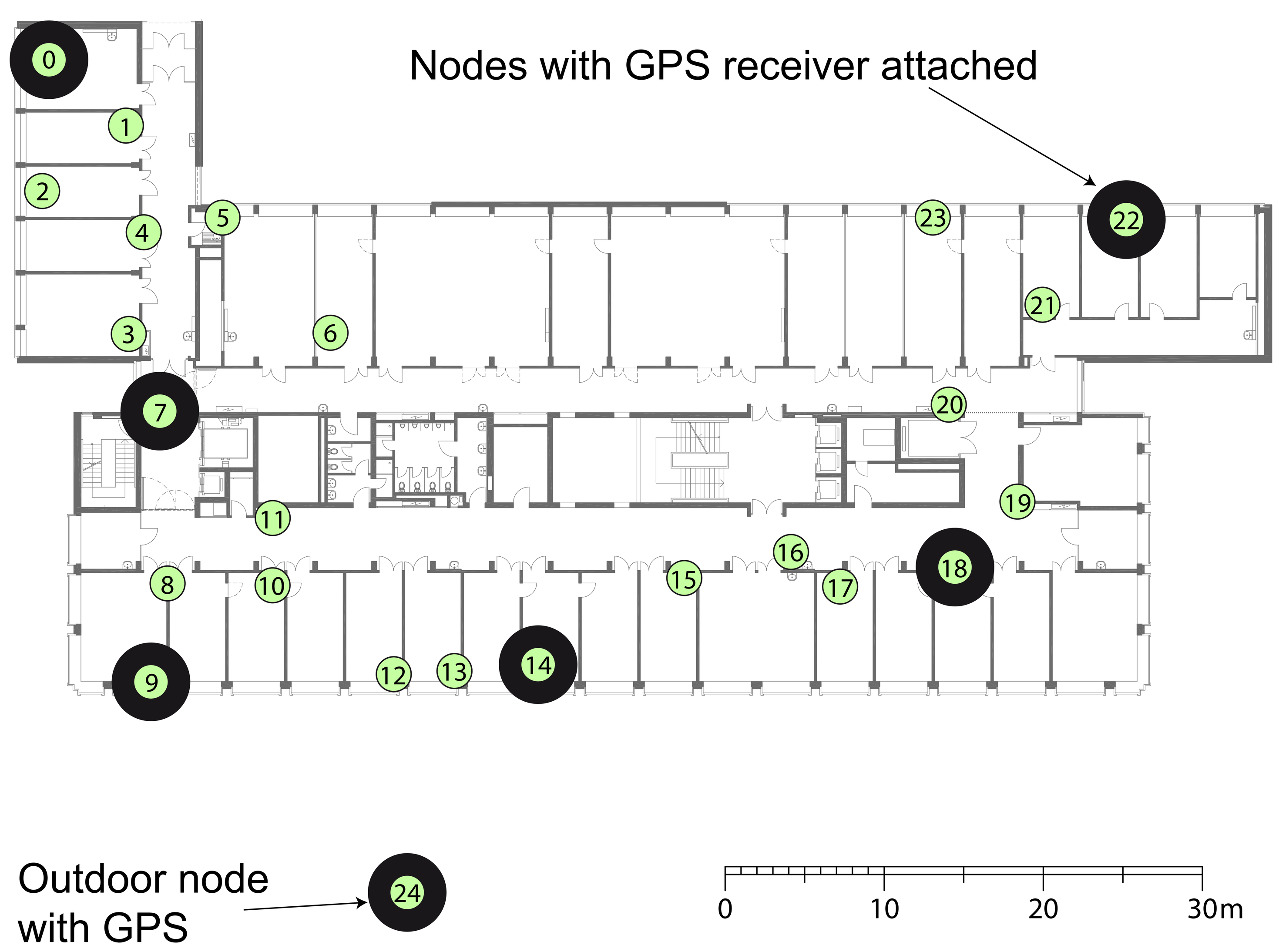
Implications on time synchronization:
(1) Synchronization ***needs to adapt to changing clocks***, e.g., by doing periodic resynchronizations.
(2) Clock drift ***limits the achievable accuracy*** using linear regression.

Larger measurement history
(1) ***reduces error due to jitter***,
(2) ***increases error due to unstable clock***.

Optimal number of measurement samples minimizes overall error.



Evaluation Setup and Results



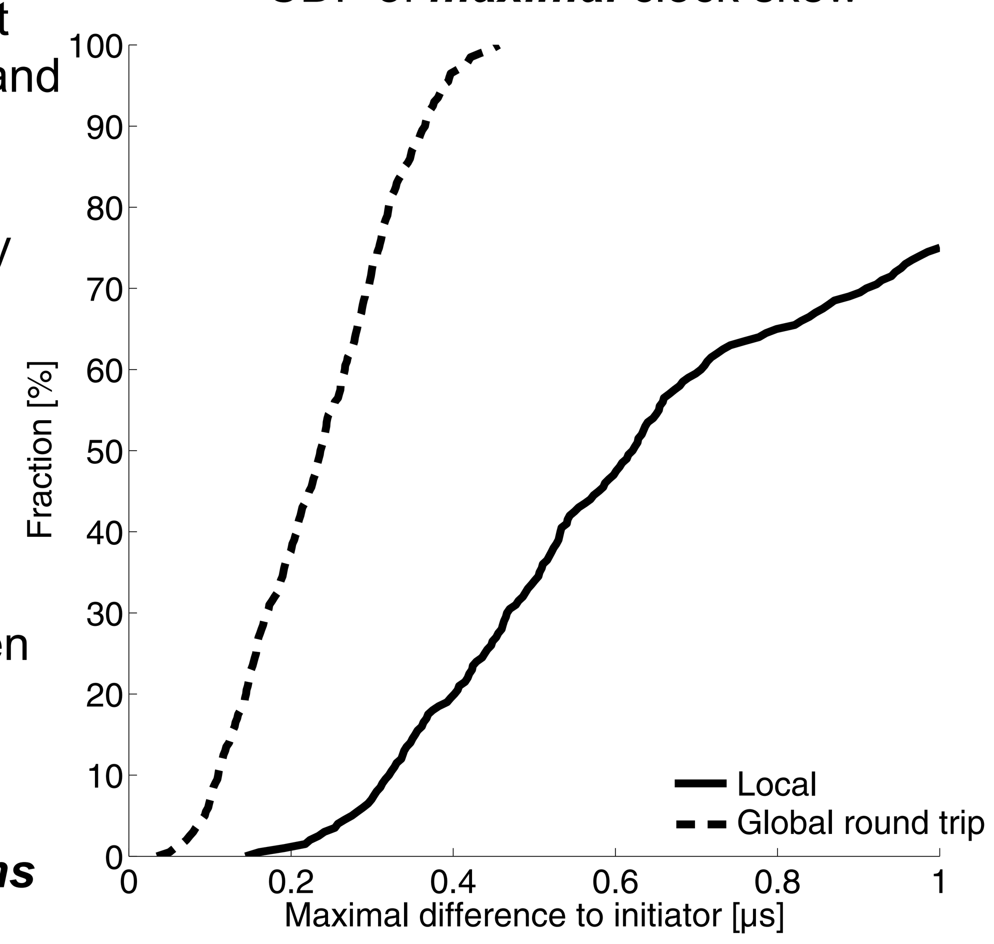
25 nodes spread over an office floor. Two different protocol versions (both using ① ***MSK*** modulation and ③ ***optimal history size***):
1) Locally estimated average propagation delay
2) Globally estimated average propagation delay
Synchronization period of 1 s.

GPS receivers generate reference events at the same time on 7 nodes. Global time stamps of these events are used to determine clock skew.

Evaluation metric: maximal clock skew between ***any*** GPS-node and node 0.

Both protocols achieve low synchronization error, while the ***global round trip estimate outperforms the local estimate by a factor of 3***.

CDF of ***maximal*** clock skew



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TIK Institut für Technische Informatik und Kommunikationsnetze