# Feedforward Temperature Compensation in High-Precison Clock Synchronization Schemes

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# Time deterministic distributed embedded systems

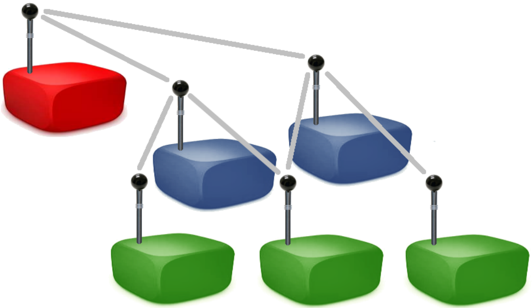
The traditional concept of embedded system is evolving

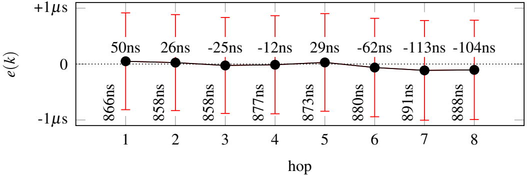
- from isolated systems to *networked* systems
- integration is fostered by long-term research and industry trends
  - Cyber-Physical Systems (CPS)
  - industry 4.0
  - Industrial Internet of Things (IIoT)

New research challenges have emerged

- meet real-time requirements in distributed embedded systems
- achieve robustness despite the unreliability of wireless links
- deal with power limitations of battery operated devices

# Context: FLOPSYNC-2





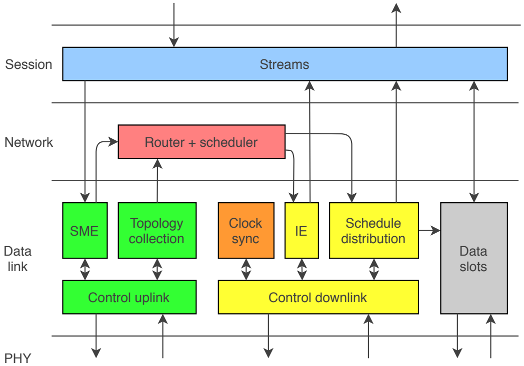
Research challenge:
Improving multi hop master-slave clock synchronization

Key innovations

- approach based on control theory
- high accuracy $< 1\mu$s
- low power overhead
- guaranteed monotonic clock

FLOPSYNC-2: efficient monotonic clock synchronisation
2014 IEEE Real-Time Systems Symposium (RTSS) `10.1109/RTSS.2014.14`

# Context: The real-time mesh networking stack TDMH



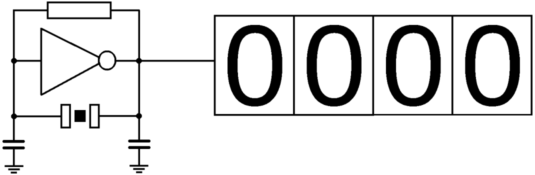
Research challenge:
Real-time mesh protocol stack

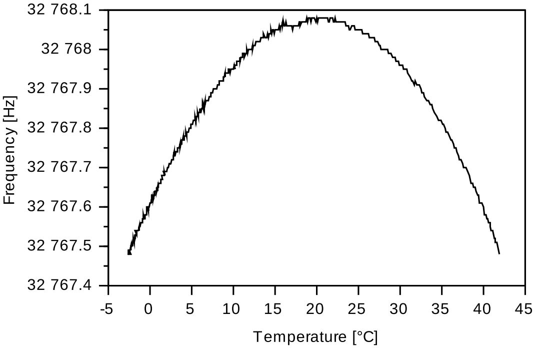
Key innovations

- distributed algorithm for on-line topology collection
- guaranteed end-to-end latency
- efficient schedule dissemination using constructive interference

TDMH-MAC: Real-Time and Multi-hop in the Same Wireless MAC
2018 IEEE Real-Time Systems Symposium (RTSS) `10.1109/RTSS.2018.00044`

# Temperature-dependence of clocks





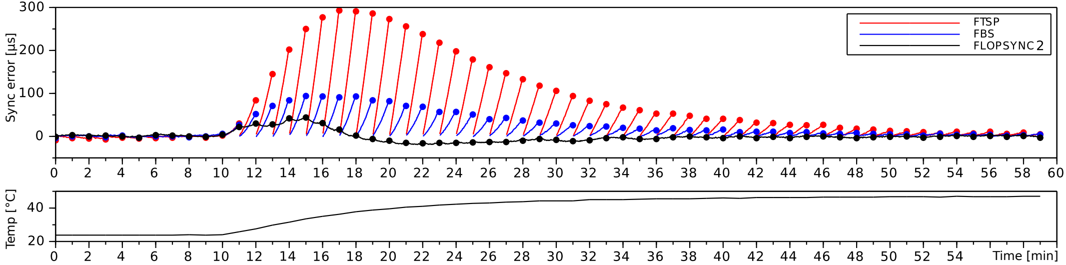
Clocks in computer systems are implemented as

- a quartz crystal oscillator
- driving a hardware counter

The frequency of quartz crystals depends on the operating temperature.

- A 0.5Hz change in a 32KHz xtal causes a 150us clock sync error in just 10 seconds.

# Effect of temperature variations on clock synchronization schemes



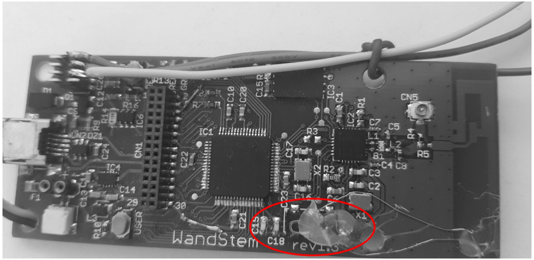
In **feedback**-based clock synchronization

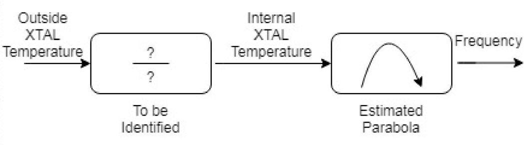
- clock error occurs during temperature *transients*
- some schemes are better than other

**Feedback**-based clock synchronization exhibit a tradeoff between

- the maximum clock error during a temperature transient
- the synchronization period

# Feedforward temperature compensation



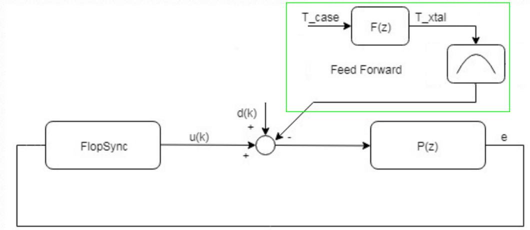


We added a *temperature sensor* in close proximity of the quartz crystal.

We designed and calibrated a *temperature to frequency* model, taking into account

- the heat diffusion into the crystal package
- the parabolic temperature-frequency curve of low power crystals

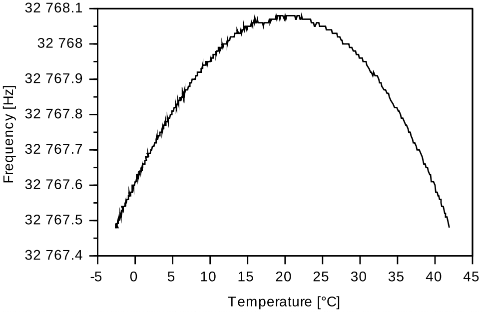
# Flopsync integration

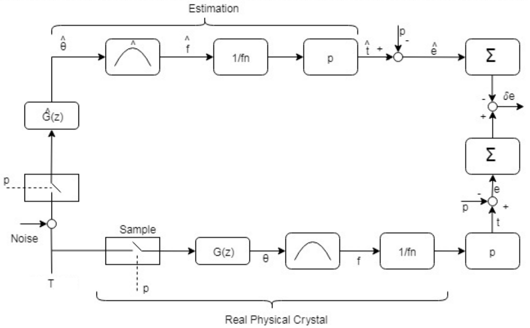


The feedforward temperature compensator is integrated with the FLOPSYNC-2 clock synchronization scheme.

This solution has several advantages

- retains the high accuracy of FLOPSYNC-2
- feedforward compensation period can be faster
  - keep number of sync packets low
  - compensate temperature in between sync periods

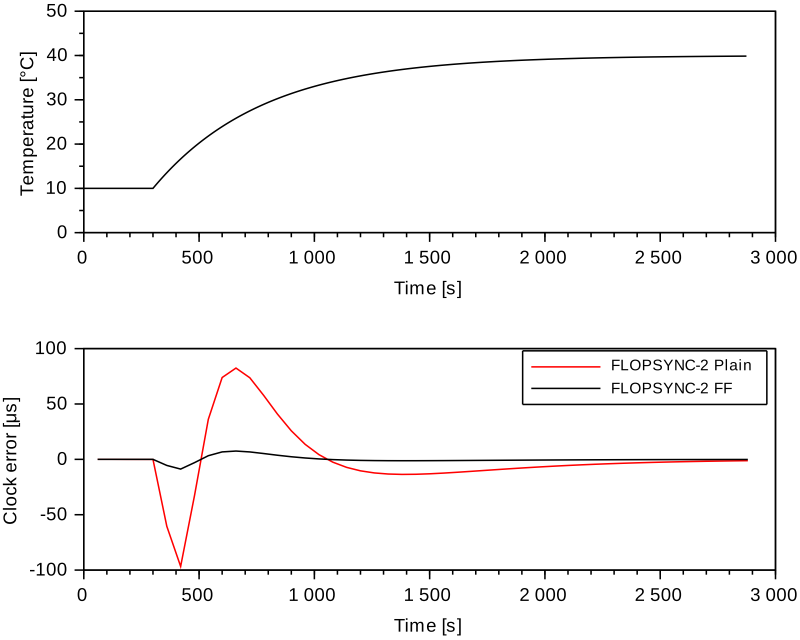




- The temperature to frequency model has been identified from experimental data.
- To date, however, the control scheme has been only tested in simulation.

The simulated ambient temperature is fed to two different paths

- one simulating the actual crystal temperature and frequency
- one simulating the estimated one
    - Measurement noise and model mismatch can be introduced


50
40
30
20
10
0
Temperature [°C]
0
500
1 000
1 500
2 000
2 500
3 000
Time [s]
100
50
0
-50
-100
Clock error [µs]
FLOPSYNC-2 Plain
FLOPSYNC-2 FF
0
500
1 000
1 500
2 000
2 500
3 000
Time [s]

A feedforward temperature compensation scheme has been designed to improve clock synchronization

- integrates seamlessly with FLOPSYNC-2
- improves clock synchronization during abrupt temperature changes
- allows to lengthen synchronization period for a given accuracy

Future work include testing its performance an a real sensor network.

Thank you

Questions?