**XCT: Crystal Compensated Timer for Low-cost, Low-drift Clocks**

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**Introduction: Time, Clocks, and Time Synchronization**

- **Definition of the Second as by NIST**
  - The second is the duration of 9'192'631'770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom.

- **Clocks**
  - Clocks come in different shapes and technologies, like the mechanical human readable clocks in watches. But most of the clocks can’t be seen and are in digital devices. They usually use a crystal, or other oscillatory circuits to generate their clock signal that make them work.

- **Time Synchronization**
  - Time synchronization is an essential service in embedded wireless networked sensing and control systems. It is used to enable tasks such as synchronized data sampling and accurate time-of-flight estimation, which can be used to locate nodes.

**Sources of Errors**

- **Local Clock Source**
  - The local clock source is the major source of error in a distributed system that needs time synchronization. If every device had an atomic clock, time synchronization would be easy. But they are too costly and energy hungry, and thus quantization effects, environmentally induced drifts, and aging play a major role in clock inaccuracies.

- **Other Errors**
  - Other errors in the time synchronization process are the time of flight of the communication channel, computational latencies (interrupts, algorithm calculations, etc), and the time stamping accuracy of a certain platform. One can not ignore these errors if one wants to design a highly accurate time synchronization

**Problem Description: Improvements for the Local Clock Stability**

- **The local clock is usually a hardware counter**
  - The hardware counter can be periodically updated by some system clock that runs at rate \( f_0 \) Hz, incrementing the counter every \( 1/f_0 \) seconds.

- **The counter reads \( c(t) = (f_0 * t + \text{mod } 2^m) \)**
  - The accuracy with which we can measure time depends on how accurately we know the rate \( f_0 \).

- **We want to minimize the drift from a reference frequency \( f_0 \)**
  - The frequency drift can be modeled as \( \delta f = \delta f_{\text{drift}} + \delta f_{\text{stabilized}}(T) \)

- **Our goal is to decrease \( \delta f_{\text{drift}} \) and \( \delta f_{\text{stabilized}}(T) \) to improve the overall frequency drift**

**Proposed Solution: Differential Drift and the Crystal Compensated Timer (XCT)**

**Theory / Simulation**

![Typical frequency drift vs. temperature curves for multiple AT-cut crystals. The crystals are cut at an angle of 35°20’0”. Our algorithm exploits this difference by measuring \( \delta C_{12} \) and thus calculating the correction term learnt in the initial calibration \( \delta C_{10} \).](http://nesl.ee.ucla.edu)

- Different crystals with different cuts result in different calibration curves.
- The flatter the calibration curve in the graph on the right hand side, the more accuracy we can achieve while compensating.
- The difference between the drifts vs. temperature is linear.

**Hardware Implementation**

- **Calibration Setup**
  - While calibrating, the platform is subjected to a temperature swing from -10°C to 60°C.
  - We measure \( \delta C_{10} \) and \( \delta C_{12} \) to generate the calibration curve.
  - The data shown on the right was collected from two 8MHz crystals from two different manufacturers.

- **Compensation Algorithm**
  - We subject the prototype to multiple temperature swings from -10°C to 60°C while compensating for the clock drift.
  - We achieve a mean stability of 0.47ppm with a sample standard deviation of 0.31ppm.

The prototype platform consists of a stock TMote sky from Sentilla (former MotelIV). We removed the standard 32kHz crystal and added a small PCB to hold the two 8MHz crystals.

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