Accurate wireless temperature measurements using passive SAW sensors and a frequency modulation interrogation approach

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Summary

• Forewords
• Resonator-based sensors
  – Typical feature of a SAW resonator
  – Practical configurations
• Interrogation system
  – Basic architectures
  – A software-controlled general purpose platform
  – Accuracy issues
  – « Phase-locking » approaches
  – Ultimate resolution
  – Active oscillator-based measurement system
• Conclusion
Wireless interrogation of passive sensors

- First paper by X. Bao, Burkhard, Varadans', describes the basic idea in 1987
- Siemens engaged work in that field, yielding first patents in 1995 (source Esp@cenet)
- Transense enters the competition in 2000 and propose advanced strategies for interrogating resonator-based sensor for pressure and torque (2001, source Esp@cenet)
- CTR, SENSeOR, senTec-Elektronik, RSSI, Sengenuity, Sensor Technology and many other actors are now contributing to the activity
Two basic approaches

**Resonators (IIF)**

![Resonator diagram](image)

(Courtesy of SENSEOR)

**Reflective delay lines:**

**Tags (FIR)**

![Reflective delay line diagram](image)

(Courtesy of V. Plesski, GVR)
SAW resonators

Single-port resonator

Two-port resonator

[Graphs showing frequency response for SAW resonators]
Various SAWR designs

- Tapered synchronous resonator
  - Synchronous resonators operate at the edge of the stopband
  - Tapering the transducer reduces lateral mode contributions
  - Asynchronous resonators (a/p or p) force resonance within the stopband
  - Adding an extra λ/4 propagation path yields middle-of-the-band resonance for non directive resonators
  - Combining all these features yields resonator optimization

- Hiccup resonator
Sensor architectures
2 SAW on Chip – 2 chips in a package

Typical response

Sensor Characterization
- Electrical admittance
- Frequency/temperature laws

(SENSeOR products)
Temperature-pressure sensor

SAW temperature-pressure sensor

SAW in ISM band: \( 433.05 < f < 434.79 \) MHz
Pressure range: 0 – 20 Bars
controlled by the membrane dimensions
SENSeOR Wireless system

Interrogation signal

Antenna

SAW sensor

Interrogator

Sensor response
A software-controlled system allowing for various interrogation strategy
in the 434 MHz – centered ISM band
Micro-controller: AduC 7026, ARM7-core-based technology
Basic scanning operation

128-point frequency scan chronogram
• The presented principle allows for temperature measurement by simply detecting the curve maxima using a fix scanning comb approach
  - Advantage :
    • Process very easy to implement
  - Flaws :
    • Inaccuracy due to the lack of coincidence of the measured max and the actual resonance peak
    • Delay of spectrum scan : $128 \times (Q/\pi) \times \tau \approx 5.76 \text{ms}$

• A first improvement approach : fitting the max by a quadratic function and defining the actual max value solving a second degree polynomia
Parabolic fit: principle

Fundaments

SAW conductance near the resonance well represented by a Lorentzian law

A parabolic function reliably fits the conductance max

The fit process can be fastly achieved using integer-based coding

Computation needs a minimum calculation resources

\[ f_0 = f_2 + \frac{\Delta f}{2} \times \frac{(s_1 - s_3)}{(s_1 + s_3 - 2 \times s_2)} \]
Application of the 3-point method to a 2-resonator temperature sensor
Tracking mode

Questioning ISM band
The magnitude answer

Parabolic fit approximation

f_0

F_{start} = f_0 - 1 \text{ step}
F_{stop} = f_0 + 1 \text{ step}

Feedback control

F_0

16 Averages

Variance

Rejected measurement

Accepted frequency measurement
5.76 ms for initialization
60 µs/point – 360µs for 2 resonances
An accuracy of 100 Hz is achieved for only 1 measurement
The stability increases along measurement delay
This reduces to 3 Hz when averaging 1000 samples
Modulation interrogation:
Detection of the frequency modulation change from \( \omega \) to \( 2\omega \) at SAW resonance
Scanning the contribution at modulation frequency $\omega$

Efficiency of the approach depends on the amplitude and frequency of the modulation.
Exploitation of the approach for phase-locking
Stability in wireless and wired configurations

(a) Stability in wireless configurations using different methods:
- Fixed Frequency Comb Method
- FM Method

(b) Stability in wired configurations:
- FM Feedback Loop
- Time constant / 2

Frequency excursion (Hz) vs. frequency (Hz)
Powered solutions

Test-Oscillator

Frequency reference

Frequency counter

0100
1110
0111

Wireless protocol

Zigbee transmitter

Computer receiving data

Zigbee receptor
Colpitts-based oscillator

Ultimate accuracy given by the oscillator stability
Phase noise below 150 dBc/Hz
Short term stability $1.5 \times 10^{-9}$ over 1 s yields sub Hz resolution, hence µK-range temperature accuracy
FPGA-based Counter

Armadeus card

128 samples/s

synthesizer
50 MHz
10 MHz

Quartz
30 MHz
clock to mesure

HP53131A
reference clock
clock to mesure

FPGA-based frequency counter stability (53131A)

AlaVar 5.2
Allan STD DEV

σ(τ)

HP frequency counter stability (53131A)
Final implementation

Oscillator + FPGA counter + Zigbee emitter

Zigbee Receiver

Interrogation distance > 30 m have been tested, 100 m achievable in theory
Conclusions

• Development of new strategies for wireless interrogation
  – Using a software-based electronics allows for implementing numerous approaches
  – Fix-comb approaches allow for accuracy in the 500 Hz at 434 MHz
  – 3-point approaches yields improved frequency resolution (100 Hz and less when averaging) as well as the system passband (measurement delay ~200µs for a 2-resonator sensor)
  – Phase-locking has been developed for reaching ultimate sensitivity provided the sensor is continuously interrogable but needs longer delays
  – Wired-powered solutions allows very large distance with coding
Applications challenges

- In-motion measurements
  - Reaching such accuracy for sensors fixed to moving parts with very high linear/rotation velocities

- Large band-width operation
  - For monitoring fast processes such as stress evolution at frequencies above 5 kHz

- Ultimate operation conditions
  - Maintaining the obtained resolution when the reader faces extreme temperature/vibration/magnetic environments