SAW Symposium 2010
Wireless Surface Acoustic Wave Sensor Symposium
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Accurate wireless temperature measurements using passive SAW sensors and a frequency modulation interrogation approach

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Summary

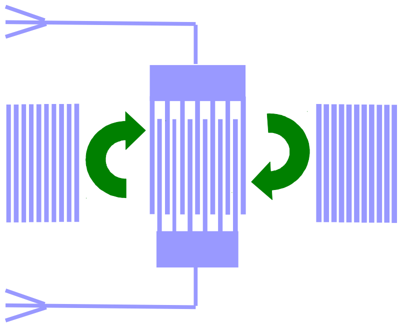
- **Forewords**
- **Resonator-based sensors**
  - Typical feature of a SAW resonator
  - Practical configurations
- **Interrogation system**
  - Basic architectures
  - A software-controlled general purpose platform
  - Accuracy issues
  - « Phase-locking » approaches
  - Ultimate resolution
  - Active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

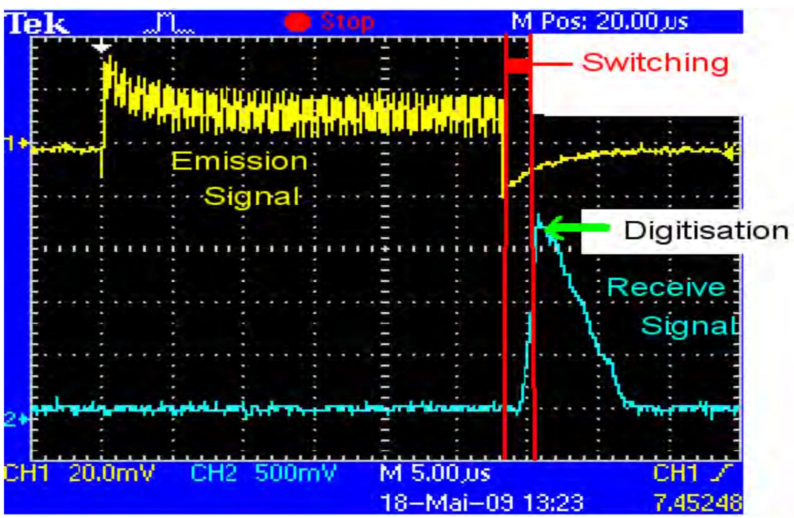
Wireless interrogation of passive sensors

- 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

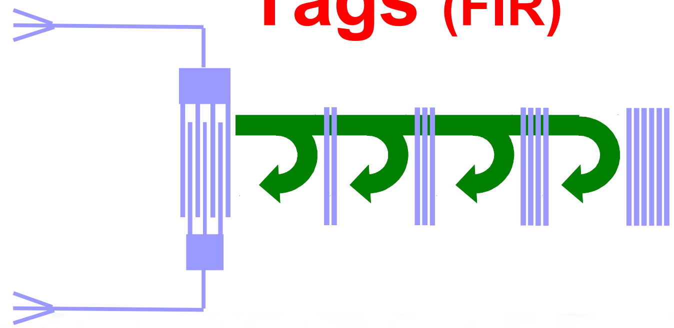
Resonators (IIF)

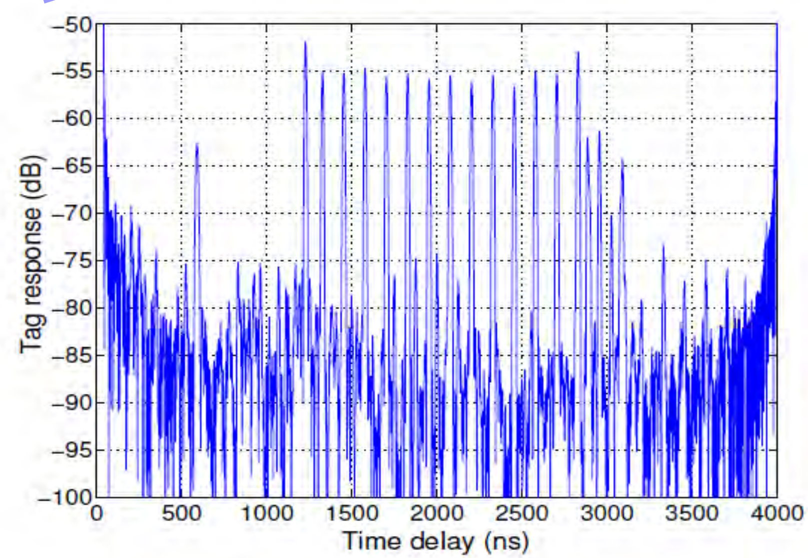




(Courtesy of SENSeOR)

Reflective delay lines : Tags (FIR)

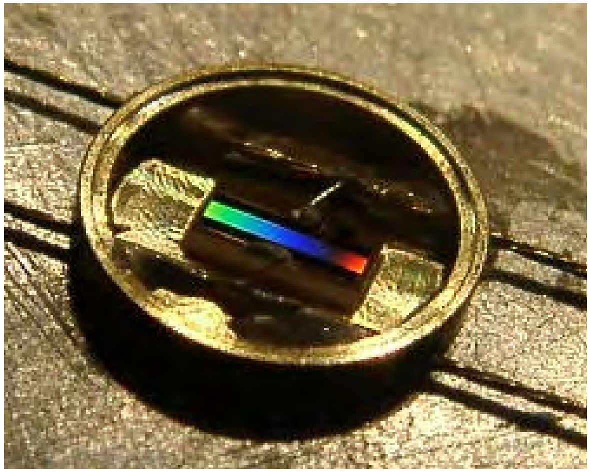


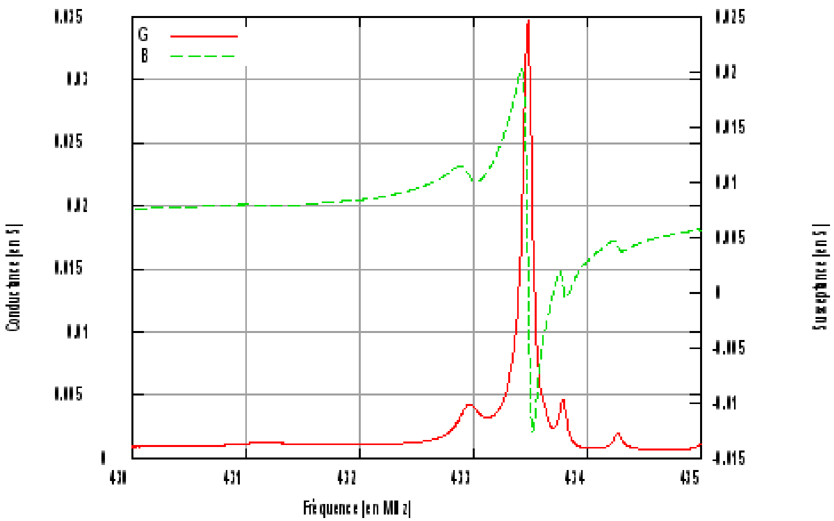


(Courtesy of V. Plesski, GVR)

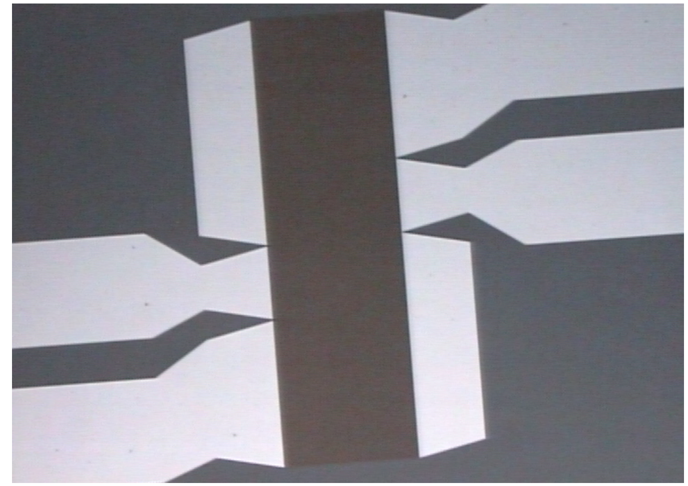
SAW resonators

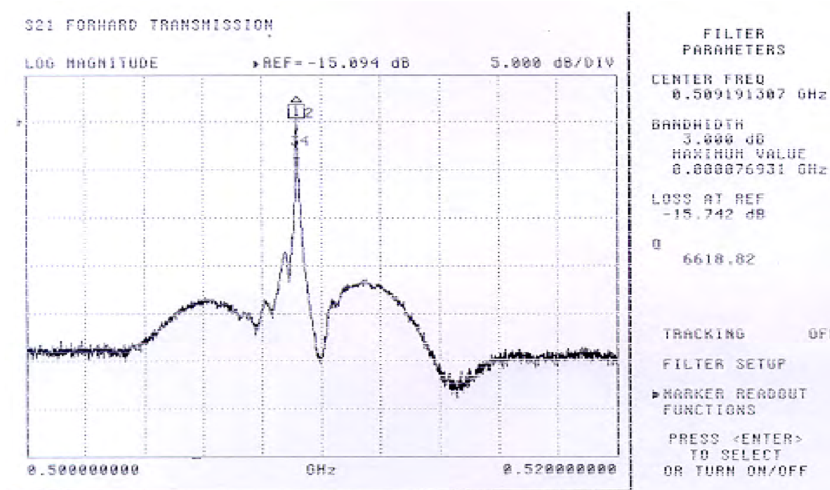
Single-port resonator



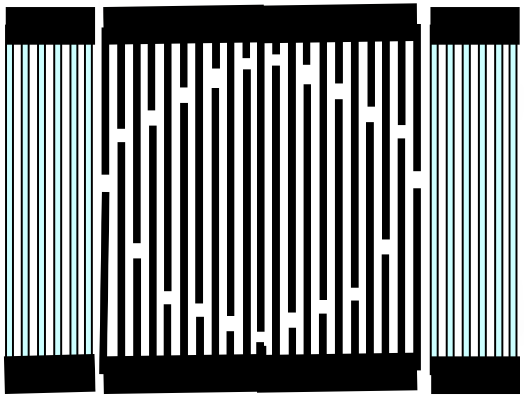


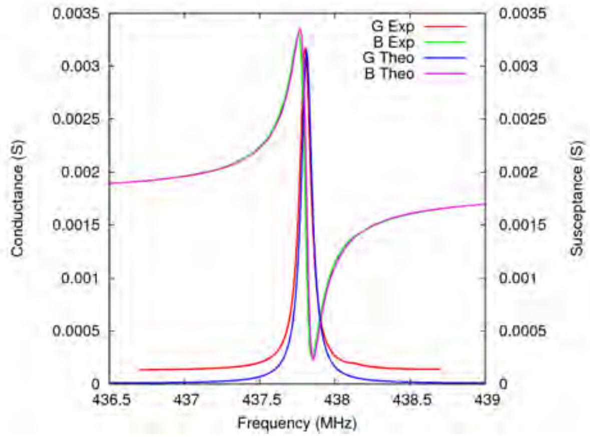
Two-port resonator

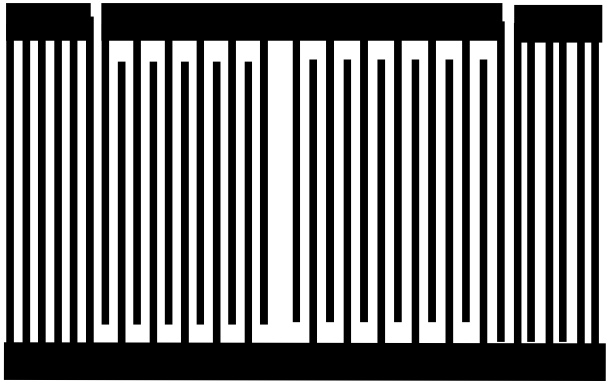




Various SAWR designs

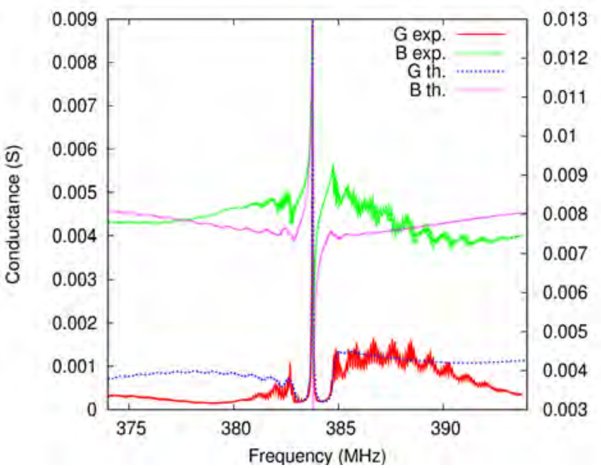






Tapered synchronous resonator

Hiccup resonator

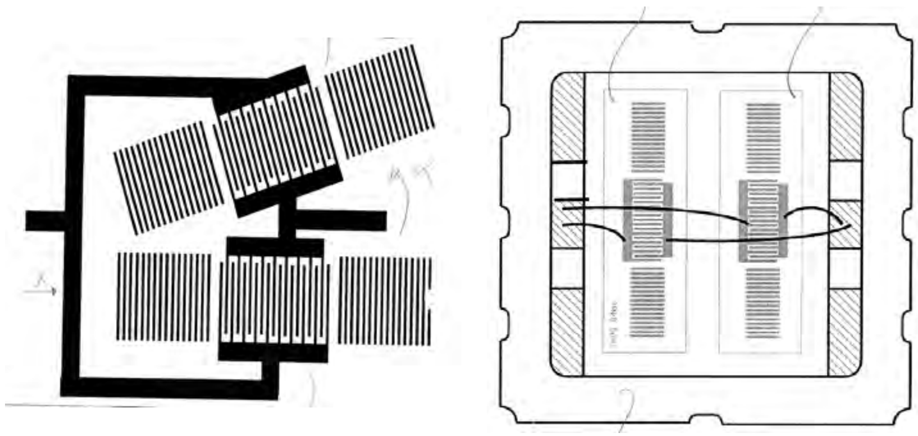


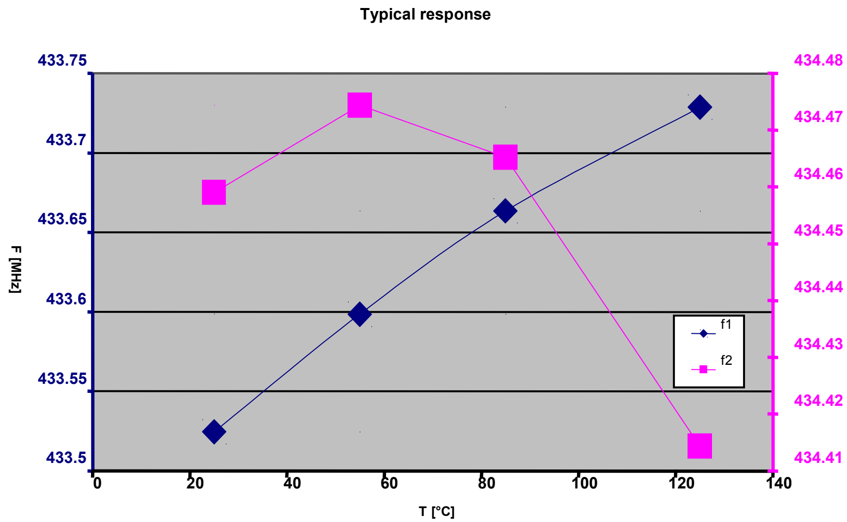
- Synchronous resonators operate at the edge of the stopband
- Tapering the transducer reduces lateral mode contributions
- Asynchronous resonators (a/p or p) force resonance within the stopband
- Adding an extra λ/4 propagation path yields middle-of-the-band resonance for non directive resonators
-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

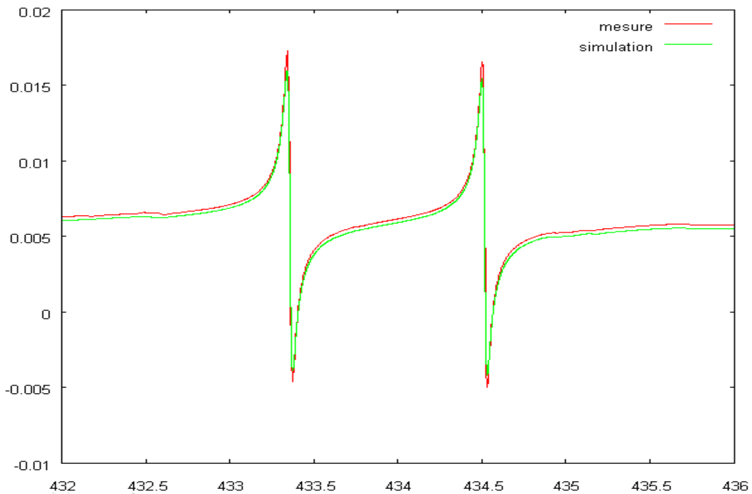
SAW Resonator temperature sensor

Sensor architectures

2 SAW on Chip – 2 chips in a package





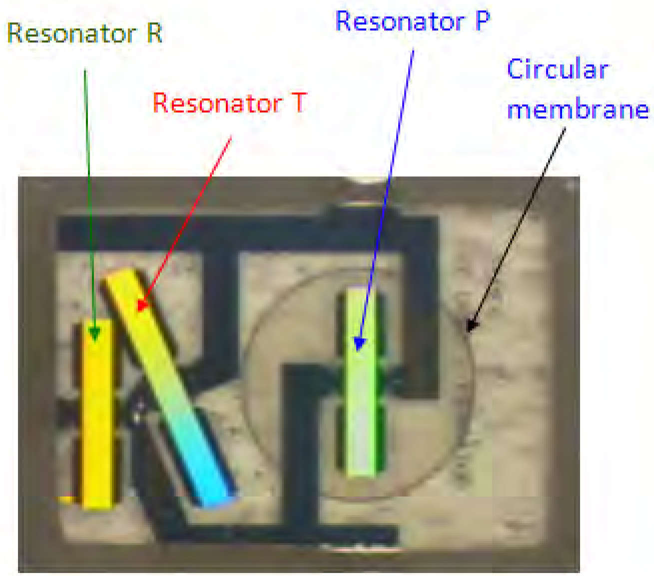


Sensor Characterization

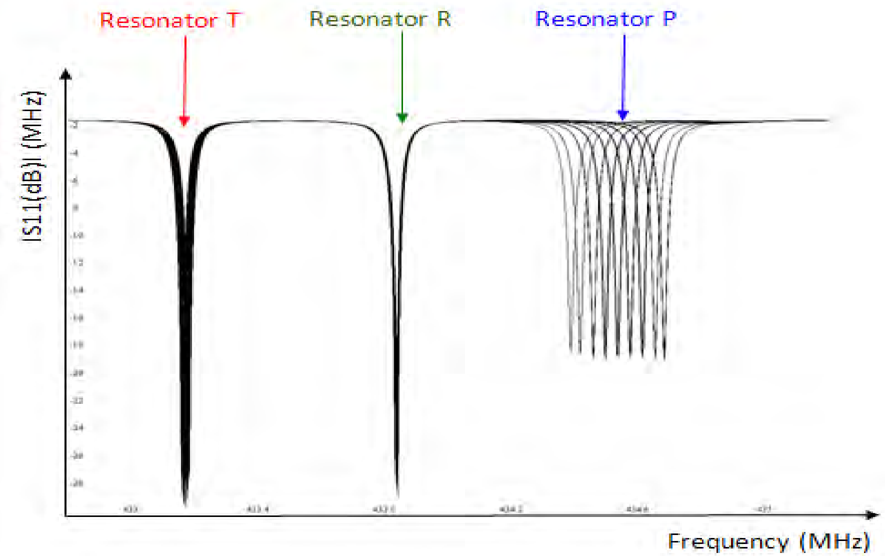
- Electrical admittance
- Frequency/temperature laws

(SENSeOR products)

Temperature-pressure sensor



(a) SAW pressure and temperature sensor 0 – 10 bars (8x4mm^2)



(c) S11 modulus variation for the SAW pressure and temperature sensor when overpressure varies from 0 to 5 bars

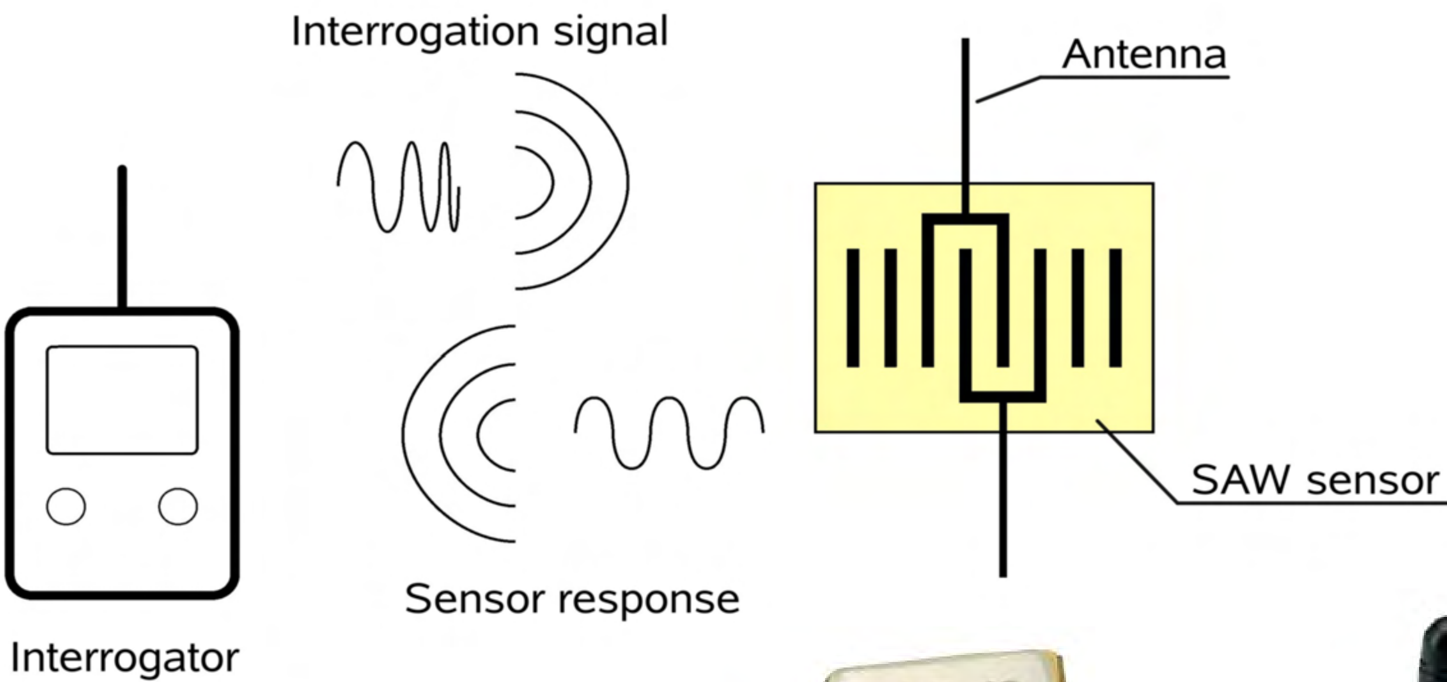
(b) Cross section of the micro-machined circular membrane

SAW temperature-pressure sensor

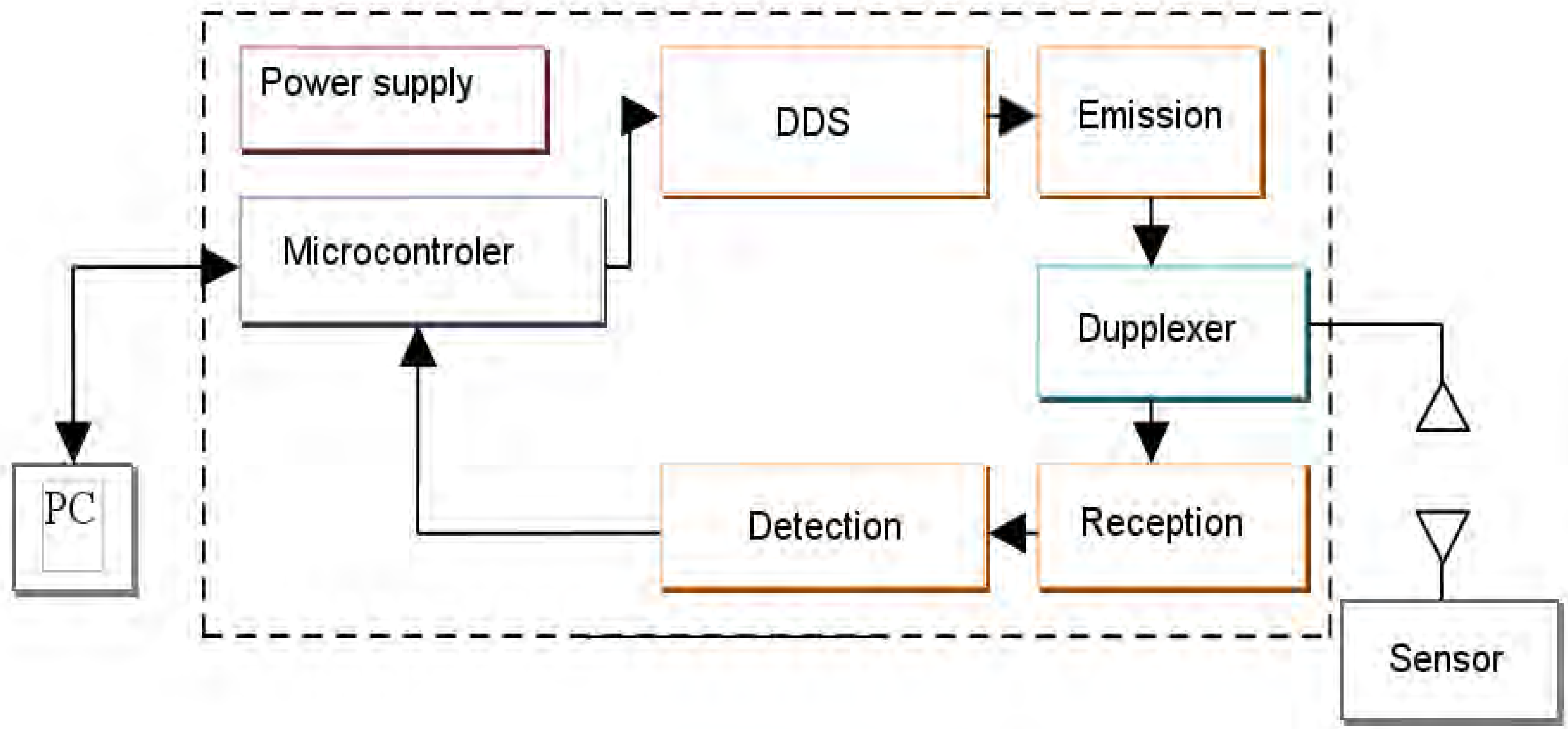
SAW in ISM band : 433.05 < *f* < 434.79 MHz

Pressure range : 0 – 20 Bars
controlled by the membrane dimensions

SENSeOR Wireless system



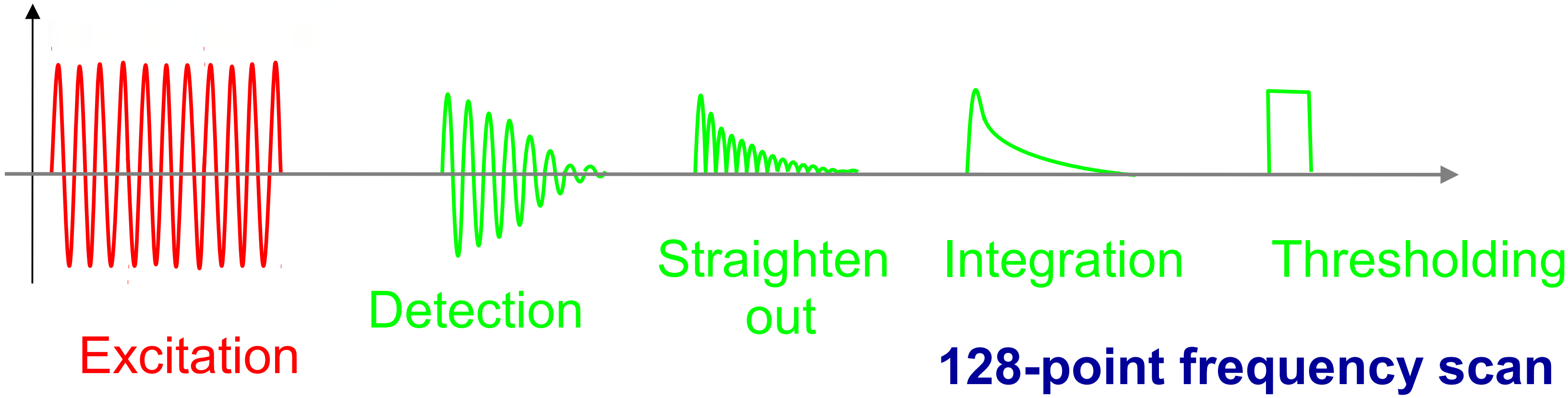
Electronics bloc diagram

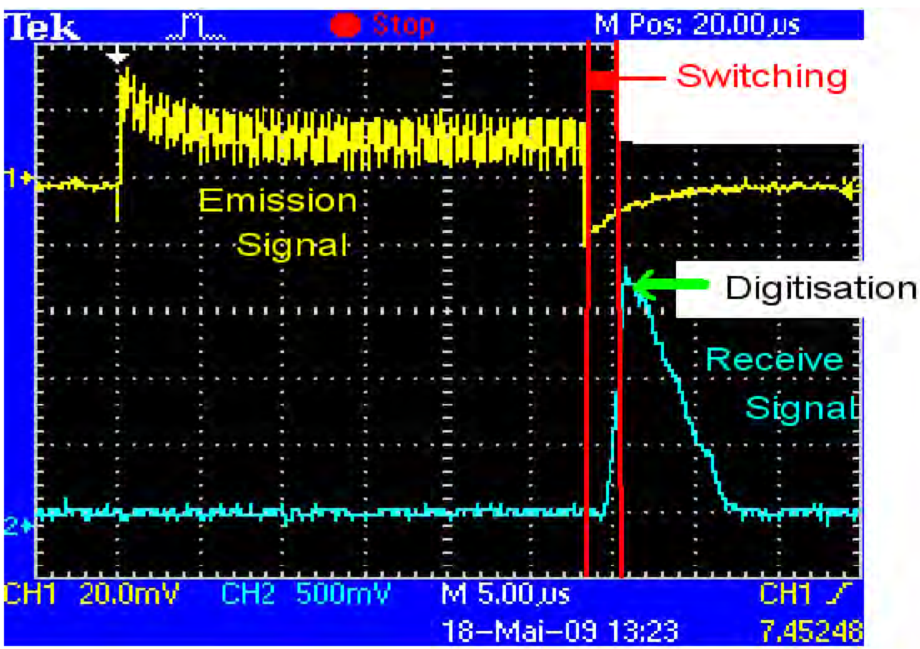


A software-controlled system allowing for various interrogation strategy in the 434 MHz – centered ISM band

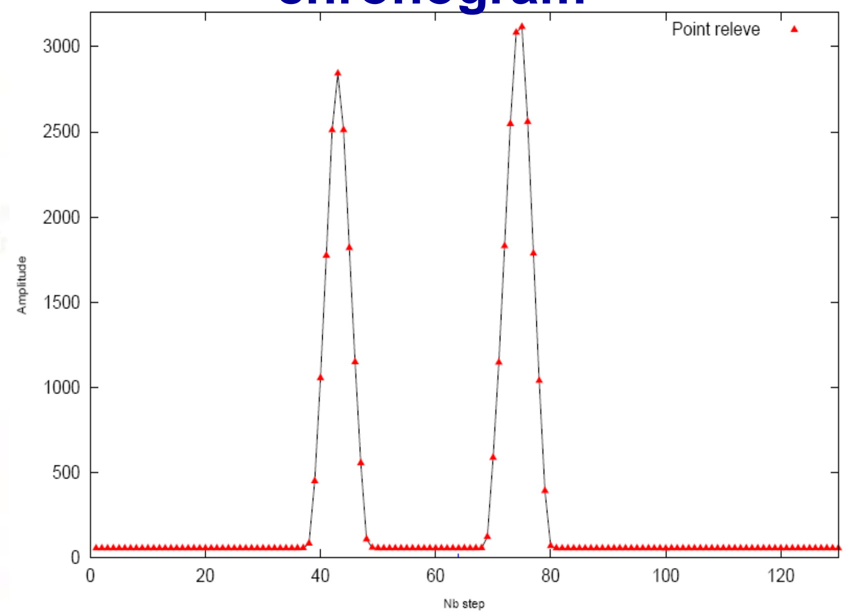
Micro-controllerr : AduC 7026, ARM7-core-based technology

Basic scanning operation





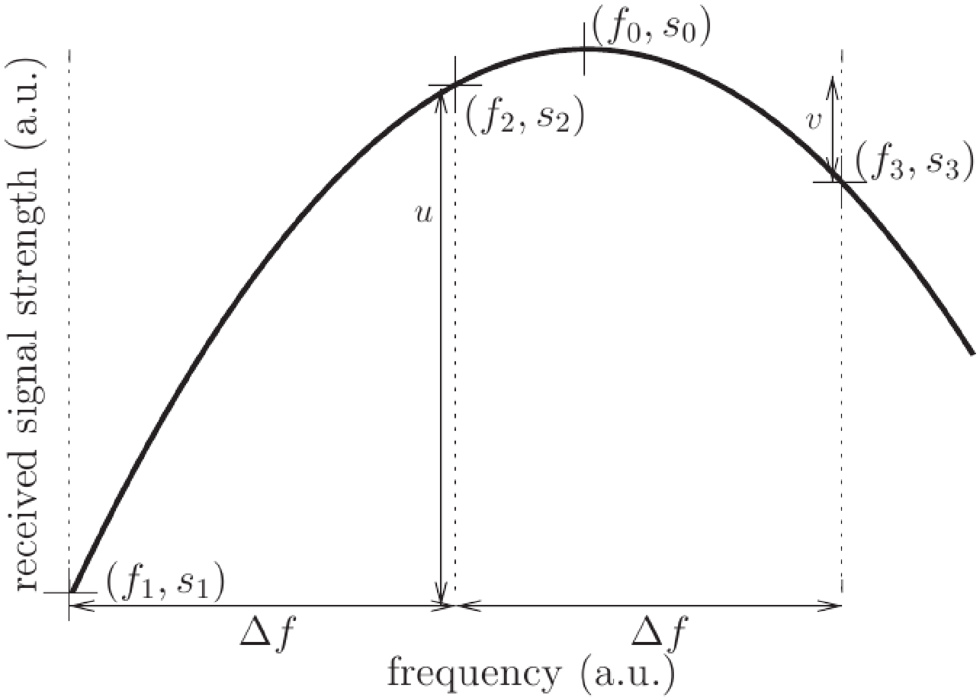
128-point frequency scan chronogram



Improving the accuracy

- **The presented principle allows for temperature measurement by simply detecting the curve maximas 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 : $128 \times (Q/\pi) \times \tau \sim 5{,}76$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 represneted by a Lorentzian law

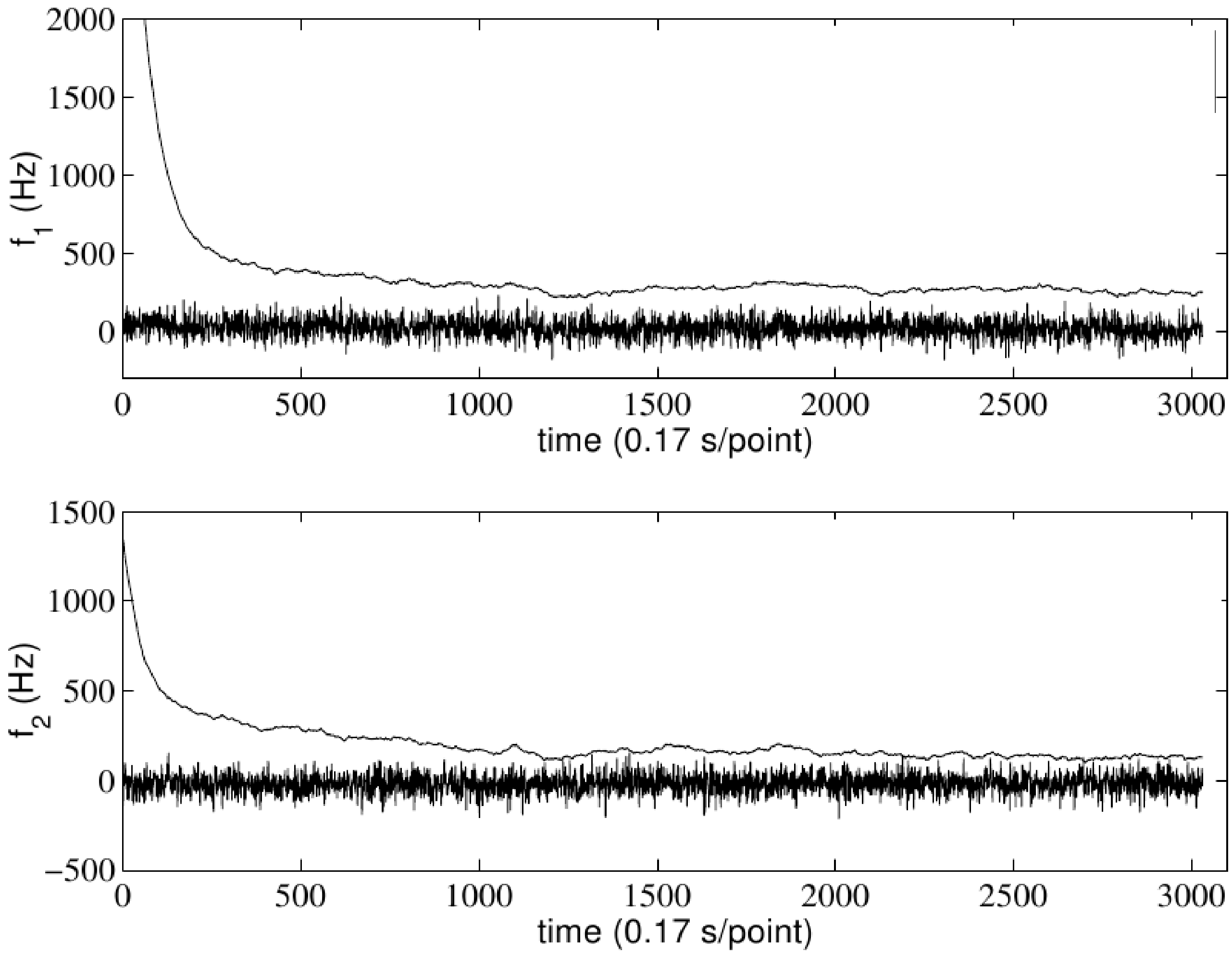
A parabolic function reliably fits the conductance max

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

Computation needs a minimum calculation ressources

$$f_0 = f_2 + \frac{\Delta f}{2} \times \frac{(s_1 - s_3)}{(s_1 + s_3 - 2 \times s_2)}$$

Application

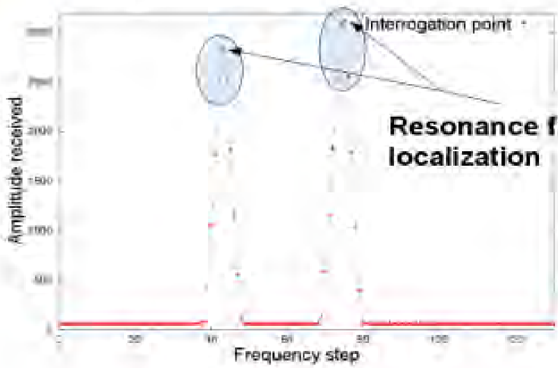


Application of the 3-point method to a 2-resonator temperature sensor

Tracking mode

Questioning ISM band

The magnitude answer



Parabolic fit approximation

f0

Fstart = f0 - 1 step

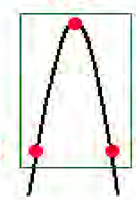
Fstop = f0 + 1 step

Feedback control

f0

16 Averages

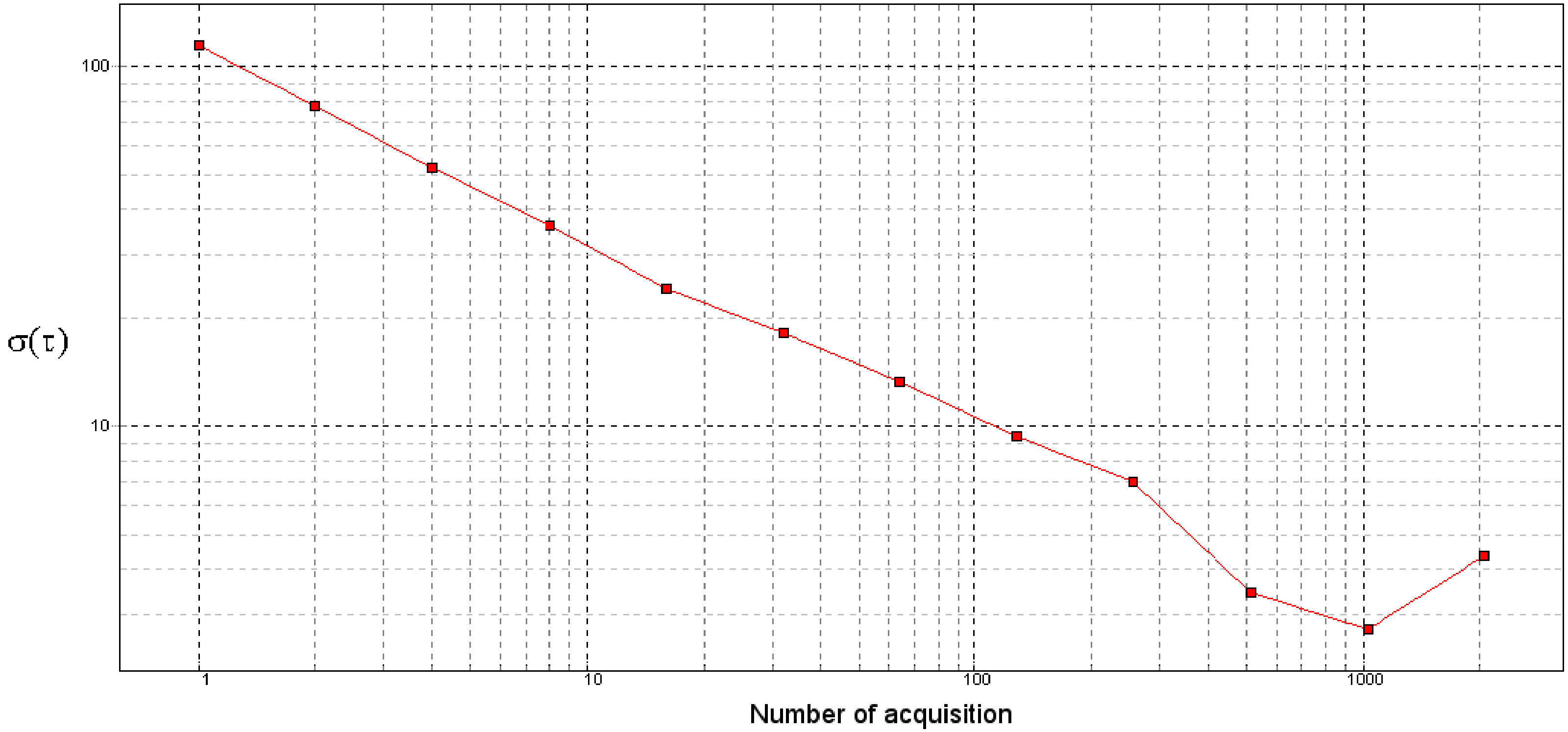
Variance



Rejected measurement

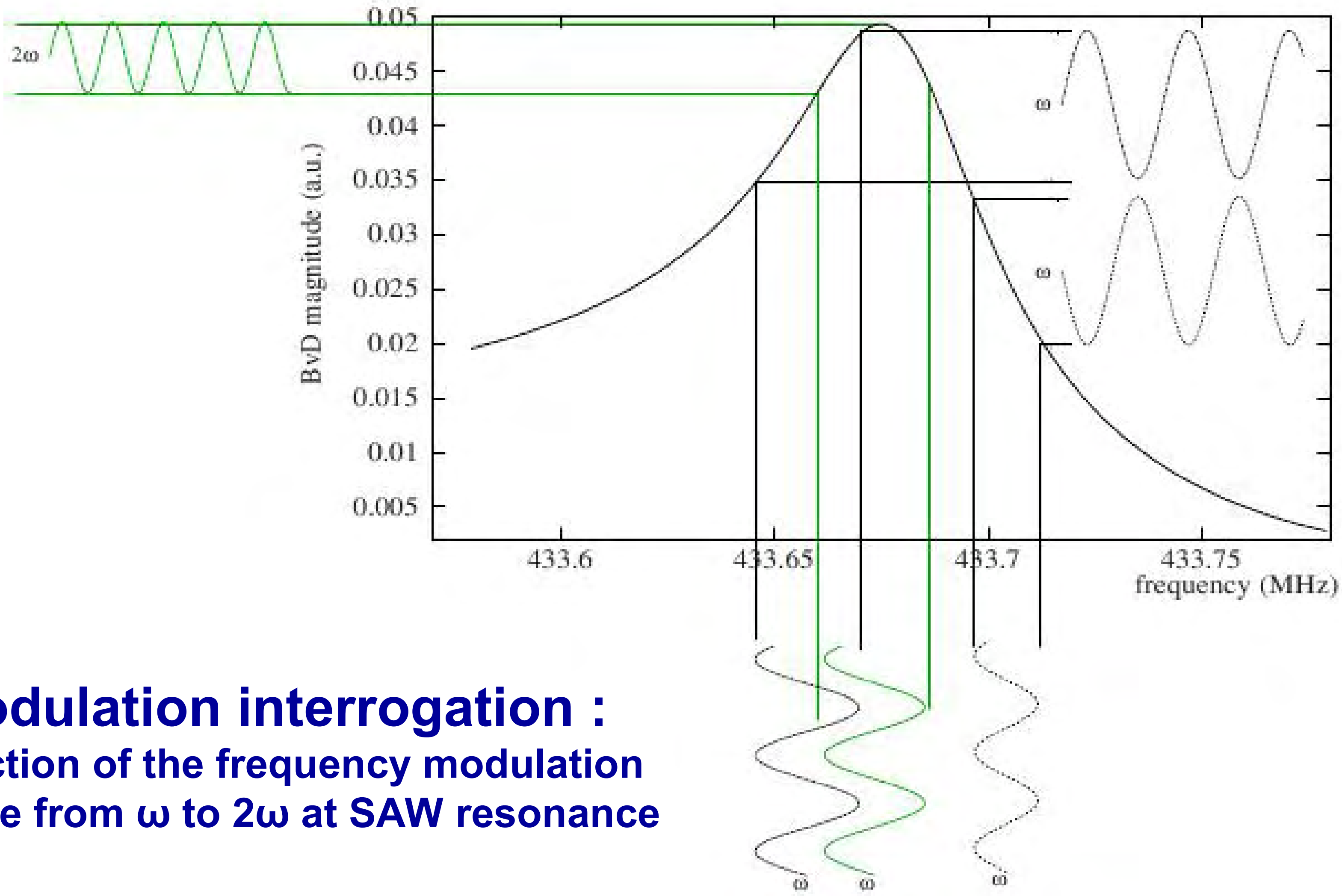
Accepted frequency measurement

Stability – Accuracy



5.76 ms for intialization
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

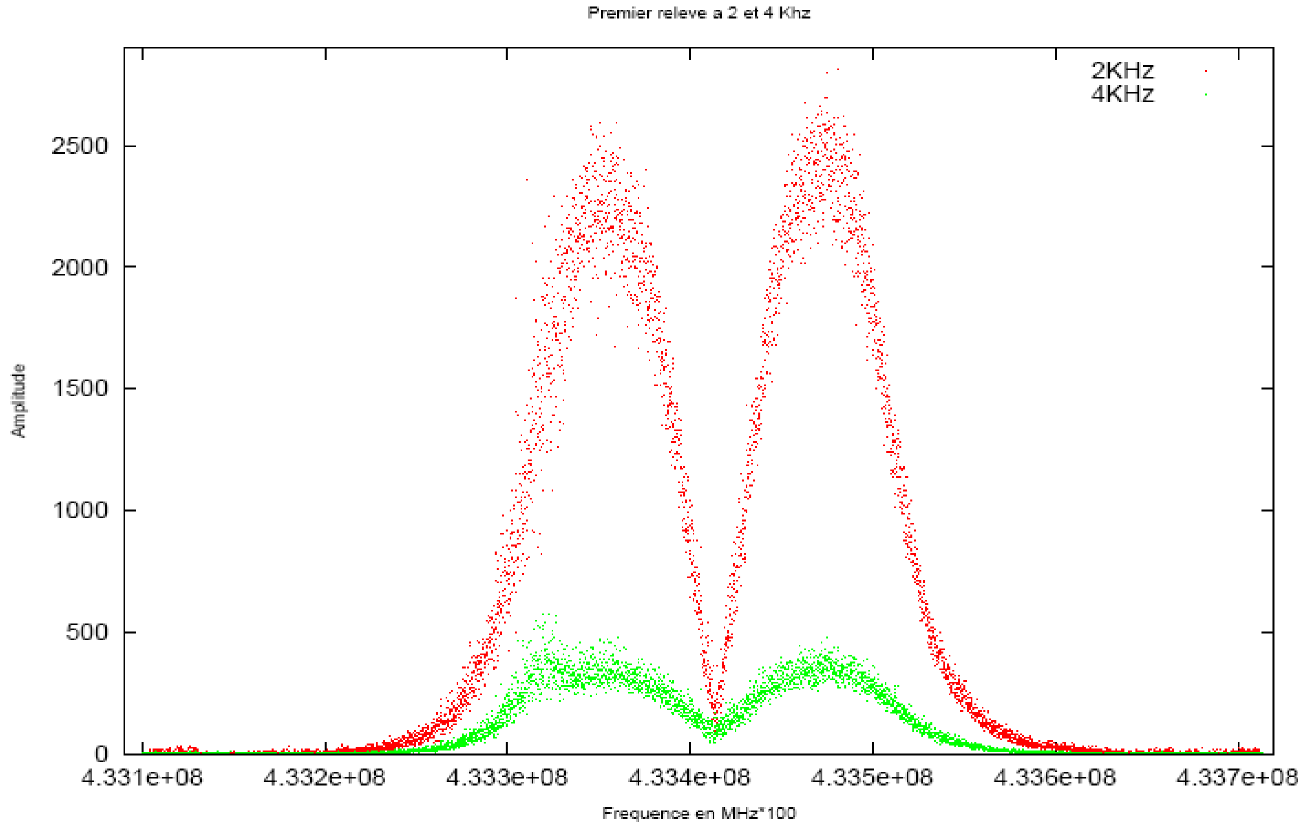
Frequency modulation strategy



Modulation interrogation :

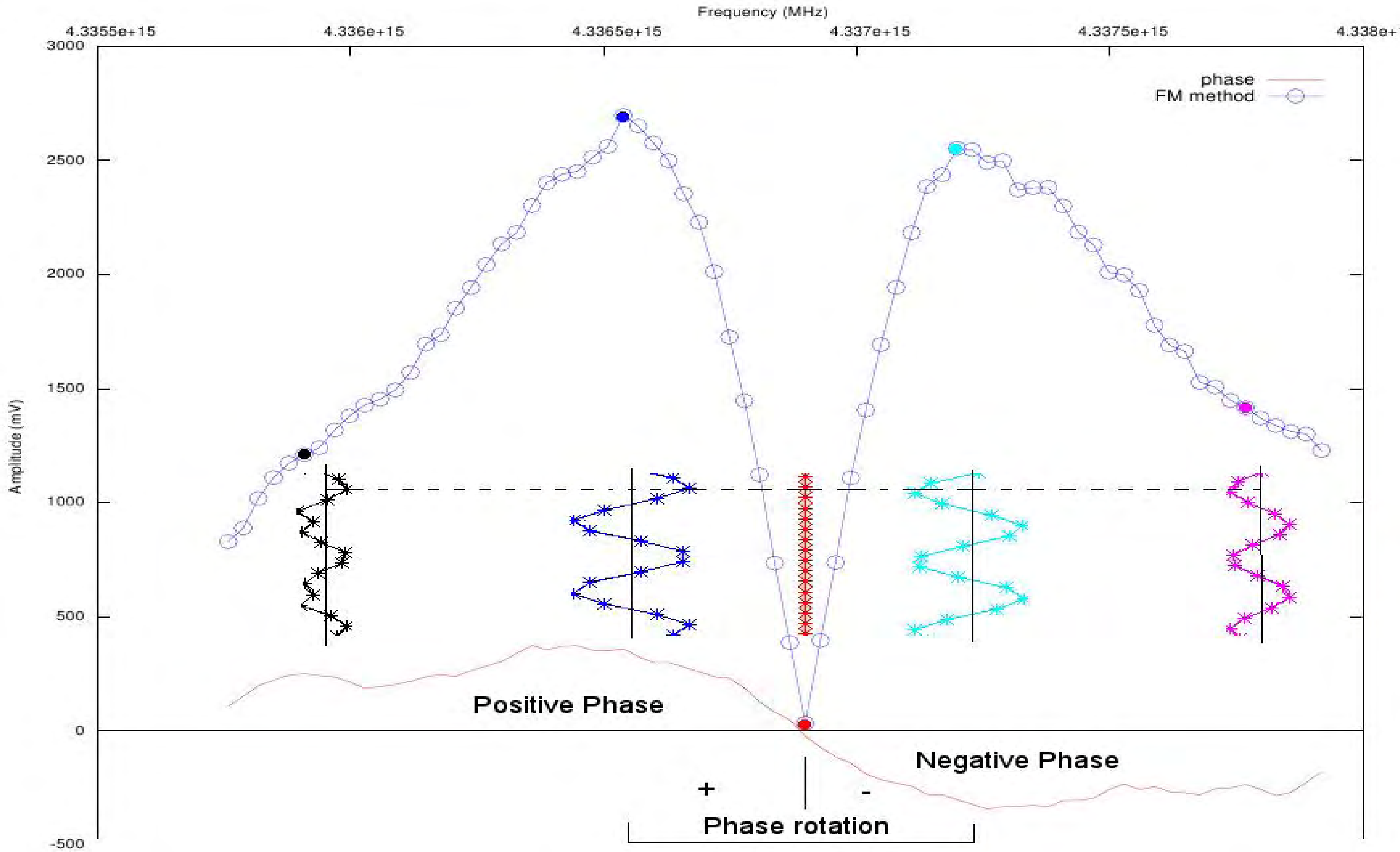
Detection of the frequency modulation change from ω to 2ω at SAW resonance

Scanning the contribution at modulation frequency ω

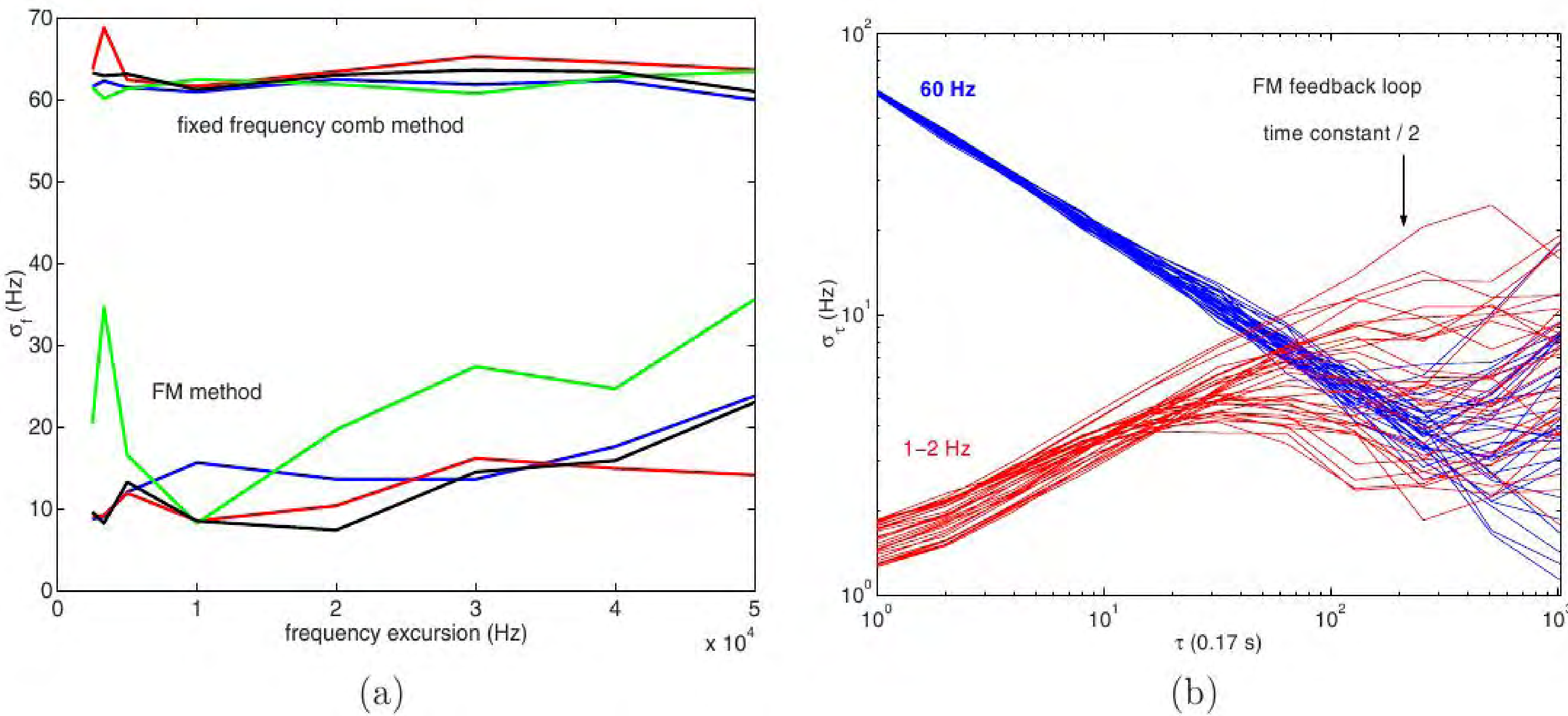


Efficiency of the approach depends on the amplitude and frequency of the modulation

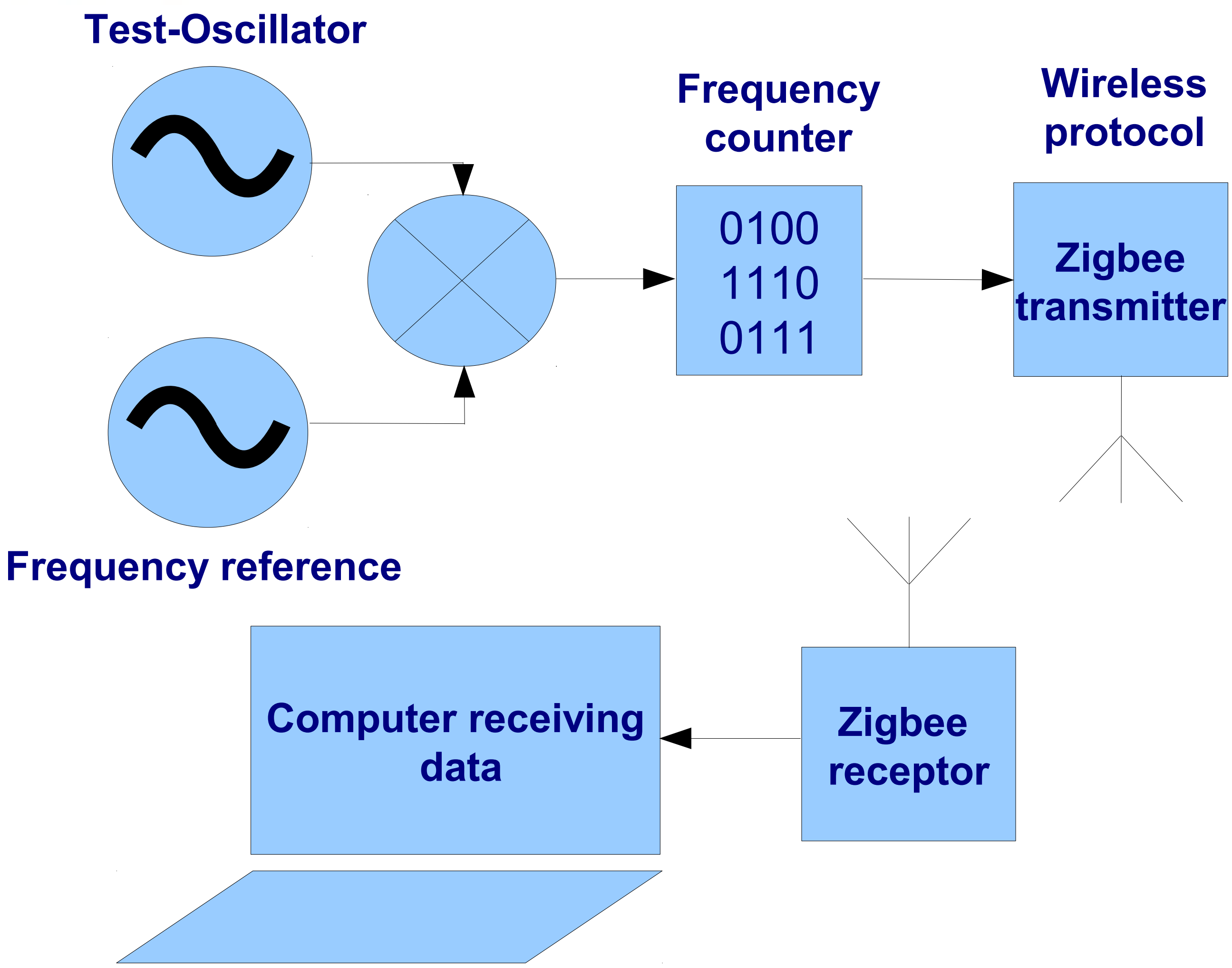
Exploitation of the approach for phase-locking



Stability in wireless and wired configurations



Powered solutions



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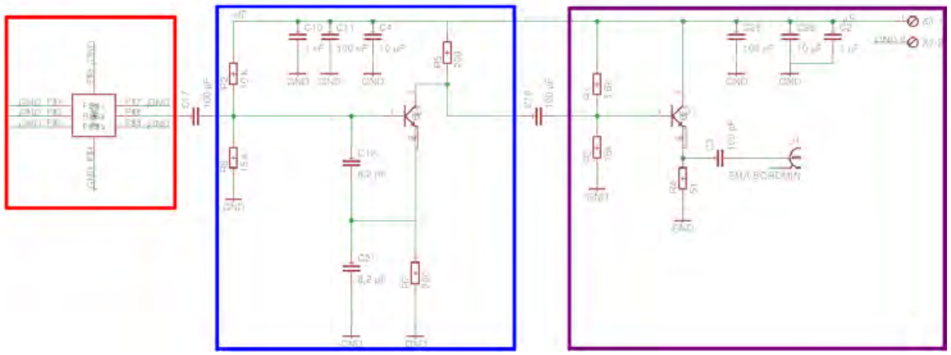
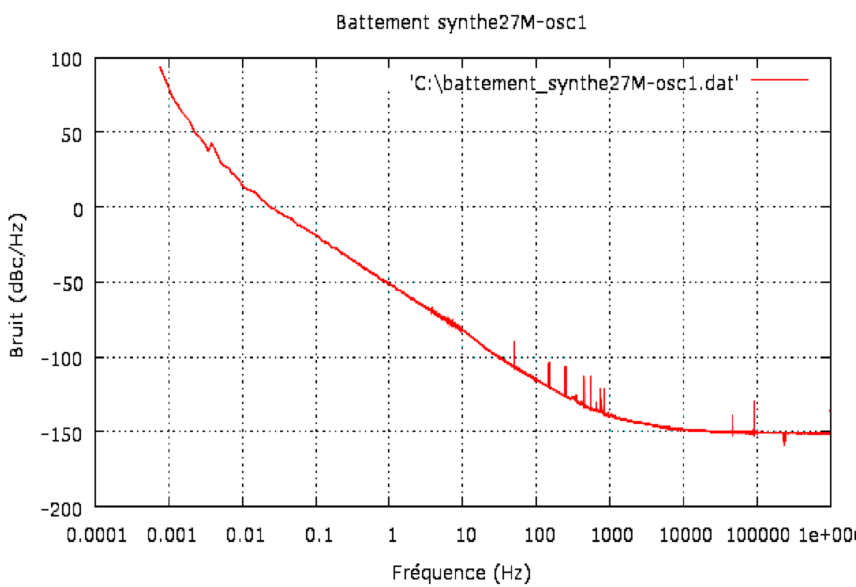
Colpitts-based oscillator

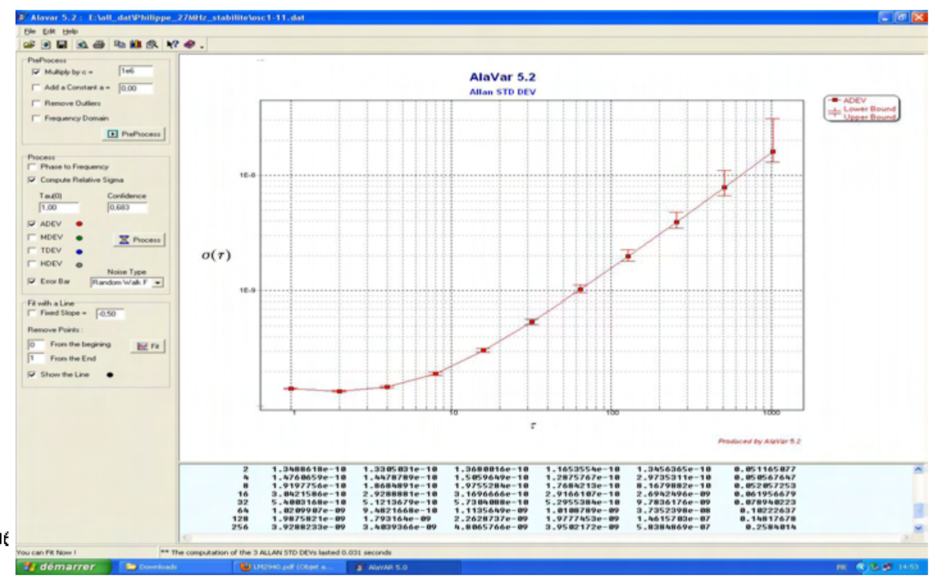


Ultimate accuracy given by the oscillator stability

Phase noise below 150 dBc/Hz

Short term stability 1.5×10^{-9} over 1 s yields sub Hz resolution, hence µK-range temperature accuracy





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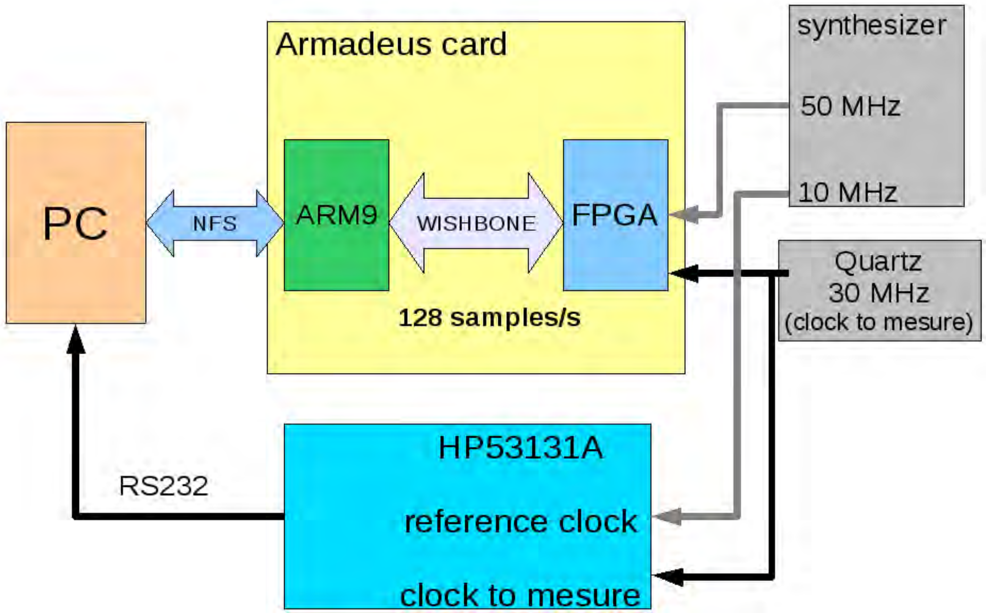
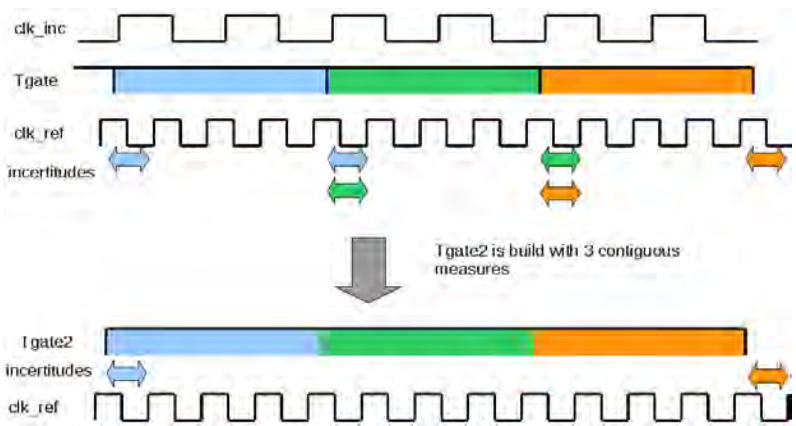
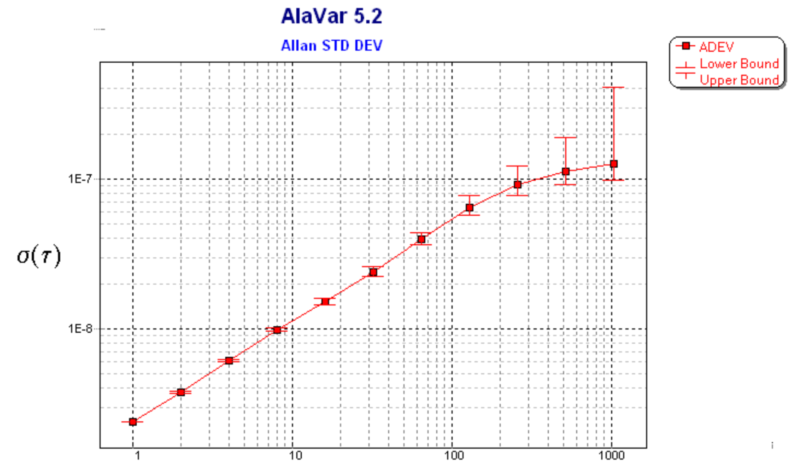
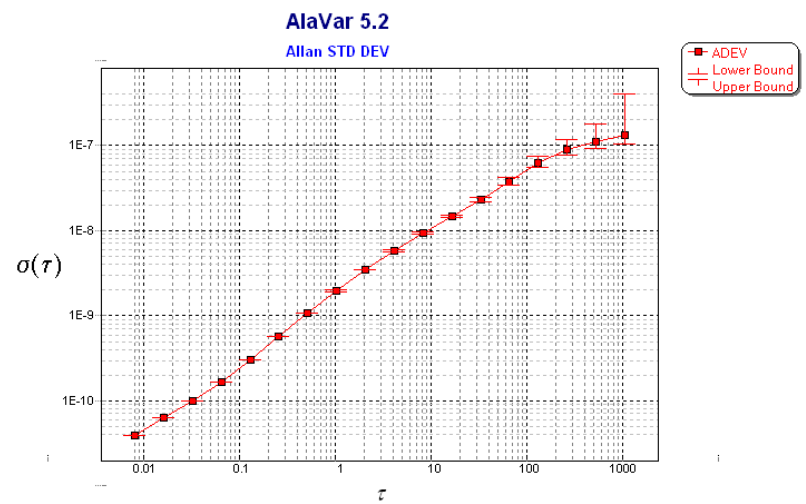
FPGA-based Counter







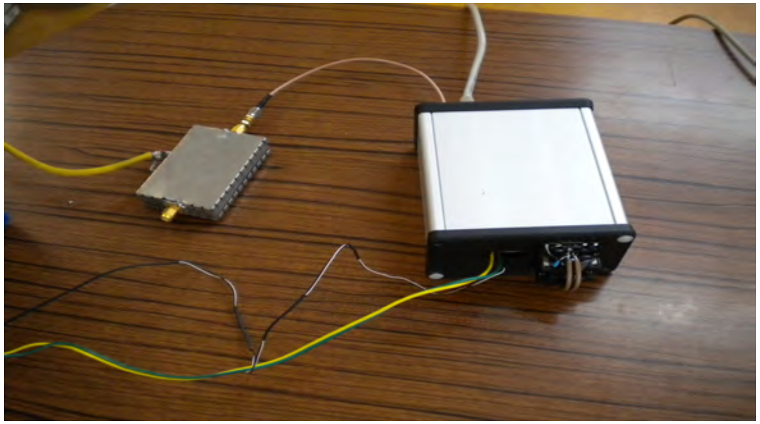
HP frequency counter stability (53131A)



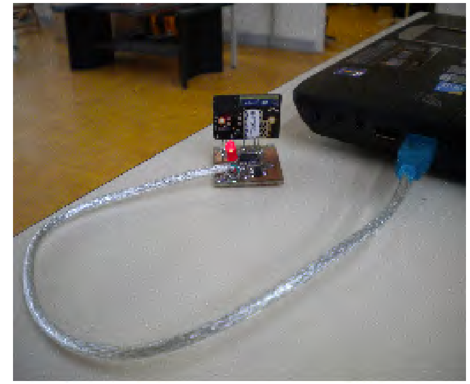
FPGA-based frequency counter stability

Final implementation

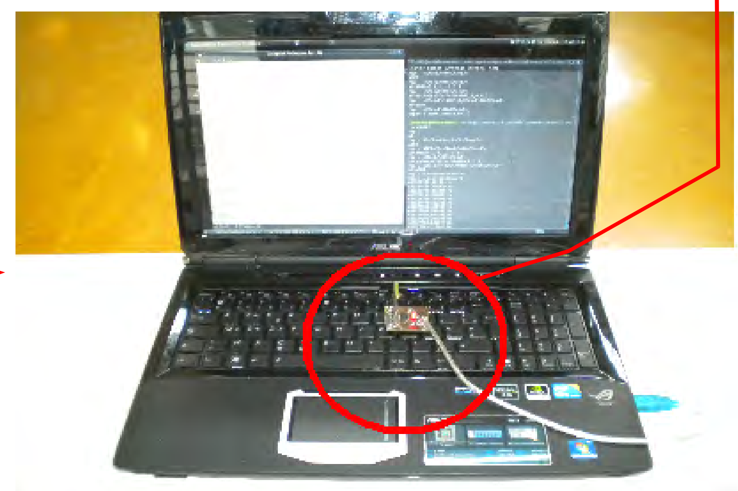
Oscillator + FPGA counter + Zigbee emitter



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 interrogeable but needs longer delays
  - Wired-powered solutions allows very large distance with coding

Perspectives

- **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