Noise RADAR and passive RADAR interrogation of passive wireless sensors

J.-M Friedt[0,1,2], W. Feng[2], G. Goavec-Mérou[1], G. Martin[1], M. Sato[2]

[0] SENSeOR SAS, Besançon, France
[1] FEMTO-ST Time & Frequency department, Besançon, France
[2] CNEAS, Tohoku University, Sendai, Japan

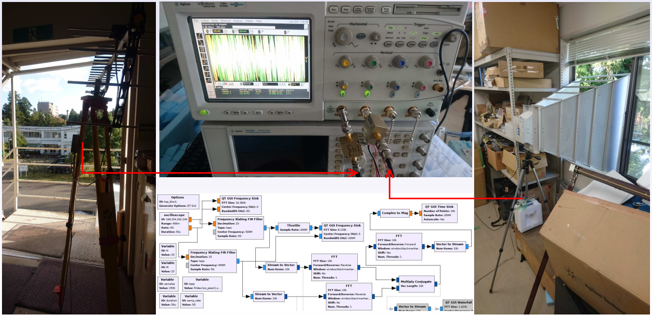
jmfriedt@femto-st.fr

slides and references at
jmfriedt.free.fr

What is passive RADAR ?

- use the emission of an existing, non cooperative emitter as radiofrequency source for RADAR measurement
- since the emitted signal is unknown, a reference channel collects the signal directly transmitted from emitter to receiver
- a second surveillance channel, ideally hidden from the direct signal, collects signals reflected by (moving) targets
- {range,Doppler} maps computed by correlating

$$rd(\tau, df) = \int meas(t+\tau)\cdot ref(t)\exp(j2\pi f_{Doppler}t)dt$$



Outline

1. passive, wireless sensor characteristics (bandwidth, time delay)
2. spectrum spreading of a carrier
3. noise RADAR (2.4 & 4.2 GHz)
4. passive RADAR (WiFi)
5. antenna array for spatial separation

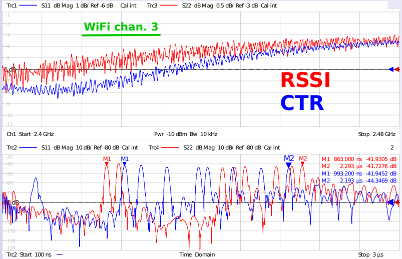
[0] H. Guo *& al.*, *Passive radar detection using wireless networks*, International IET Conference on Radar Systems (2007)

[1] K. Chetty *& al.*, *Through-the-Wall Sensing of Personnel Using Passive Bistatic WiFi Radar at Standoff Distances*, IEEE Trans. Geoscience & Remote Sensing (2012)

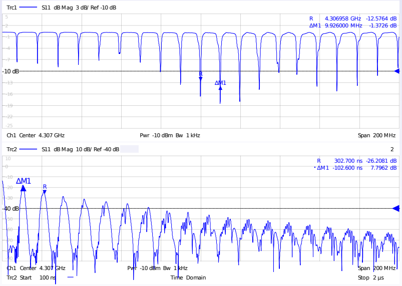
In this paper, we investigate the feasibility of **uncooperatively and covertly** detecting people moving behind walls using passive bistatic WiFi radar at standoff distances. A series of experiments was conducted which involved personnel targets moving inside a building within the coverage area of a **WiFi access point**. These targets were monitored from outside the building using a 2.4-GHz passive multistatic receiver, and the data were processed offline to yield range and Doppler information. The results presented show the first through-the-wall (TTW) detections of moving personnel using passive WiFi radar. The measured Doppler shifts agree with those predicted by bistatic theory. Further analysis of the data revealed that the system is **limited by the signal-to-interference ratio** (SIR), and not the signal-to-noise ratio.

Passive, wireless sensor characteristics

- Underlying philosophy: delay sensor response beyond clutter
- Convert electromagnetic waves to the 10^5 times slower acoustic wave
- 1-2 μs delay introduced by a 1.5-3 mm long acoustic path
- Surface Acoustic Wave (SAW) delay line up to 2.5 GHz (lithography limitation: $\lambda = 1.2~\mu$m)
- High-overtone Bulk Acoustic Resonator above (4.2 GHz here)



Commercial, off the shelf acoustic reflective delay lines provided by RSSI & CTR



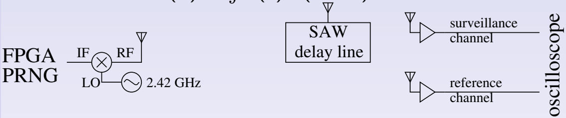
HBAR characterization

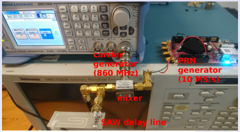
Frequency (top) & time (bottom) domain characterization of transducers

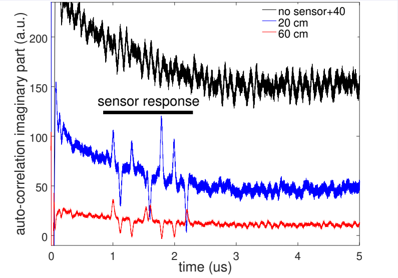
Noise RADAR

Range (delay) resolution $\propto$ bandwidth $1/B \Rightarrow$ maximize B, $\forall f_c$

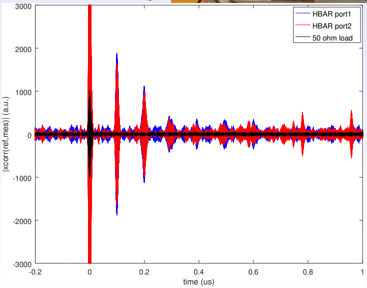
- short pulse = broadband spectrum (pulse RADAR)
- frequency sweep and measure scattering coefficient at each frequency (FSCW)
- linear frequency sweep and beatnote $\propto$ delay (FMCW)
- **pseudo random phase modulation of carrier: noise RADAR**
- Binary Phase Shift Keying (BPSK) by mixing carrier frequency (LO) with 20-bit long pseudo-random sequence generator (IF)
- **Correlation** $(\tau) = \int r(t)m(t+\tau)dt$







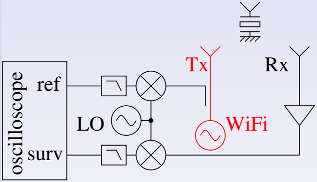
0.2 and 0.6 m range, SAW delay line

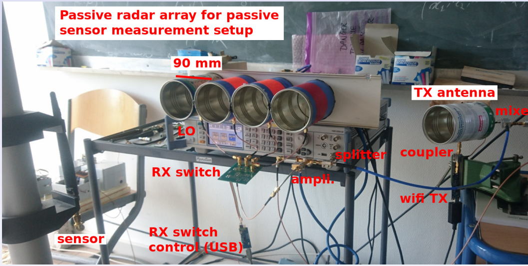


$f_c = 4.3$ GHz, 150 MHz bandwidth, HBAR

Passive RADAR

- Radiofrequency spectrum is a scarce resource ⇒ strong regulations on emission
- Solve certification challenge by using existing emitters
- Detect **time-delayed copies** of the emitted signal: **static** target detection (**no** frequency transposition SNR improvement).



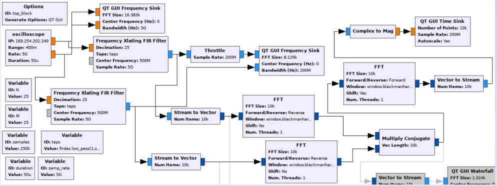


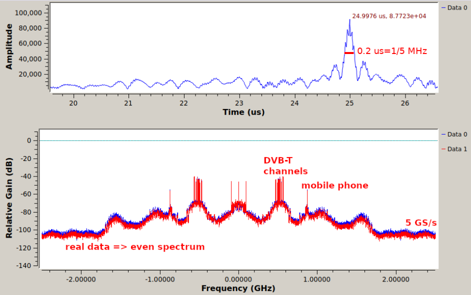
- WiFi emitter as (pseudo-random) signal source (monitoring mode)
- Out-of-band downconversion (prevent WiFi from dropping connection)
- Collect (coupled channel) the **reference** signal
- Observe the **suveillance** signal
- Measurement duration improves SNR, while source bandwidth defines timing resolution

gr-oscilloscope real time display

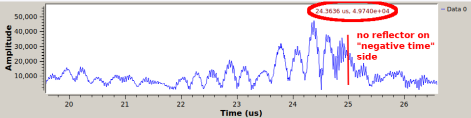
- $FFT(conv(x,y)) = FFT(x) \cdot FFT(y)$
- $FFT(corr(x,y)) = FFT(x) \cdot FFT^*(y)$
- RF-grade oscilloscope (100 MHz=10 ns=3 m range resolution) used as real data source
- two **synchronous** channels provide reference and measurement
- feed GNURadio with streams of **discontinuous** measurements from a multi-channel oscilloscope
- custom block `gr-oscilloscope` easily adapted to any oscilloscope (VXI11, GPIB or USBTMC)

`github.com/jmfriedt/gr-oscilloscope`



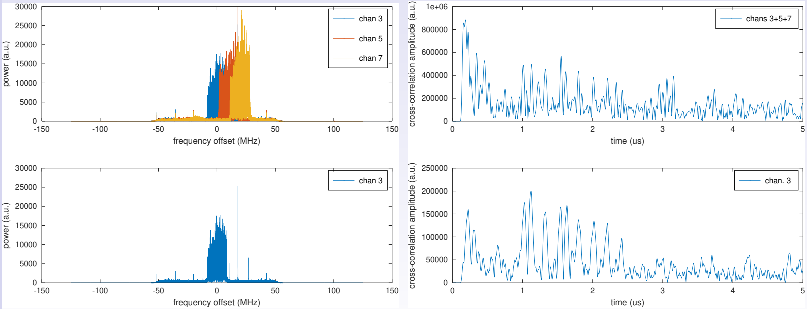


Autocorrelation ↑ – Crosscorrelation ↓



Passive RADAR: signal processing

- **Cross-correlation** magnitude for coarse estimate of the echo delays
- Each WiFi channel is 15 MHz wide (=67 ns resolution)
- Multiple channel accumulation for increased bandwidth: WiFi channels 1..11=2.412..2.462 MHz ($\simeq$ 15 ns resolution)
- All data collected at the same rate and different carrier frequencies: sum in the frequency domain after mixing with fixed LO



8-echo delay line, recorded with WiFi channels 3-5-7 (2422, 2432, 2442 MHz)

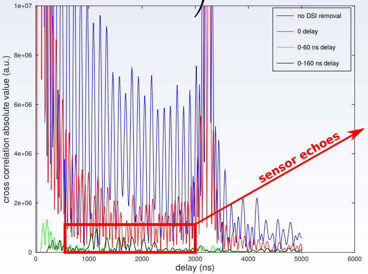
Direct Signal Interference removal

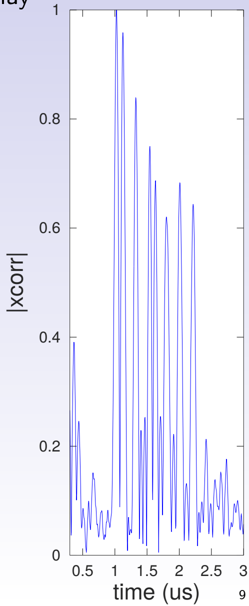
- Ideal noise: correlation = Dirac function @ delay
- WiFi signal: correlation within signal hides delayed echoes
- Least square method for Direct Signal Interference removal:

$$DSI_{weights} = \underbrace{(X^t \cdot X)^{-1} \cdot X^t}_{\texttt{pinv(X)}} \cdot meas$$

with

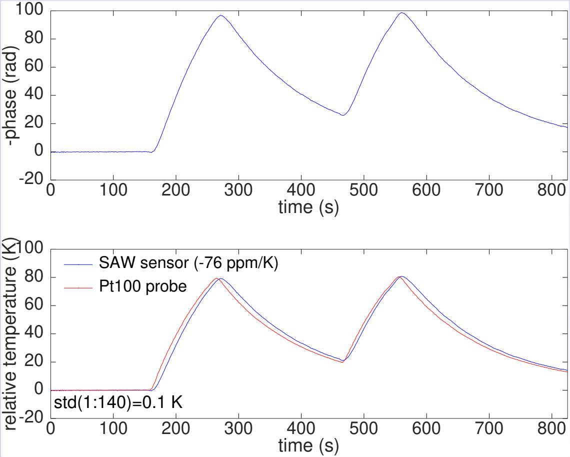
$$X = \begin{pmatrix} ref_1 & 0 & 0 & 0 \\ ref_2 & ref_1 & 0 & 0 \\ ref_3 & ref_2 & ref_1 & 0 \\ ref_4 & ref_3 & ref_2 & ref_1 \\ \dots & & & \end{pmatrix}$$





Temperature measurement

- Fine time delay τ measured as a phase: $\varphi = 2\pi f_c \tau$
- Correlation is a linear operation: phase is conserved
- Correlation **phase difference** for acoustic velocity measurement independent of range

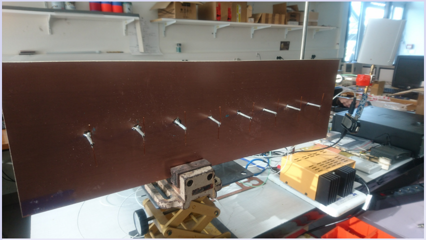


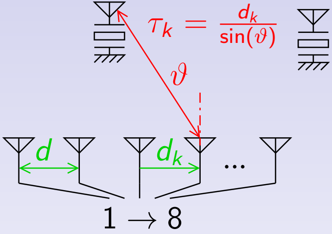
Example of temperature measurement: the sensor is heated twice – temperature sensitivity taken as -76 ppm/K (YXl/128° LNO)

$$d\varphi/\varphi \cdot (1/T) \triangleq S = 60 \text{ ppm/K} \Rightarrow T = d\varphi/\varphi \cdot (1/S) = d\varphi/(S \cdot 2\pi f \tau)$$

Receiver antenna array

Problem of **collision**: how to separate the signals from two sensors visible from the surveillance antenna ?





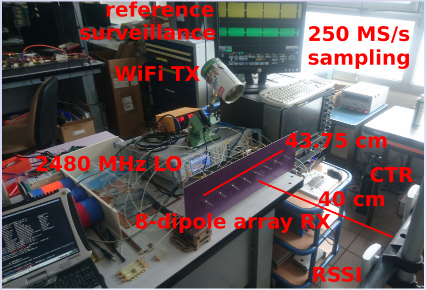
Narrowband – $B \ll c/(Kd) = 680$ MHz – plane wave approximation: $mes = ref(t)a(\vartheta)$ with $a(\vartheta) = \left[\exp(j2\pi \frac{kd \sin \vartheta}{\lambda})\right]$, $k = 0..K_{=7} \Rightarrow mes \cdot conj(a)$ for focusing in time-ϑ plane $\vartheta_{3dB} = \frac{0.89\lambda}{Kd}$ rad=15° since $d = \frac{\lambda}{2}$ and $K = 7$

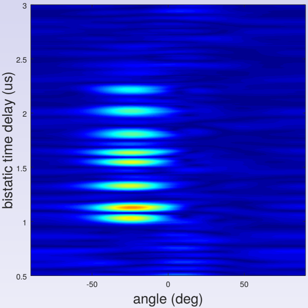
- antenna **array** for spatial separation [1] (8 dipoles separated by $\lambda/2 = 6.25$ cm)
- all antennas must see all sensors ($\neq$ cantennas, too directional)
- switch between antennas, extract complex correlation, and apply inverse phase due to time of flight (SAR processing)
- ... alternatively, move a single antenna to known positions

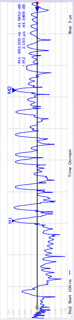
[1] G. Charvat, *Small and short range RADAR systems*, CRC Press (2014), p.300

Receiver antenna array

Problem of **collision**: how to separate the signals from two sensors visible from the surveillance antenna ?





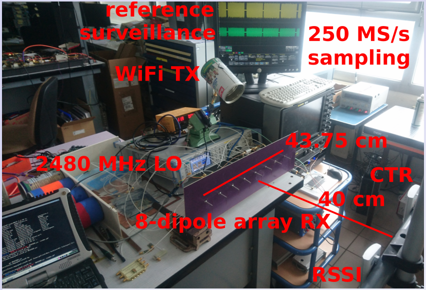


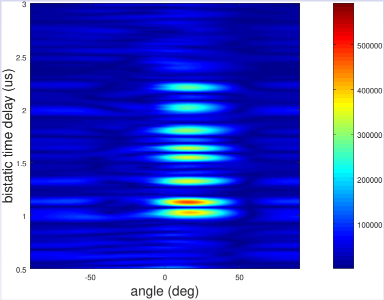
- antenna **array** for spatial separation [1]
  (8 dipoles separated by $\lambda/2 = 6.25$ cm)
- all antennas must see all sensors ($\neq$ cantennas, too directional)
- switch between antennas, extract complex correlation, and apply inverse phase due to time of flight (SAR processing)
- ... alternatively, move a single antenna to known positions

[1] G. Charvat, *Small and short range RADAR systems*, CRC Press (2014), p.300

Receiver antenna array

Problem of **collision**: how to separate the signals from two sensors visible from the surveillance antenna ?



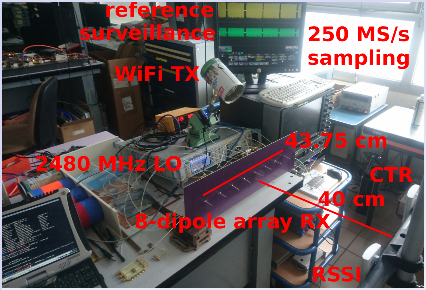


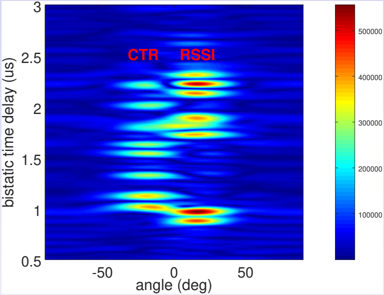
- antenna **array** for spatial separation [1]
  (8 dipoles separated by $\lambda/2 = 6.25$ cm)
- all antennas must see all sensors ($\neq$ cantennas, too directional)
- switch between antennas, extract complex correlation, and apply inverse phase due to time of flight (SAR processing)
- ... alternatively, move a single antenna to known positions

[1] G. Charvat, *Small and short range RADAR systems*, CRC Press (2014), p.300

Receiver antenna array

Problem of **collision**: how to separate the signals from two sensors visible from the surveillance antenna ?



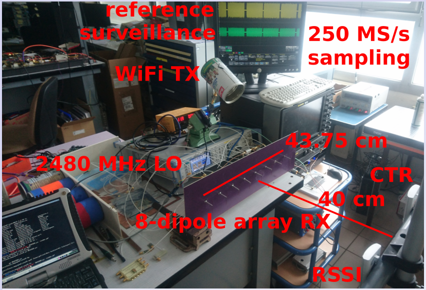


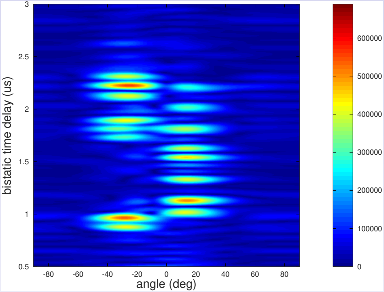
- antenna **array** for spatial separation [1]
  (8 dipoles separated by $\lambda/2 = 6.25$ cm)
- all antennas must see all sensors ($\neq$ cantennas, too directional)
- switch between antennas, extract complex correlation, and apply inverse phase due to time of flight (SAR processing)
- ... alternatively, move a single antenna to known positions

[1] G. Charvat, *Small and short range RADAR systems*, CRC Press (2014), p.300

Receiver antenna array

Problem of **collision**: how to separate the signals from two sensors visible from the surveillance antenna ?



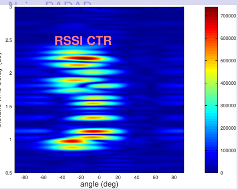


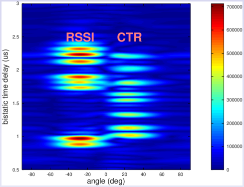
- antenna **array** for spatial separation [1]
  (8 dipoles separated by $\lambda/2 = 6.25$ cm)
- all antennas must see all sensors ($\neq$ cantennas, too directional)
- switch between antennas, extract complex correlation, and apply inverse phase due to time of flight (SAR processing)
- ... alternatively, move a single antenna to known positions

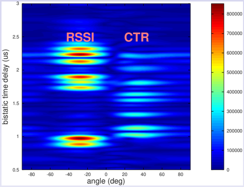
[1] G. Charvat, *Small and short range RADAR systems*, CRC Press (2014), p.300

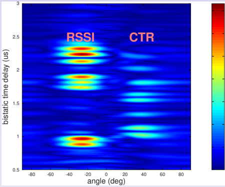
SAR processing

Fixed distance (50 cm) from dipole array to sensor axis.
Varying distance between sensors with a broader antenna:



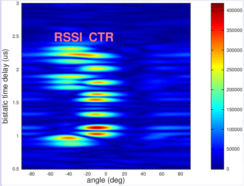


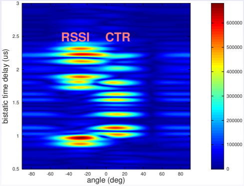


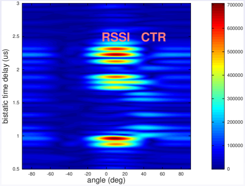


16 cm | 39 cm | 47 cm | 65 cm

Varying position with fixed distance between sensors (broader antenna)





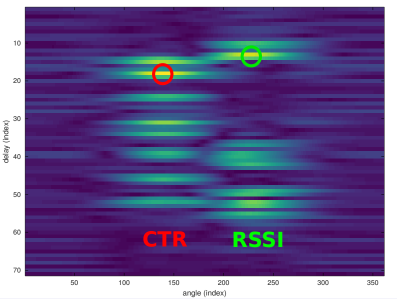


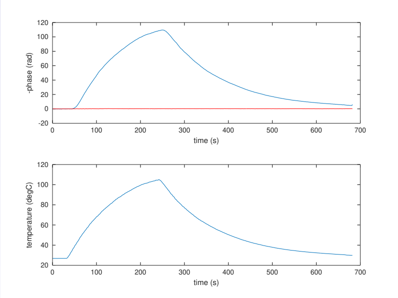
28 cm left | 28 cm | 28 cm right

Emitting & sensor antennas: Huber-Suhner SPA-2400/70/9/0/LCP
(8.5 dBi, 70° horiz. beamwidth @ 3 dB)

Sensor separation + temperature measurement

- Azimuth compression + individual sensor phase measurement
- only one sensor is heated, the other remains at room temperature

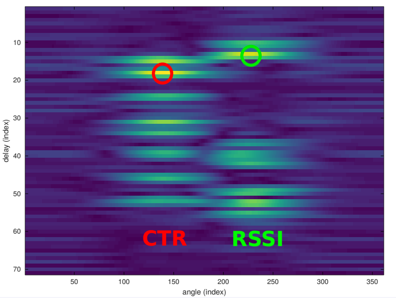


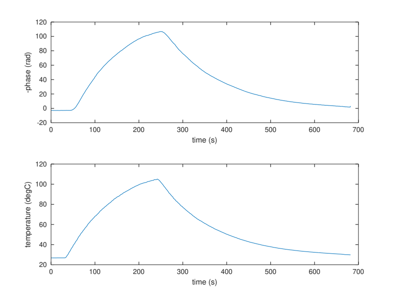


Problem with **super-resolution** algorithms (e.g. MUSIC): loss of phase, only magnitude available ⇒ loss of fine time delay information needed to recover temperature

Sensor separation + temperature measurement

- Azimuth compression + individual sensor phase measurement
- only one sensor is heated, the other remains at room temperature

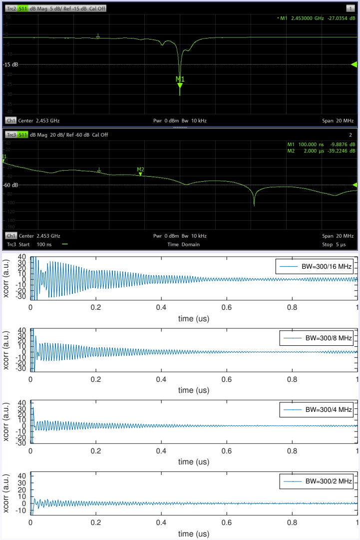




Problem with **super-resolution** algorithms (e.g. MUSIC): loss of phase, only magnitude available ⇒ loss of fine time delay information needed to recover temperature

What about resonators ?

- **Delay line**: discrete delays easy to interpret
- **Resonator**: continuous exponential decay of returned signal ...
- nevertheless, correlation = impulse response of system.
- $\Rightarrow$ noise radar interrogation of resonators exhibits the exponentially decaying response, with an amplitude dependent on emitted signal bandwidth.
- $Q \simeq 2000$ @ $f = 2.4$ GHz
  $\Rightarrow$ decay time constant is
  $Q/(\pi f) = 260$ ns$\simeq 1/4$ MHz
  $\Rightarrow$ how to recover a frequency with kHz resolution (Prony, Levenberg-Marquardt [2]) ?

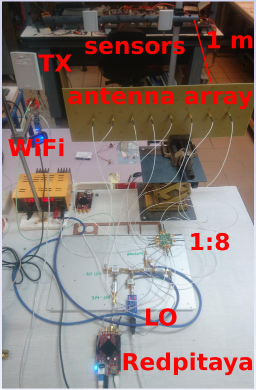


SAW Components 2.4 GHz resonator

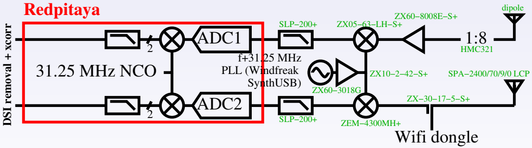
[2] J.-M Friedt *& al*, *High-overtone Bulk Acoustic Resonator as passive Ground Penetrating RADAR cooperative targets*, J. Appl. Phys **113** (13), 134904 (2013)

Conclusion

- Demonstrated **noise RADAR** interrogation of passive wireless sensors using a dedicated, pseudo-random BPSK modulated source
- Demonstrated **passive RADAR** interrogation of passive wireless sensors using a COTS WiFi transceiver
- DSI removal to extract useful signal from non-cooperative emitter auto-correlation
- Physical quantity measurement through correlation phase analysis
- Antenna array for source separation



Outlook: fully embedded implementation based on Redpitaya/Zynq 7010 + on-board processing



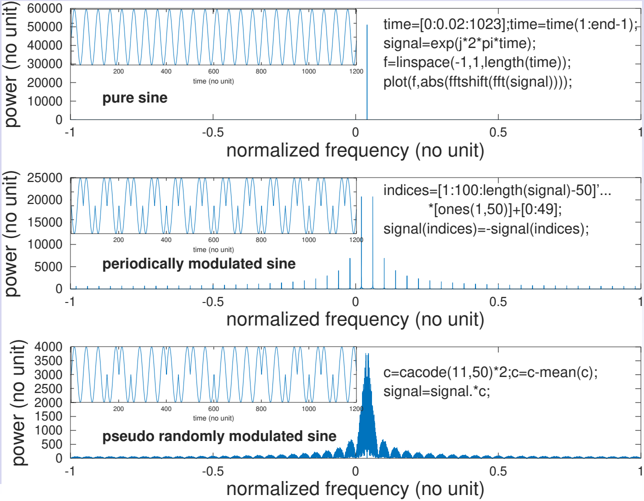
References:

[3] W. Feng, J.-M. Friedt, G. Goavec-Merou, M. Sato, *Passive RADAR measurement of acoustic delay lines used as passive sensors*, accepted IEEE Sensors (Sept. 2018)

Spectrum spreading numerical experiments

Carrier frequency and bandwidth are two unrelated quantities which can be tuned independently for **matching each sensor spectral characteristics**

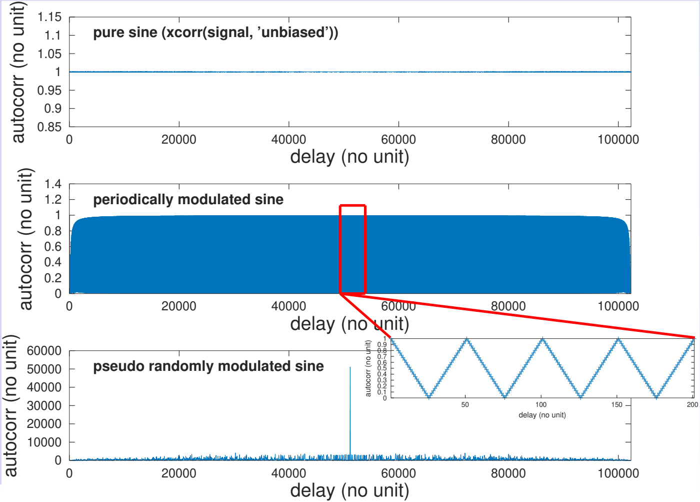
Binary Phase shift keying: $\varphi \in [0;\pi]$ for spectrum spreading



Spectrum spreading numerical experiments

Carrier frequency and bandwidth are two unrelated quantities which can be tuned independently for **matching each sensor spectral characteristics**

Binary Phase shift keying: $\varphi \in [0; \pi]$ for spectrum spreading



Least square DSI identification

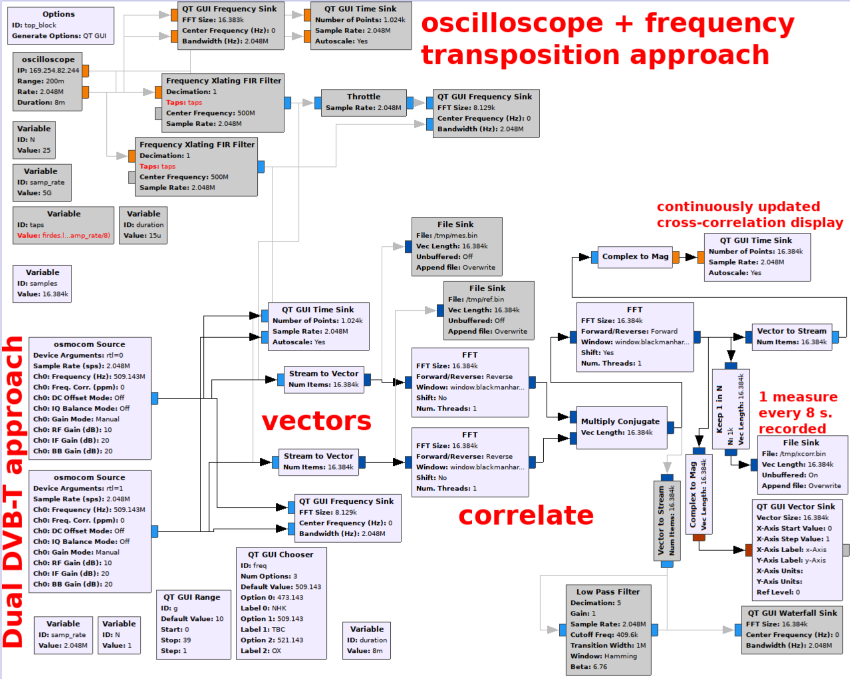
Least square parameter identification (demonstration by G. Cabodevila):

- Output y is a weighted sum of inputs x with noise ε.
- We want to identify weights ϑ from observations of y.
- $y = x\vartheta + \varepsilon$ minimizing the error $\sum e^2 = e^t e$ with $e = y - x\vartheta$
- Criteria
$J = (Y - X\Theta)^t(Y - X\Theta) = Y^tY - (X\Theta)^tY - Y^tX\Theta + (X\Theta)^tX\Theta = Y^tY - \Theta^tX^tY - Y^tX\Theta + \Theta^tX^tX\Theta$
- $\Rightarrow \frac{\partial J}{\partial \Theta} = 0 - X^tY - (Y^tX)^t + 2X^tX\Theta = -2X^tY + 2X^tX\Theta = 0$ at extremum
- $\Rightarrow 2X^tX\Theta = 2X^tY \Leftrightarrow \Theta = (X^tX)^{-1}X^tY = \mathtt{pinv}(X)$

Reminder[2]: $\frac{\partial v^t a}{\partial v} = \frac{\partial a^t v}{\partial v} = a$

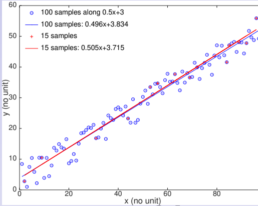
[2] https://atmos.washington.edu/~dennis/MatrixCalculus.pdf

oscilloscope + frequency transposition approach



github.com/jmfriedt/gr-oscilloscope

X is $N_{samples} \simeq 2^{16}$ to 2^{20} long and $N_{delay} \simeq 26$ wide (4 ns sampling $\Rightarrow$ 104 ns delay or 31 m $\ll$ 1-2.5 μs echoes)



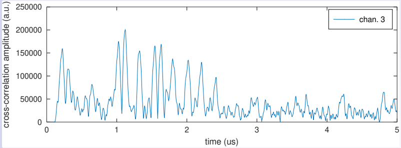
- Reduce computation time by selecting a random subset of the $N_{samples}$ lines
- Reduce computation time by selecting a subset of linear combinations of the $N_{samples}$ lines
- Improve DSI identification with sub-sampling period accuracy [2]

```
Idx1=0;Idx2=26;
X1=zeros(nt,Idx2-Idx1);te=1;
for kk=Idx1:Idx2  % full matrix
 X1(:,te)=[zeros(kk-1,1);
           ref(1:end-kk+1)];
 te=te+1
end
```

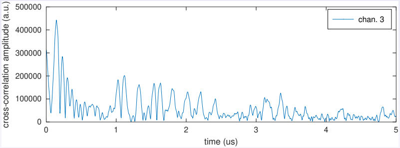
26 sampling steps (104 ns)

```
indices=randi(length(X1),4096,1);
X1s=X1(indices,:);  % matrix subset
meas=meas-X1*(pinv(X1s)*meas(indices));
```

X1: 1048576×27 → X1s: 4096× 27



Elapsed time is 7.40 seconds.



Elapsed time is 0.08 seconds.

[4] W. Feng, J.-M Friedt & al. *Direct path interference suppression for short range passive bistatic SAR imaging based on atomic norm minimization and Vandermonde decomposition*, submitted IET Radar, Sonar & Navigation