# Time reversal: a flexible approach for identifying and measuring surface acoustic wave delay lines acting as wireless, passive sensors

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***Abstract*— In order to provide a solution to both measurement capabilities of delay lines and anti-collision when probing multiple passive sensors from a single reader through a wireless link, we discuss the use of time reversal so that a single transducer answers a probe signal matching its impulse response. A process for batch manufacturing such devices using a single basic pattern which is adapted during a post-processing step by severing some of the connections to the electrodes is proposed, with some algorithm for selecting transducers among a family which maximizes the returned power and the orthogonality by minimizing cross correlation and sidelobes. The application of this concept to temperature measurement is demonstrated by tracking the sampling frequency of an arbitrary waveform generator emitting the time-reversed impulse response of a sensor.**

## I. Introduction

Acoustic transducers have demonstrated their compatibility with the application of batteryless tags interrogated through a wireless (radiofrequency) link. Two classes of SAW sensors have attracted most attention : delay lines and resonators. While the latter are compliant with the spectral limitations of the narrow low frequency (434 MHz European ISM band or 315 MHz Japanese and North-American License-Free band) unlicensed bands, their poor information content only allows for an identification through frequency multiplexing. Indeed, resonators are characterized by only two parameters – resonance frequency and quality factor – with only the former easily accessible through a wireless link. On the other hand, delay lines provide a rich set of information, hence requiring a wide radiofrequency range which is only compatible with the 2.45 GHz ISM band. SAW delay line identification is classically performed by time-domain coding : within a given timeslot, returned energy is associated with one bit state while the lack of returned energy is associated with the other bit state [1], [2].

The most intuitive and naive approach in probing acoustic delay lines consists in recording the impulse response of the transducer, either thanks to energy loading by a broadband energetic pulse (pulse-mode RADAR) or following the inverse Fourier transform of a frequency-swept continuous-wave RADAR [3]. However, because the complex electromagnetic signal returned from multiple sensors probed by a given pulse add [4], individual extraction of the information returned by each signal is impossible without some unrealistic assumption : this is called collision of the returned signals, and means that only a single sensor must be visible from the RADAR antenna at any given time. Various schemes of coding have been demonstrated [5], [6], but none solves the collision issue when probing multiple tags by recording impulse responses. On the other hand, time reversal has demonstrated its ability to focus a scattered signal on its source, assuming the direct signal phase and magnitude has been recorded by an array of transceivers [7], [8], [9]. In the case of acoustic transducers, this strategy is equivalent to the preliminary recording of each sensor response in its environment.

Beyond a basic threshold identification, it is well known that signal processing techniques provide significant improvement of the signal to noise ratio under the assumption that the shape of the returned signal is known [10]. As an example, the returned chirp from a RADAR pulse is known to be a scaling of the initial emitted pulse due to the Doppler effect, and cross correlation is one expression of applying the matched filter to the returned signal of the emitted pulse shape. In the context of SAW delay line identification, cross correlation between the returned echos from a transducer excited by a pulse and a database of possible responses significantly improves the signal to noise ratio and hence the identification capability, with best results when using orthogonal coding [11].

In this article, we demonstrate the use of time reversal to perform the computationally intensive [12] cross-correlation through the physical principle of SAW delay line interrogation. Furthermore, this interrogation strategy not only provides identification capability, but also anti-collision, compatible with the simultaneous interrogation of multiple sensors within range of a single interrogation unit (RADAR-like reader). Finally, design rules aimed at maximizing the autocorrelation function of each sensor (maximum returned power) while minimizing side-lobes (measurement capability) and cross-correlation with the response of other devices (anti-collision capability) are considered.

## II. BACKGROUND

Time reversal is a technique developed for focusing a beam in a diffusive medium : after recording the signal resulting from the propagation of a wave in the complex medium using multiple receivers, the propagation channel is characterized by the phase and magnitude of each recorded signal. If each recorder then acts as a signal generator, and emits a time reversed copy of the recorded signal then, under the assumption that the propagation channel has not significantly changed between the recording and emission steps, the waves generated by all the emitters focus on the original emitter. Another approach of this method is to simulate the position of a virtual emitter identified from the time reversal of the signals recorded by multiple receivers, with no preliminary assumption on the propagation channel [13].

This formalism is suitable for the purpose of defining a solution providing best use of the available bandwidth : emitting a signal which will match best a single transducer in order to meet two requirements : identification and anti-collision of SAW transducers. Within the previous description of the time reversal technique, anti-collision stems from the fact that only the propagation channel (in our case the SAW transducer) matching the emitted signal will efficiently focus (concentrate) energy, while the emitted signal will diffuse in all the other channel configurations, yielding no coherent accumulation (constructive interference of the incoming signals).

An acoustic aspect of these concepts is associated with the following considerations : it is known that an acoustic device performs the convolution between its transfer function and the incoming electromagnetic signal :

$$output\_conv(t) = \int s(\tau)s'(t-\tau)d\tau$$

Time reversal of one of the terms of the convolution yields a correlation :

$$output\_corr(t) = \int s(\tau)s'(\tau-t)d\tau$$

Only if the incoming signal $s'$ matches the transfer function $s$ of one transducer will a returned cross-correlation signal be significant. Hence, within the context of SAW device identification, applying the time reversal technique is equivalent to using the cross correlation performed by the physical system during the interrogation process. In terms of interrogation speed, a typical SAW delay line will have reflected all incoming energy within 10 $\mu$s, much less than the time needed to perform a digital computation of a cross-correlation of the returned signal with all the possible recorded responses [12].

### A. Transducer interrogation

Two distinct steps are needed to apply the proposed strategy : a first step creates a database of the impulse responses of all transducers seen by the interrogation unit. This database is either the result of a network analyzer characterization over a frequency span compatible with the interrogation bandwidth, followed by an inverse Fourier transform ; or a time domain recording of the I and Q components of the returned signal when the device is excited by a short pulse ; or finally the result of a simulation since acoustic delay lines are accurately modeled using, for example, a FEM-BIM method (Fig. 4) [14], [15].

The second step performs the interrogation itself, by emitting successively the time-returned response of each possible transducer. A significant returned signal, as defined by a returned voltage above a given threshold, indicates that the particular sensor under investigation has responded to our request. This strategy is applied to two acoustic delay lines with transfer functions in the 2.4-2.48 GHz range provided by Carinthian Tech Research (CTR, Villach, Austria). In order to demonstrate the identification and anti-collision capability of this method, the time-reversed impulse response of each chip is emitted using an arbitrary function generator sampling at 10 Gsamples/s, and the returned cross-correlation signal is monitored as a function of time on a digital oscilloscope (Fig. 1). Even though only a single bit differentiates these two delay lines and no design towards orthogonality of the codes has been considered, the returned power is significantly larger for the SAW delay line whose time-reversed response has been emitted. The cross-correlation maximum is located at 400 ns after the emission has been switched off – this offset being due to the removal of the 400 ns-long emission signal – and side lobes are obviously visible due to the lack of orthogonality of the codes.

Although this strategy is applicable to any reflective SAW design and has been demonstrated with devices provided by CTR, including an 8 bit coding (Fig. 1), manufacturing individual delay lines with different coding is not cost-effective, especially since anti-collision strategies require orthogonal coding and hence increased complexity of the mirror pattern definition. We will hence illustrate a novel reflective SAW delay line most suitable to our purpose. We will focus on devices complying with the 2.45 GHz ISM band, *i.e.* requiring less than 80 MHz bandwidth during the wireless radiofrequency probing.

### B. Transducer design

Ideally, orthogonal responses will maximize the signal to noise ratio. However, manufacturing a large number of orthogonally coded transducers is not technically sound since each device requires a given pattern. Since our purpose is to separate as much as possible the transfer function of each transducer with respect to the other responses of the transducer population, we aim at maximizing the information concentration by generating a random pattern. Practically, multiple reflectors are patterned on a single piezoelectric substrate, and boundary conditions are defined during a post-processing step. Since all interdigitated transducers (IDT) connected to the bus act as source, while each IDT left at floating potential acts as a mirror, the response of such devices is expected to be much more complex and sensitive to the time reversal approach than that of classical reflective delay lines in which a single

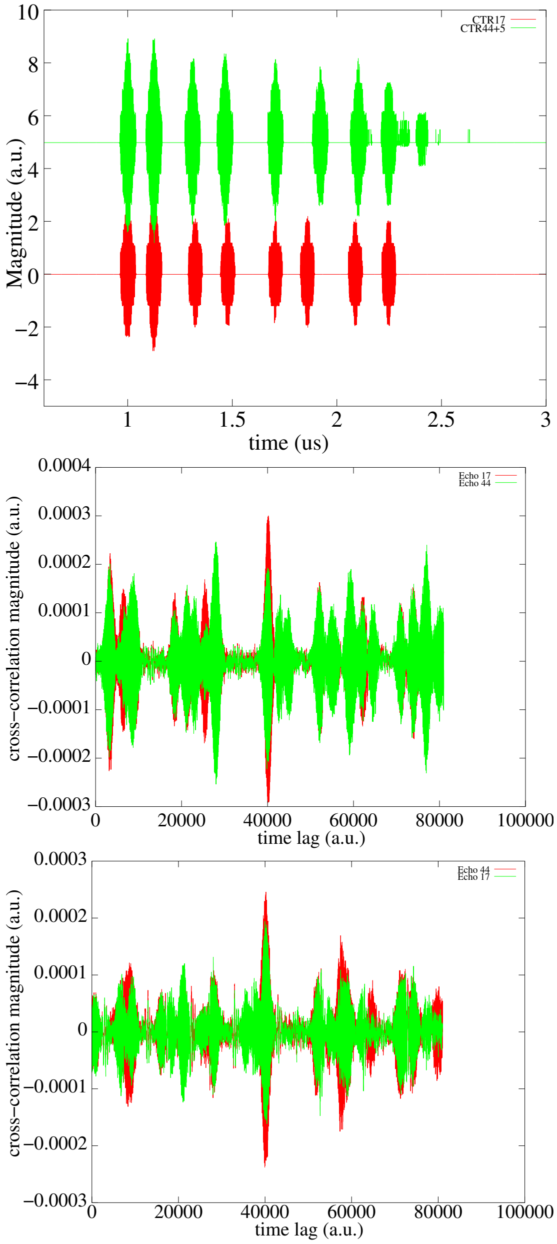


Fig. 1. From top to bottom : the impulse response of two chips, references 17 and 44 ; application of the time reversed impulse response of both chips to chip 17 ; application of the time reversed impulse response of both chips to chip 44.

transducer generates an acoustic wave reflected over multiple mirrors [16].

| $d_1$ | $d_2$ | $d_3$ | $d_4$ | $d_5$ | $d_6$ | $d_7$ |
|---|---|---|---|---|---|---|
| 600 | 1050 | 1500 | 1950 | 2400 | 2850 | 3300 |

TABLE I
TECHNOLOGICAL PARAMETERS OF THE DESIGN COMMON TO ALL TRANSDUCERS UNDER INVESTIGATION : THE SPACING BETWEEN ADJACENT IDTS IS GIVEN IN MICROMETERS.

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The basic design of the SAW delay line is common to all devices, as shown in Fig. 2 : eight IDTs are patterned on lithium niobate ($LiNbO_3$-128) and connected to a same electrical potential. The spacings between adjacent IDTs are reported in table I.

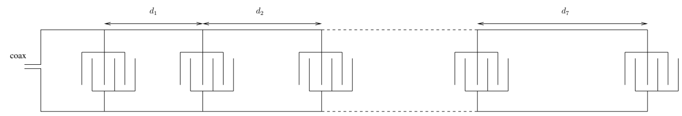


Fig. 2. Common SAW device design : this pattern is etched thanks to a single lithography step on a whole lithium niobate wafer to provide the basic reference design for the further processing steps.

Following the batch manufacturing at a wafer scale of identical acoustic delay lines, post-processing consists in severing tracks connecting the interdigitated combs to the bus. Table II exhibits whether the transducers are (1) or not (0) connected to the bus for this population.

| n$^o$ | connection to electrical bus | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 |
| 2 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 |
| 3 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 |
| 4 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 |
| 5 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 |
| 6 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 |
| 7 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 |
| 8 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 |

TABLE II
LIST OF CONNECTIONS OF THE IDTS TO THE BUS.

Because each IDT connected to the bus acts as a source, predicting the time-domain response of such devices requires accurate numerical modelling and can hardly be intuitively deduced from the IDT pattern. As an example of modelling, Fig. 4 exhibits a comparison of a mixed matrix modelling of the time-domain $S_{11}$ transfer function of the reflective delay line, and the experimental measurement obtained through inverse transform of the characteristics recorded on a network analyzer.

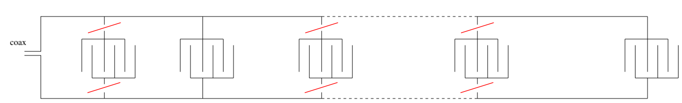


Fig. 3. As an example of SAW device individualization and identifying the parameters reported in table II, this schematic describes the layout of SAW device number 7.

## III. EXPERIMENTAL RESULTS

### A. Experimental setup

A arbitrary-function radiofrequency generator Tektronix AWG7122B sampling at a nominal rate of 10 GHz is used to program the emitted radiofrequency pattern. A digital oscilloscope records the baseband signal reflected from the transducer. While all demonstrations are performed in a wired configuration, the concept is applicable to a wireless transmission when connecting the two instruments either in a monostatic or bistatic antenna configuration : here, the wired setup is representative of a monostatic antenna configuration since the oscilloscope triggers on the emitted signal.

### *B. Initialization step*

The response of each transducer must first be recorded individually during the initialization step. This response is either obtained through simulation or experimentally, as shown in Fig 4. This recorded signal will be time-reversed before emission by the arbitrary function generator so that the probed transducer physically performs the cross-correlation and returns a significant power only if matching conditions occur.

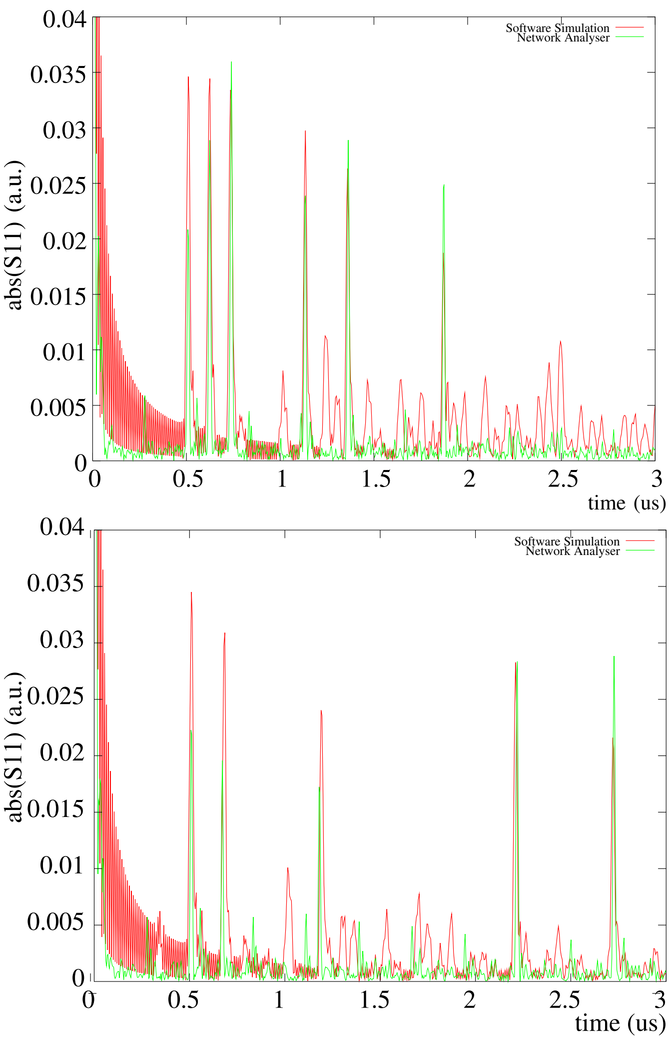


Fig. 4. Comparison between simulation and experimental $S_{11}$ transfer functions of devices number 2 (top) and 7 (bottom). The network analyzer results are scaled by 5.5 for matching the magnitudes of the reflection peaks.

A comparison of the magnitude of the returned signal for all devices under investigation – recorded here through inverse Fourier transform of the $S_{11}$ network analyzer measurement – is shown in Fig. 5. The diversity of impulse responses is emphasized by the few echos occurring at the same delay.

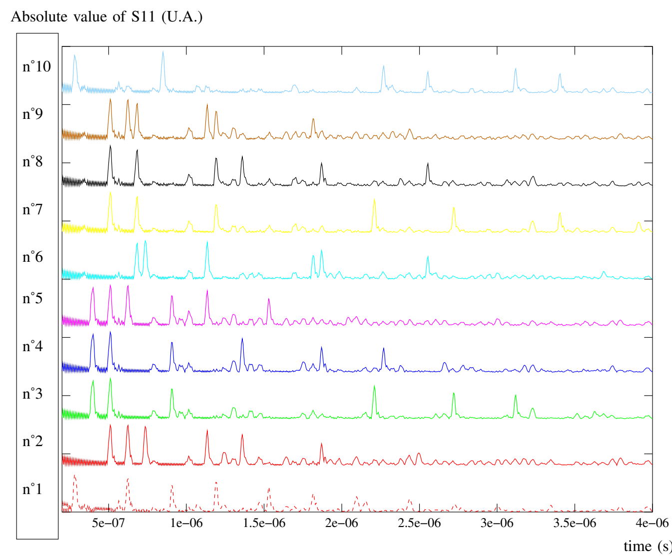


Fig. 5. Result of the measurement of the ten devices under investigation by inverse Fourier transform of the network analyzer $S_{11}$ data.

Practically, the network analyzer record (as opposed to the result of simulations) is used for the next experiment. In fact, some mechanical effects have not been simulated, such as manufacturing parameter dispersion. The population of SAW device responses was recorded between 400 ns and 3.6 $\mu$s, and will later be used after time domain reversal.

### *C. Identification of diffusive delay lines*

Having recorded the time-domain response of a given SAW delay line, the time reversed transfer function is sent by the arbitrary function generator. Among the list of all stored time-domain responses, two devices were probed in this way, numbers 2 and 7, with the signal generator sending the vector lasting 400 ns, and the oscilloscope recording the response of the SAW device after the end of the excitation signal emission.

We observe, since the the SAW transducer performs the convolution of its transfer function and the incoming signal and hence the cross-correlation between its transfer function and the recorded transfer function, a maximum returned power when the emitted signal matches the transfer function of the probed delay line. Since no orthogonal coding was used in designing this particular set of transducers, the ratio of the maximum returned power to the background signal of the unmatched transducer is two (Fig. 6).

### *D. Temperature measurement on diffusive delay lines*

Having identified time reversal as an interrogation strategy able to identify an acoustic transducer among a population (Fig. 7), the remaining issue lies in the physical quantity measurement. The quantity under investigation – temperature – yields a velocity change if the acoustic wave propagation on the sensor surface, observed as a scaling of the time domain (Fig. 8). This figure exhibits the excellent selectivity capability

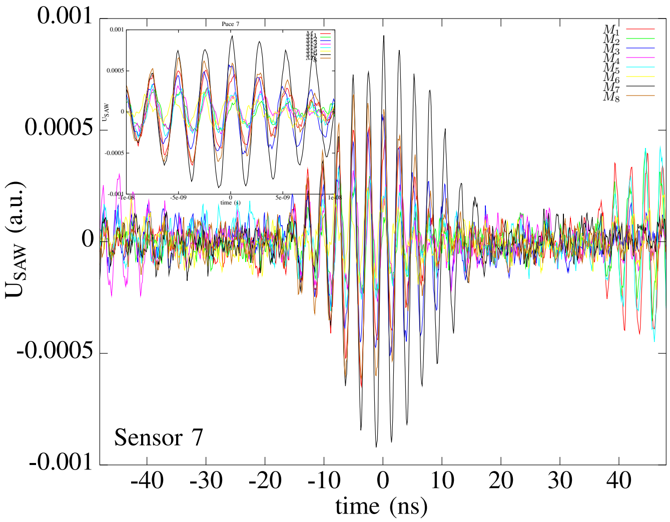


Fig. 6. Voltage of SAW device number 7, 400 ns after sending the recorded, time-reversed, reference signal using the arbitrary waveform generator. The returned power from the matching transducer is twice as large as the returned power (cross correlation) of all the other transducers.

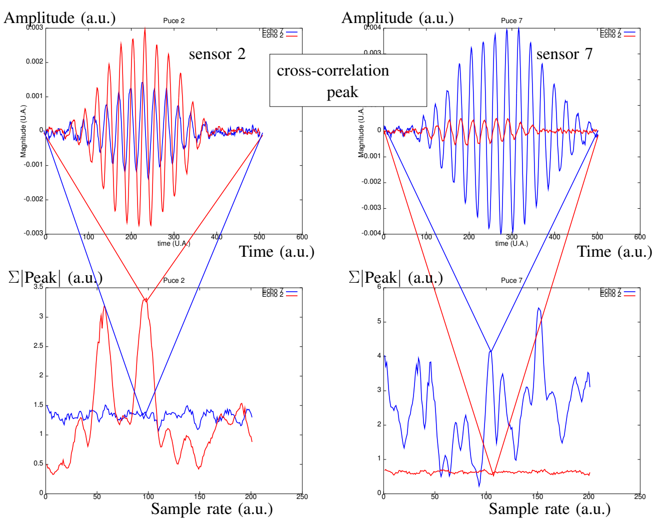


Fig. 7. Anti-collision capability between the two chips – references 2 and 7 – described earlier. Although the sidelobes are significant, the cross correlation as a function of sampling frequency is maximized for the probed transducer.

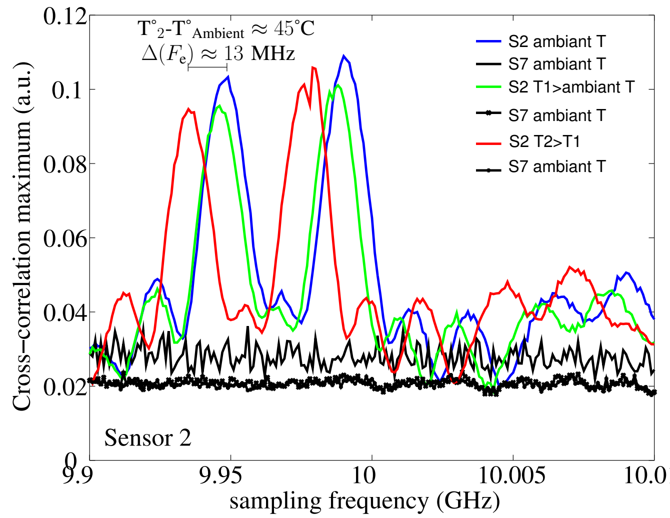


Fig. 8. Scaling of the sampling frequency of the emitted wave as a function of temperature. Tuning the sampling frequency allows for identifying the sensor temperature since it compensates for the velocity change due to temperature. This scaling does not prevent the anti-collision capability since the cross-correlation of one time-domain response to another transducer never reaches the level of the identified sensor.

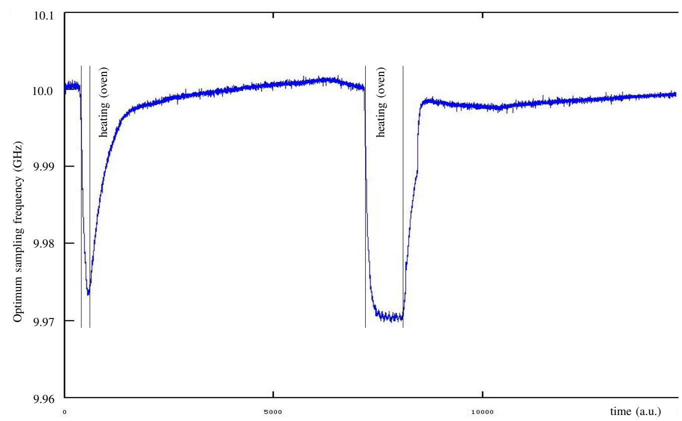


Fig. 9. Temperature measurement by tracking the sampling frequency of the emitted waveform in order to maximize the cross-correlation returned signal.

of the algorithm : while applying the time reversed response of sensor number 2 to the chip number 7 always yields a constant and low cross-correlation maximum value, applying the same sequence to chip number 2 (the chip whose response matches the interrogation signal) yields significant maxima : the sampling frequency for which these maxima are observed is related to the acoustic velocity and thus the physical quantity under investigation. Sweeping a whole frequency range is not practical due to the excessive interrogation time, so a feedback control aimed at maximizing the cross-correlation peak by tracking the emitted wave sampling frequency is implemented. The temperature of a sensor located in an oven is thus monitored (Fig. 9).

## IV. Sensor family selection

Thanks to the advent of rapid modelling capabilities, all possible impulse responses for combinations of IDT connections to the bus are computed for a design including 8 reflectors. Criteria for selecting [17], [18], among all these combinations, a subset of transducers so that the identification and measurement capability within this family are considered. We have considered the following criteria :

1) maximize the returned power, *i.e.* the number of reflectors. This criterion aims at removing all the transducers with very few reflectors which obviously maximize the cross-correlation (since reflectors do not overlap in the time domain) but with such a low returned power that the interrogation range is degraded,
2) minimize the cross correlation in order to optimize the identification capability by reducing the returned power

from all other sensors when the returned time-domain response of a given sensor is emitted,

3) minimize the sidelobes in order to reduce the chances, during the measurement step, to lock the sampling frequency feedback loop on a sidelobe whose magnitude might drop within the measurement range.

The map of these criteria for all sensor combinations with 8 reflectors is shown in Fig. 10.

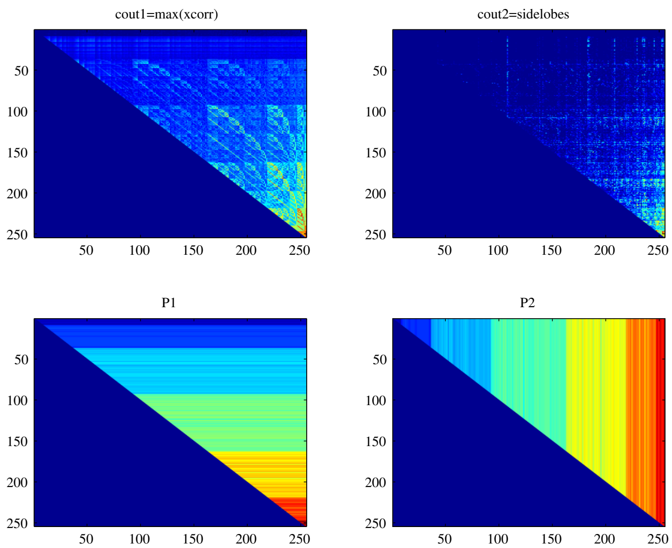


Fig. 10. Cost function based on an analysis of the modelled responses of all possible 8-reflector combinations of delay lines. Bottom : autocorrelation should be maximized (maximum returned power). The returned power for the first (P1) and second (P2) chip considered in the cross-correlation calculation are considered, so that P1 (left) and P2 (right) provide the same information. Top : cross correlation maximum (left) and sidelobes (right) should be minimized. The complex structures of the latter graph, especially when a large number of IDTs act as emitters, hint at a complex selection process of the optimal family.

## V. Conclusion and perspectives

We have considered the time-reversal interrogation strategy as a means to probe multiple radiofrequency acoustic transducers from a single reader, providing measurement and anti-collision capability. When used with a single antenna, this interrogation method is similar to a cross-correlation approach in which emitting the time reversed impulse response of the sensor uses the latter as a matched filter returning a maximum cross-correlation pulse.

A strategy for large scale manufacturing of such devices is considered by severing the connection of some of the IDTs to the bus. Although in this work the connexion of each transducer to the bus has been selected manually, we have considered systematic criteria to select chips within a family aimed at minimizing their cross-correlation and this anti-collision capability. Since modelling the transfer function of these acoustic transducers accurately describes the practical behavior, more robust strategies aimed at generating a set of orthogonal codes should be used, including genetic algorithms which appear ideal candidates to yield a set of devices as far away from each other as possible.

Dedicated hardware electronics with a sampling rate of 10 GS/s was needed to play back the time reversed impulse response of each sensor during an experimental demonstration of temperature tracking : reducing this sampling rate in order to provide embedded electronics with similar capability has shown significantly degraded performances, and thus remains a challenge.

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