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Adaptive Filtering for FSCW Signal-to-noise Ratio Enhancement of SAW Interrogation Units

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Abstract. A digital filter that improves the signal-to-noise ratio of the response of a FSCW (Frequency Stepped Continuous Wave) scheme is presented. An improvement in signal-to-noise ratio represents an enhanced readout distance. This work considers this architecture as an interrogation unit for SAW tags with time and phase encoding. The parameters of the proposed digital filter, which is a non-linear edge preserving filter, were studied and tested for this specific application. An improvement of around 20dB in the SNR level was achieved. This filter preserves the phase of the signal at the time position of the reflectors, which is critical for correct identification of the code in phase encoding schemes.

1 Introduction

RFID technology is one of the most important breakthroughs of modern technology. This is because it is cheap, versatile and handy. Lately, RFID has appeared to be an interesting sensor design platform. RFID sensor tags have been emerging in the market, capable of detecting temperature, pressure, strain and other physical parameters [1] [2]. These devices are made by laying thin metallic fingers over a piezoelectric substrate in a periodic arrangement, generating a structure known as inter-digital transducer (IDT). When an electric potential is set on the transducer, the electrical energy contained in the transducer is converted into mechanical energy, by the inverse piezoelectric effect, generating an acoustic wave that propagates over the surface. When this wave hits other metallic fingers along the propagation path, the reflected wave travels back to the transducer. This second metallic structure is known as reflectors. Then, when the wave travels back to the transducer, such transducer converts the acoustic wave back into an electric potential that contains the information of each reflector; specifically, the time delay it generated. The combination of all reflections generates a unique response, which represents a code. This configuration is known as time encoding scheme, as seen in Figure 1.

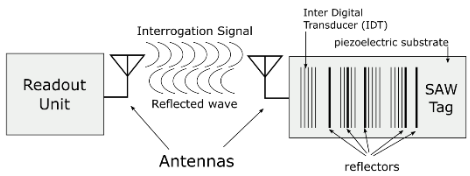

Figure 1. Overall Interrogation Configuration

Because no other energy source rather than the interrogation signal is required to obtain the code, it is possible to have passive sensor SAW tags. This condition sets an upper bound for the number of reflectors a tag may have; hence, restricting the number of possible codes. Fortunately, this data restriction was overcame by the global SAW tag. The global SAW tag is capable of having a data capacity up to 96 bits, making it EPC compatible [3]. To achieve this, the global SAW tag combines two types of encoding: time and phase encoding schemes. The second scheme, phase encoding, generates a change in the phase of the reflected signal by slightly moving the reflectors from their original time encoding position. Consequently, information is contained in the time position of the reflector and in the phase of the reflected signal [4]. Additionally, global SAW tags may be used as sensors [5]. The key to exploit the full RFID SAW technology is to count with an adequate interrogation unit.

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The Frequency Stepped Continuous Wave (FSCW) scheme is commonly used for SAW tag interrogation. The signal used by this architecture is a frequency varying signal, i.e. a chirp waveform, in which frequency varies through time (see Figure 3). Although the reflectors are time encoded, it is possible to identify the position in time of each reflector by detecting the frequency difference between the interrogation signal and the reflected signal.

The main blocks of the interrogation unit are depicted in Figure 2. A great advantage of this configuration is that it is compatible with the time and phase encoding scheme. To guarantee this compatibility, some parameters of the interrogation unit must be slightly adjusted.

The data processing module may present different structures [6], but one of the most studied processing schemes is the inverse Fourier transform. If the inverse Fourier transform is applied to the signal, it is possible to obtain the time location of each reflector. To achieve accurate detection, is necessary to perform a pre-processing. This pre-processing procedure is known as windowing [7]. After passing the signal through the window, the code is identified by locating the peaks that cross a defined threshold, which correspond to the reflectors response.

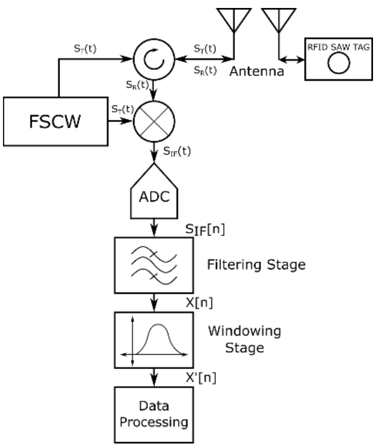

Figure 2. FSCW Scheme for SAW tag interrogation

This paper proposes an adaptive filter approach to improve the difference between the noise floor and the peaks of each reflector, which represents the signal-to-noise ratio, by using a non-linear edge preserving filter. The greatest advantage of this filter is its compatibility with the FSCW scheme, and the fact that it preserves the original phase of the reflected signal, independent from the parameter set of the filter. If the noise floor is reduced, the threshold level may be lowered and the readout distance may be enhanced

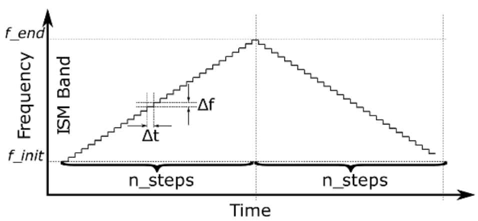

Figure 3. FSCW Interrogation Signal

2 Filtering Stage Design

2.1 Finite Impulse Response (FIR) Filter

The interrogation signal, $S_T(t)$, shown in Figure 3, is as follows:

$$S_T(t) = A_T \cos\left(2\pi\left(f_0 + \frac{K}{2}\cdot n\right)\cdot t\right) \qquad (1)$$

Where f_0 is the initial frequency and $K/2$ corresponds to ΔF.

Consequently, the intermediate band signal is given by:

$$S_{IF}(n) = \sum_{i=1}^{p} A_i \cdot \cos(2\pi K \tau_i n + 2\pi f_0 \tau_i) \qquad (2)$$

Where τ is $2d/c$, in which d represents the complete propagation path, from the readout antenna to the tag, and c is the speed of light. Each f_i frequency corresponds to the product between $f_i = K\tau_i$. These condition implies that the reflector information, i.e. the delays of each reflector, are contained both in the frequency of the reflected signal as in its phase.

Based on the latter, the cut-off frequency of the linear low pass filter must be chosen accordingly to the minimum band where the reflector information is contained. This imposes two constraints for the cut-off frequency of the filter. The first one is that the frequency must be two times greater than the highest frequency generated by the frequency generating module. In the case of the second constraint, this cut-off frequency must be less than two times f_0, for the selected SAW encoding scheme [3]. Regarding the reflector delays, the highest τ_i must be approximately $1.2\mu s$, which corresponds to an interrogation K value of $120\ KHz$. This represents that the cut-off frequency is selected to be greater than $K\tau_i$; therefore, the cut-off frequency should be at least 144Hz.

2.2 Non-Linear Edge Preserving Filter

In the FSCW interrogation scheme, frequency varies in a ladder waveform as a function of time. Every step of this ladder presents a discrete variation of frequency. This is indeed an edged signal, as shown in Figure 4.

It is critical for the SAW time and phase encoding scheme that the filter does not introduce phase distortion, because such distortion would prevent the correct detection of the tag's code. This is why the non-linear edge preserving filter was considered. Its topology is compatible with edges, as the ones present in any FSCW signal. Additionally, the filter preserves the original phase of the signal, independent from the filter's parameters.

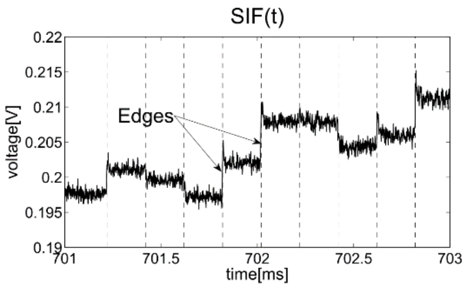

Figure 4. Edged response in a section of SIF(t)

The filter described in equation 3 is a filter that adaptively adjusts its response to the signal's nature, rather if it is a smooth or and edged signal [8]. According to this, the filter can be modelled as:

$$\hat{s}_i = \frac{\sum_{j=1}^{N} w(r_j - \tilde{s}_j) \cdot r_j}{\sum_{j=1}^{N} w(r_j - \tilde{s}_j)} \qquad (3)$$

Where:
$r'_j s$ is the j^{th} value of the data that requires filtering,
$\tilde{s}_j$ is an an estimate of the original signal in the moving window,
$w(\cdot)$ represents the weighting function,
$\hat{s}_i$ represents the filtered signal, and N is the filter's length.

The weighting function of the filter is defined as follows:

$$w(x) = \begin{cases} 1 \; for \; |x| \leq h \\ 0 \; for \; |x| > h \end{cases}$$

Figure 5 depicts the selected scheme. This is a representation of the filter's operation in the sample domain. For value estimation, a horizontal window of N samples is introduced. It is necessary to calculate an estimator $\tilde{s}_j$ for each sample window. In this particular case, the estimator corresponds to the data median. It is possible to use any other estimator at this stage. However, the median estimator selection is due to the simplicity of its implementation. Consequently, this filter calculates the median of all the r_j values that meet the condition of being at a distance not greater than h from the median. Those outside this distance are simply dismissed. This data selection scheme guarantees that for an adequate N value, the filter will detect the signal's edges. Yet, impulsive values that are far from the median will not be considered.

2.3 Filter Implementation

2.3.1 Finite Impulse Response Filter

Figure 6 presents a portion of the $S_{IF}[n]$ signal through the FIR lineal filter described in 2.1. As it can be seen in the figure, the filter smooths the plain regions of the signal; unfortunately, it is not capable of preserving the edges of it. This is due to the characteristic response of the filter, i.e. its inertia, which estimates the future values based on a defined quantity of former values. This previous data quantity depends on the filter's order. Higher order filters generate higher inertia. However, reducing the filter's order has a negative impact on its quality.

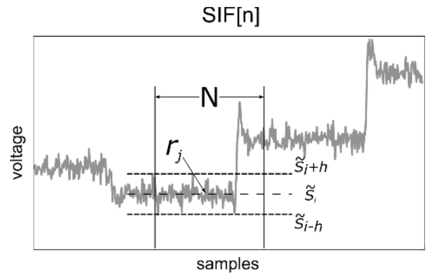

Figure 5. Edge Preserving Filter Scheme

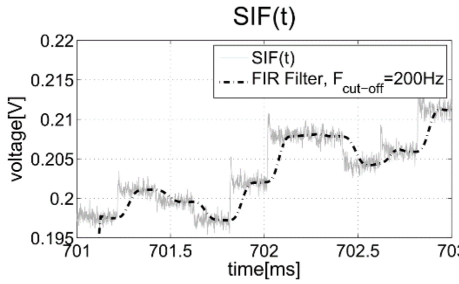

Figure 6. FIR Filter Resonse, cut-off frequency=200Hz

2.3.2 Non Linear Edge Adaptative Filter

Figures 7 and 8 show a portion of the $S_{IF}[n]$ signal and the response of the adaptive filter, $X[n]$. The two design parameters of the filter are N y h, which represent the window size and the horizontal and vertical orientation of such window.

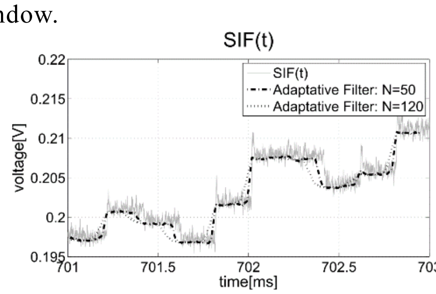

Figure 7. Adaptative Filter Response @N=20, h=0.001[V]

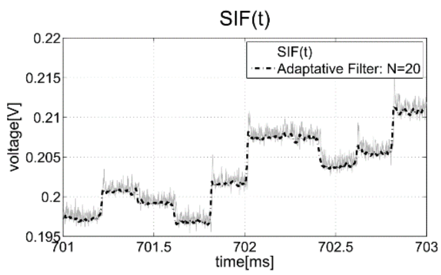

Figure 8. Adaptative Filter Response @N=50,120, h=0.001[V]

For small values of N, the filter performs an accurate edge detection, as it may be seen in Figure 7.Still, the data amount considered for estimation is not enough to generate a smooth response in the plain sections of the signal. Oppositely, if N is considerably increased, plain sections are smoothed but the edges are lost (see Figure 8). This is the case in which $N=120$. There is a clear trade-off that must be considered for the adequate selection of N. The optimal value of N mostly depends on the filtered signal's nature. According to the experimental data, the optimal value of N for this application is 50. This adjustment may be considered on any other application by evaluating the edge preservation and the desired smoothness of the signal.

In the case of h, this parameter was calculated according to the standard deviation of the noise floor of the signal. Consequently, the selected filter threshold h, which has volts units, is calculated according to the system's noise floor value σ_n^2. Equation 5 shows the relation between these two parameters.

$$\sigma_n^2 = 20log_{10}(h) \tag{5}$$

For the acquired data, the mean value of h was $0.001[V]$. Again, this value may be calculated for any application by doing an iterative algorithm that detects the system's noise floor before performing any filtering.

2.4 Experimental Setup

Our interest was to verify the effectiveness of the filter in a real SAW interrogation scheme. To achieve this, we used a software defined radio platform, which is connected to a computer that generates a 60MHz chirp signal (see Figure 3), in the 2.45GHz ISM band. This signal was the input of a microwave circulator, that had a planar antenna connected at port 2, and the radio platform's receiving input at port 3. This configuration can be seen in Figure 9.

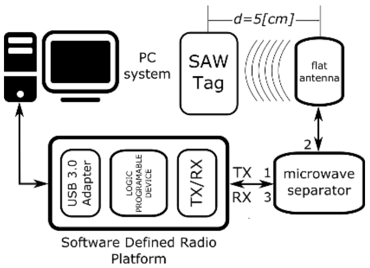

Figure 9. Experimental setup

For the SAW tag, a ST2450C tag from SAW Components [9] was used. These tags have high data capacity, which correspond to time and phase encoding schemes.

The tag was set at a 5cm distance of the antenna an interrogated by the radio platform. The platform digitalized the received signal and transferred the sampled intermediate frequency response of the received signal to a text file.

This text file was then loaded in MATLAB, where each filter was implemented in different scripts. After obtaining the filtered response for both types of filters, the window function, which was also implemented in MATLAB, was applied.

3 Results

Figure 10 presents the comparison between the response of the FSCW scheme without filter and after the FIR filter is applied. In both cases, the reflected signal is always passed through the window function. As seen in the figure, the FIR scheme improves the SNR level in about 10dB. This difference corresponds to the difference of the mean value of the noise floor for each case. As desired, the reflection delay peaks maintain their amplitude despite of the presence of the filter.

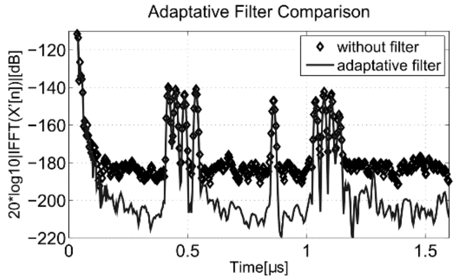

Figure 10. None vs. linear filter comparison

Figure 11 illustrates the non-filter scheme compared to the adaptive filter scheme. The configuration for the adaptive filter is $N=50$ and h is set according to section 2.3. The SNR level enhancement in this case is about 18dB, and as in the FIR implementation, reflection delay peaks maintain their original amplitude. The improved noise reduction, compared to the FIR filter, is due to the moving mean that the filter applies at each window. With such moving window, noise sources tend to be ignored because the mean is close to zero. This supports the hypothesis of setting h as the initial noise floor of the received signal.

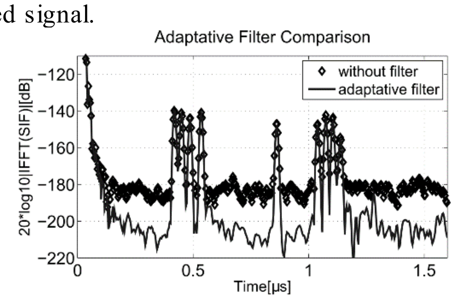

Figure 11. None vs. Adaptative filter comparison

Figure 12 presents the phase of the $X'[n]$ signal when the lineal filter is applied. The vertical asymptotes represent the maximum peaks. In the case of the FIR filter, if the filter window spots two consecutive edges, this filter is not longer capable of predicting the original phase, even when the SNR response is good. These FIR filters are not capable of adapting; hence, there is a risk of losing the phase information if the received signal changes.

Therefore, filter's order is a design parameter for the FIR configuration. However, it is difficult to re-calibrate this parameter during the interrogation execution. On the other hand, if the filter's order is reduced to avoid phase distortion, the SNR level enhancement is reduced. This is the consequence of a widened filter's rejection band that allows certain amount of noise.

Regarding the adaptive filter, the phase is preserved in every scenario. This is due to the robustness that emerges from the edge detection that the window performs. Every vertical asymptote's phase in the non-filter scheme matches with the phase of the adaptive filter scheme (see Figure 13).

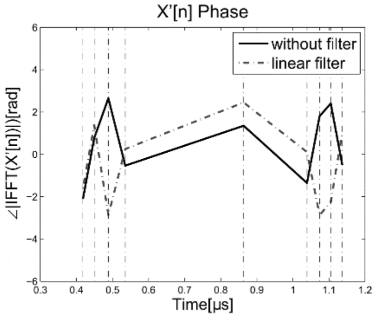

Figure 12. *X'[n]* phase for linear filter

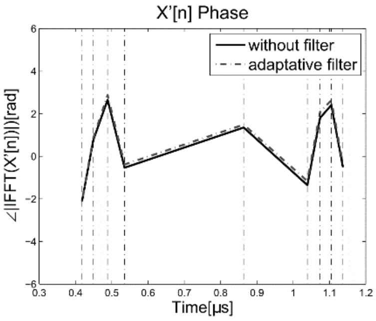

Figure 13. X'[n] phase for adaptative filter

4 Discussion

By applying a filter before the window function, it was possible to increase SNR level from the reflected signal. The increase of the SNR level was achieved by using two types of filters, FIR and non-linear edge preserving filters. However, the FIR configuration distorts the phase if the filter's order is not selected correctly. Because FIR filters are not capable to identify the edges of the signal, a previous processing in the signal must be performed to select an adequate order. This may result complicated if implemented. Additionally, this is undesirable for accurate phase detection. Oppositely, the edge preserving filter maintains the phase independently from the parameters of the filter. Consequently, non-linear edge preserving filters are adequate for SAW tag identification schemes where FIR filter adjustment cannot be performed on-line.

Additionally, the parameter configuration was also presented. These parameters, N and h, are dependent of the type of signal and the interrogation scheme. Still, this dependence is easy to detect. The sample number of the window, N, has an optimal value of *50* for this application. The noise median value, h, was set according to the initial noise ratio, i.e when no filter is applied. To guarantee this in a future implementation, a first iteration of the interrogation procedure must be executed to extract the noise level. Then, the digital filter is applied to improve the SNR level.

5 Conclusions

It is possible to enhance the SNR level by including a digital filter stage, rather if it's a FIR or an adaptive filter. This is very convenient because other SNR enhancing techniques are more complicated. For example, changing the radio-front section of the FSCW scheme may be expensive and time consuming. Similarly, using a data processing scheme, different from the IFFT, may result in complicated algorithms that are time consuming in computational terms and can represent an obstacle for the implementation.

The adaptive filter may be additionally enhanced by considering several estimators, beyond the median estimator considered. The estimator effects on the SNR improvement level may be also evaluated. Moreover, an on-line adjustment of the filters parameters may be achieved by performing a first iteration of interrogation without code detection. Smoothness and edge preservation parameters define the N parameter, and the system's noise floor is detected to set parameter h.

Regarding the implementation of the whole FSCW filtered scheme, this topology is compatible with commercial digital FPGA-based platforms. Hence, by introducing this filter in such platforms, the improvement of the readout distance can be experimentally verified.

Acknowledgement

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