Designing of a SAW RFID/Sensor Interrogator System

By

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13448

Dissertation submitted in partial fulfilment of

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(Electrical & Electronic Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved by

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Project Supervisor

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TRONOH, PERAK

May 2014

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Ahmed Saad Abdelhamid Mohamed Aboulnaga

ABSTRACT

The purpose of this report is to provide a brief idea about the final year project of the author and the progress achieved so far. The project aims to design a SAW RFID interrogator system on a lab scale, that interrogator would ideally be able to identify each of the SAW tags in its range. The project requires the combination of different scopes of fields such as wireless communication, signal processing and embedded systems.

In pursuit of these objectives, extensive research was carried out to find the proposed solutions by previous researchers. System simulation was used to assist in choosing the appropriate solution. This is followed by the design stage where the actual prototype is produced. The next stage is prototype testing and performance assessment. The project is now in the final stages, and should be completed in the few coming days.

ACKNOWLEDGEMENTS

The completion of my final year project and its report required a lot of assistance and guidance from a lot of people, and I would like to use the following lines to show my gratitude to all of them.

First and foremost, I would like to thank God Almighty, who is the ultimate source of all good, and who made everything that I have achieved possible.

Next, I would like to thank my parents for everything that they have done, and will do, for me throughout my life, my sister for her continuous support and encouragement, and all my family and friends as well.

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Table 1: List of Abbreviations

Abbreviation	Description
FYP	Final Year Project
WSN	Wireless Sensor Network
RF	Radio Frequency
RFID	Radio Frequency Identification
SAW	Surface Acoustic Wave
IDT	Inter-Digital Transducer
SNR	Signal to noise ratio
OFC	Orthogonal Frequency Coding
FMCW	Frequency-Modulated Continuous Wave
FSCW	Frequency-Stepped Continuous Wave
TDM	Time Division Multiplexing
FDM	Frequency Division Multiplexing
VNA	Vector Network Analyzer
CAT	Cable and Antenna Analyzer
SA	Spectrum Analyzer
VSG	Vector Signal Generator
VSA	Vector Signal Analyzer
MCU	Microcontroller Unit
ISM	Industrial, Scientific and Medical
AWGN	Additive White Gaussian Noise

Chapter 1
Introduction

1.0 Background of the Project

In industry, the presence of sensor networks is essential for monitoring and controlling purposes. They carry out the task of obtaining information about vital objects and processes and delivering them to the decision making units, these information can take the form of a certain physical or chemical property. The traditional medium for information transmission used to be wires, with their various types. However, there are situations where the presence of wires becomes unsuitable or even hazardous, especially in complex chemical processes. This is where Wireless Sensor Network (WSN) comes into picture. By using wireless communication techniques, WSN can deliver information from one location to another without the added complexity and potential danger of wires.

A wireless sensor network consists of several sensors which are distributed in different locations and are able to communicate with each other and/or with the decision making unit. There are various schemes and configurations for these networks each suitable for a different application. If the sensors are active, meaning that they are not only responsible for sensing, but also communicating that information, this will result in a very high power consumption at the sensors and will require the presence of a constant power source such as a battery, besides the frequent replacement of such batteries at each sensor. Depending on the conditions at which the sensors are operating, the process of replacing batteries could be difficult and dangerous, other than the danger of having batteries there in the first place. The alternative that overcomes this issue is a passive sensor. Passive sensors do not need to be active all the time. Only when they receive an external triggering signal do they send their information to the reader which is the only part of the WSN that requires access to a power supply [1, 2].

Another technology of interest is Radio Frequency Identification (RFID). It is capable of identifying different items by using radio waves to interrogate a tag. Interrogating means to extract the information encoded within the tag that would assist in identifying the item of interest. RFID is mainly used for management, security and access control applications.

A technology that combines both passive sensing and RFID is Surface Acoustic Waves (SAW). A SAW sensor consists of a piezoelectric substrate upon which lies an inter-digital transducer (IDT) and some metallic reflectors. The IDT receives the interrogation signal via the antenna and converts it, using the piezoelectric properties, into acoustic waves propagating along the surface of the crystal. Reflectors which are built in specific locations will cause successive partial reflections of the SAW which are received by the IDT, converted back to an RF and sent to the reader [3].

By analyzing the reflected signal at the reader, it is found that the interrogation signal has undergone certain attenuation due to the reflectors' effect. Changing the location or the reflectivity of the reflectors will change the attenuation pattern accordingly. That is why SAW devices can be used for object tagging and identification. By arranging the reflectors on each saw device, each device will display a unique response to the same interrogation signal. This is the concept behind SAW RFID technology [3].

SAW RFIDs are favorable over normal IC RFIDs due to their wide range, small size, low power requirement, and their ability to withstand extreme environmental conditions [3]. Another advantage over IC RFIDs is that SAW RFIDs can deliver information about their surroundings. Changes in physical properties such as temperature, pressure, strain and so on will cause a change in the crystal's dimensions which will affect the velocity of the SAW. Therefore, by analyzing the reflected wave of the SAW devices and comparing it to a reference response, it is possible to get a sense of that physical property. That is the reason why SAW devices are used as passive wireless sensors [4].

1.1 Problem Statement

In a network of SAW RFIDs/sensors, it is required to have a reader that is responsible for interrogating all the SAW sensors. This reader is basically a transceiver that transmits the interrogation signal that triggers the passive sensors. Each sensor has a unique tag built on it, in the form of metallic reflectors. With the help of these reflectors, the sensors encodes its identification information as well as the information it sensed onto the interrogation signal which is reflected back to the reader [5].

Once the reader receives the reflected signal it must be able to carry out signal processing to extract the information encoded within. The main challenge is when there are multiple sensors in the readers range and the reader must be able to differentiate the reflected signals from each sensor effectively. Another challenge that faces the reader design is to have a wider range without sacrificing the performance of the reader itself, and without consuming too much power.

1.3 Scope of Study

Completing this project requires three main scopes of study. First of all, the most obvious scope of study is the reader design which includes the hardware designing of the reader itself. Wireless communication is another necessary scope of study. It is required to perform the process of communication between the reader and the SAW RFIDs which is a wireless communication process. Finally, a big part of the project lies under signal processing field. It will become useful in the signal design stage as well as after the signal is received in order to decode the information contained within it.

Chapter 2

Literature Review

When it comes to the reader design, the reader is required to generate the interrogation signal and receive and decode the reflected signals. It can be broken down into a transmission path and a receiving path. The transmission path consists of a signal generator that generates the appropriate interrogation signal, an RF frontend that converts the generated signal to radio frequency, and an antenna that transmits the signal. The reflected signal is received at the antenna then is fed into an analog baseband for further adjustment before finally arriving at the digital signal processing unit to extract the information from it[6-8].

The first challenge that faces the design is that after the antenna transmits the signal, a residual transmit power will remain there for a period of time, and will interfere with the received signal messing with the accuracy of the extracted information. Which means that an efficient reader must be able to achieve separation between the transmission and receiving paths. A simple solution is to use two separate antennas for transmission and receiving, however, it will increase the complexity and the cost of the design. Alternatively, a single antenna could be used with a separation element such as a circulator or a hybrid. Yet the performance of the reader becomes limited by the isolation capability of that element. Another approached which is called switched FSCW takes advantage of the slow propagation rate of surface acoustic waves on the substrate which is approximately 3400-3500 m/s [3, 9]. During the transmission phase, the receiving path is completely terminated from the antenna, and it remains that way until the residual transmit power have decayed, and vice versa [6].

Undoubtedly, the main challenge is when the reader is dealing with multiple tags. The more tags there is, the more likely it is that two or more of them will have very nearly the same distance from the reader, and therefore their reflections will arrive at the reader at almost the same time from different angles resulting in an interference which can either be constructive or destructive. Many research has been done to overcome this obstacle. The most obvious solution is to design the sensor network such that sensors will have distinct distances from the reader relative to the wavelength of the interrogation signal [6].

In many cases, the previously mentioned solution is not practical and therefore other alternatives have been proposed. One of these solutions is by using matched filters. If all the tags within the measurement range are known, and their impulse responses are known as well, then by using the time inverse of one of those impulse response as the interrogation signal, then the reflected signal of that tag will have the autocorrelation peak while the signals reflected from all other tags will be the result of a cross correlation and will have a lower amplitude [10].

Another approach to this problem is the utilization of multiple readers or antennas. By distributing multiple readers/antennas all over the measurement range the function of each reader becomes much simpler and the measurement becomes faster. The main drawback of this approach is the substantial increase in the complication of the hardware design as well as the cost. If the measurement speed was not a priority then we can reduce the complexity and the cost by continuously switching between antennas instead of operating them in parallel. Alternatively, having multiple antennas can be used for Digital Beam-Forming (DBF). By having an array of uniformly spaced antennas, the phase delay of the signal at each antennas will be different. A spatial filter then uses these information to separate signals based on the angle of their arrival[6].

Now when it comes to the signal design itself, there are many alternatives. The most commonly-used technique is to send a very narrow pulse and measure the received signal which is the impulse response of the tags. The problem with this method is that a narrow pulse contains very little energy within it, and therefore, the signal-to-noise ratio (SNR) would be very high. An alternative to this method is by using Spread Spectrum techniques. Spread spectrum implies sending the signal that has undergone spread coding over a much wider bandwidth than what was required for the original signal. Therefore, the signal would have a much signal to noise power ratio compared to the original impulse. The received signal is then correlated with the spread code to produce the impulse response [11].

Pulsed-interrogation can also be used with Orthogonal Frequency Coding (OFC). Instead of having conventional delay-line SAW devices, which contain reflectors that merely reflect the interrogation signal after a certain delay, OFC devices are used. In OFC devices, the reflectors are resonators that resonate at a predetermined frequency in response to the interrogation signal. Each OFC resonator has its own center frequency that is orthogonal to the center frequencies of the other resonators. That is to say that the interrogation pulse is amplitude-modulated with a continuous wave at the resonator's center frequency. Therefore, the response signal is a series of chips of continuous waves at different frequencies. OFC can be combined with Time Division Multiplexing (TDM) or Frequency Division Multiplexing (FDM), for multiple-sensor scenarios [12-15].

A SAW interrogator is, in concept, no different than a radar. That is why different radar techniques are being used with SAW sensor networks. For example, alternatives to pulsed-interrogation are Frequency-modulated Continuous Wave (FMCW), and Frequency-stepped Continuous Wave (FSCW). FMCW is basically a sinusoid whose frequency is stepped up continuously over the interval of interrogation while in FSCW the stepping up is discrete. In other words, FMCW and FSCW can be thought of as frequency modulating a ramp function and a ladder function respectively. Since the tags respond to changes in the interrogation signal frequency, the received signal is the frequency response of the tags, and must undergo Discrete-time Fourier Transform (DTFT) if we are to analyze the impulse response[9, 16, 17].

As for signal processing, most researchers carry out the signal processing via a personal computer and using software filters designed by MATLAB codes [7, 8, 18]. Finally, [19] suggests using a software-defined radio instead of a hardware reader. This is to increase the system's flexibility and compatibility with highly dynamic situations.

Chapter 3

Methodology

3.1 Project Methodology

According to what have been explained earlier in the literature review, there are many alternatives in each part of the design, each alternative has its own advantages and disadvantages. So, in order to select between these alternatives, system simulation must be carried out. System simulation is to be carried out using MATLAB software and Simulink Toolbox. The results of this simulation is to be studied in order to find out which alternative yields the best results in our situation.

Since carrying out this project requires channel characterization via impulse response measurement, the author must be trained in that area. The training is to take place on two stages. First of all, the author is to be trained to use a Vector Network Analyzer (VNA) for channel characterization. Then channel characterization using both Vector Signal Generator (VSG) and Vector Signal Analyzer (VSA) is the second stage of training.

After training, the final stage is the implementation stage. The reader is to be designed using a Microcontroller Unit (MCU) Development Board. The board will serve as the signal generation and the signal processing units of the readers. An RF module will also be required to complete the project.

There are a few obstacles that stand in the way of producing a complete prototype. Firstly, the development board only produces a digital output which is incompatible with RF modules. Which means that the prototype would require a DAC/ADC module to interface between the board and the RF module, and that module should be able to accept a digital input via the expansion port or a USB port which are the available peripherals at the board. Another obstacle is that the suitable RF module could not be identified. Seeing that the RF module must be able to operate at the center frequency of the SAW devices, and since SAW devices rarely operate in the 2.4 GHz ISM band, where most RF modules are available, a complete prototype requires designing the RF module to be tailor-made to the SAW devices at hand. All of which is beyond the scope of our final year project.

Another obvious issue here is that in order to evaluate the performance of the system, it is required to have the actual SAW tags present then. However, the designing of the tags is an independent project and the timelines of the two projects were not aligned. Therefore, it is more practical to exclude the RF module and the DAC/ADC module from the prototype and focus on programming the MCU to generate the required signals, which can be measured using an oscilloscope, and perform the required processing in the Baseband. Moreover, since no SAW tags are available, project evaluation shall take place in a simulated environment.

3.2 Project Flow Chart

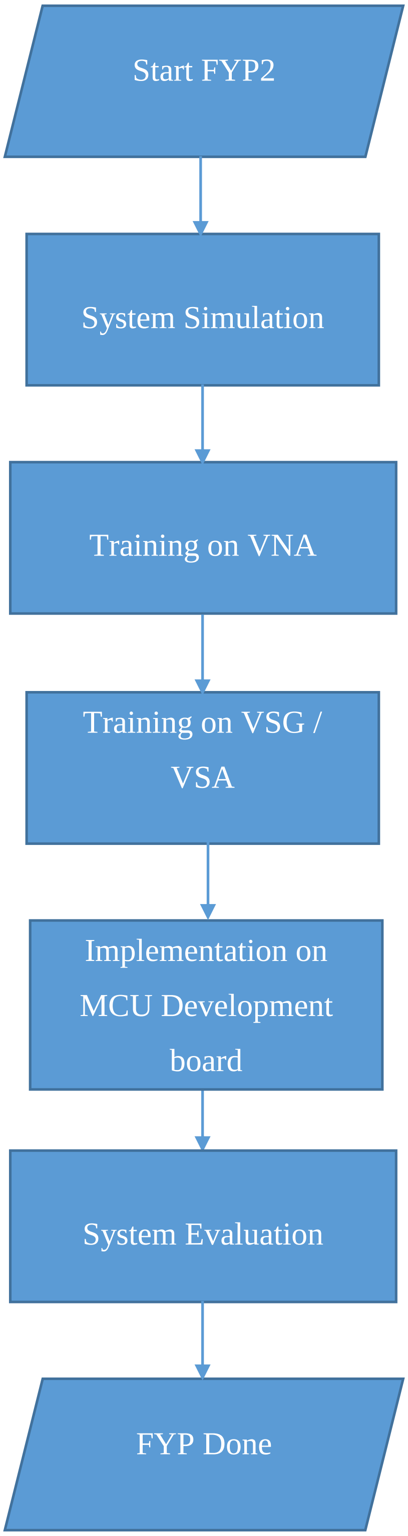


Figure 1: Flow chart for the project

3.3 Gantt Chart and Key Milestones

Table 2: Gantt Chart

Task \ Week	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Project Simulation	🟩	🟩	🟩	🟩	🟩	🟩								
VNA Training							🟩	🟩	🟩					
VSG/VSA Training									🟩	🟩	🟩	🟩		
MCU Implementation										🟩	🟩	🟩	🟩	🟩
System Testing and Evaluation														🟩

Table 3: Key Milestones

Milestone	**Duration**
Project Simulation	6 weeks
VNA/VSG/VSA Training	6 weeks
MCU Implementation	5 weeks
Testing and Evaluation	1 week

3.4 System Parameters

The following section provides justification for all the parameters used in the system simulation. In order to carry out the system simulation, a complete visualization of the system has to be obtained. There are many scenarios where SAW RFIDs can be used. One scenario is that there are multiple tags in the reader's range, the response of each tag is known, but the location of each of them is unknown, this is also known as localization. In this case the reader uses its prior knowledge of the response of each tag to determine the distance between each tag and the reader. Localization is much easier when there is only one SAW device. In that case, not just the distance, but two-dimensional coordinates of the tag's location can be obtained using multiple antennas.

Another possible scenario is that there is a single tag whose location is known but whose response is unknown, like in the case of SAW sensors where the response depends on the value of the measured property. In that case, the reader must have a reference response, e.g. the response of a temperature sensor at a reference temperature, and use this to determine the value that the sensor is measuring. The scenario chosen in this project is the first one; multiple tags of known responses but unknown locations.

The desired output is a lab-scale prototype, which is supposed to be operating in an indoor wireless communication scenario. The system consists of one reader or interrogator in addition to the tags. The channel is assumed to be AWGN channel with signal to noise ratio of 50 dB. The reader is supposed to operate in the 2.4 GHz ISM band, so the bandwidth is around 100 MHz. Since the propagation speed of the radio waves in space is five orders of magnitude faster than the SAW wave, the multipath components are lumped together and their effect is neglected. That is why the free-space path loss model is chosen to study the signal attenuation between the reader and the tags and vice versa.

The tagging system is assumed to be a 2-bit tag system which would result in a maximum of $2^2 = 4$ tags. The tags represent binaries 00, 01, 10 and 11. Each tag consists of three reflectors; one reference reflector and two reflectors that generate the unique tag. The delay of each reflection is determined by the location of the reflector. We assume that the tags are designed in a way so that the reference reflection takes place after a delay of 1 μs, bit zero would have a delay of $0.1\ \mu s$ and bit one would have a delay of $0.15\ \mu s$. This means that for the tag "01", if the signal arrives at the tag at time $\frac{t_0}{2}\ \mu s$, there would be a reference reflection at $(t_0 + 1)\ \mu s$, a reflection for bit zero at $(t_0 + 1.1)\ \mu s$ and another reflection for bit one at $(t_0 + 1.25)\ \mu s$.[1]

The four tags are stationed at 1, 2, 3 and 4 meters away from the reader. This would result in a maximum transmission delay of $\frac{2\times 4m}{3\times 10^8 m/s} = 26.667\ ns$, and maximum propagation delay of $(1 + 0.15 + 0.15)\ \mu s = 1.3\ \mu s$. The total delay of the system is then $1.33\ \mu s$. For FSCW the interrogation signal is supposed to have a bandwidth of 10 MHz divided into 10 steps of 1 MHz each. As for OFC System, for simplicity, only 1 tag with 5 OFC chips has been considered. The RF up-conversion and down-conversion have also been neglected in the OFC system model for the same reason. The OFC tag consists of 5 chips having the frequencies 20, 60, 100, 40 and 70 MHz.

Assumptions made are summarized at the following table:

Table 4: Assumptions for system simulation

Variable	**Value**
Communication Scenario	Indoors (Laboratory)
Bandwidth	100 MHz ($f_c = 2.45\ GHz$)
Signal Attenuation Model	Free-space path loss
Number of bits per tag	2
SAW Tags	00, 01, 10 and 11
Delay for reference reflector τ_r	1 μs
Delay for bit zero τ_0	0.1 μs
Delay for bit one τ_1	0.15 μs
SNR	50 dB
Simulation time	1.5 μs
FSCW Bandwidth	100 MHz
FSCW Step Size	10 MHz
OFC chips per tag	5

---

[1] For a complete journey, the radio frequency travels from the reader to the tags and back. So the total time delay for the RF in the air is $t_0\ \mu s$

Chapter 4

Results and Discussion

4.1 System Simulation

The Simulink model for the reader is as follows:

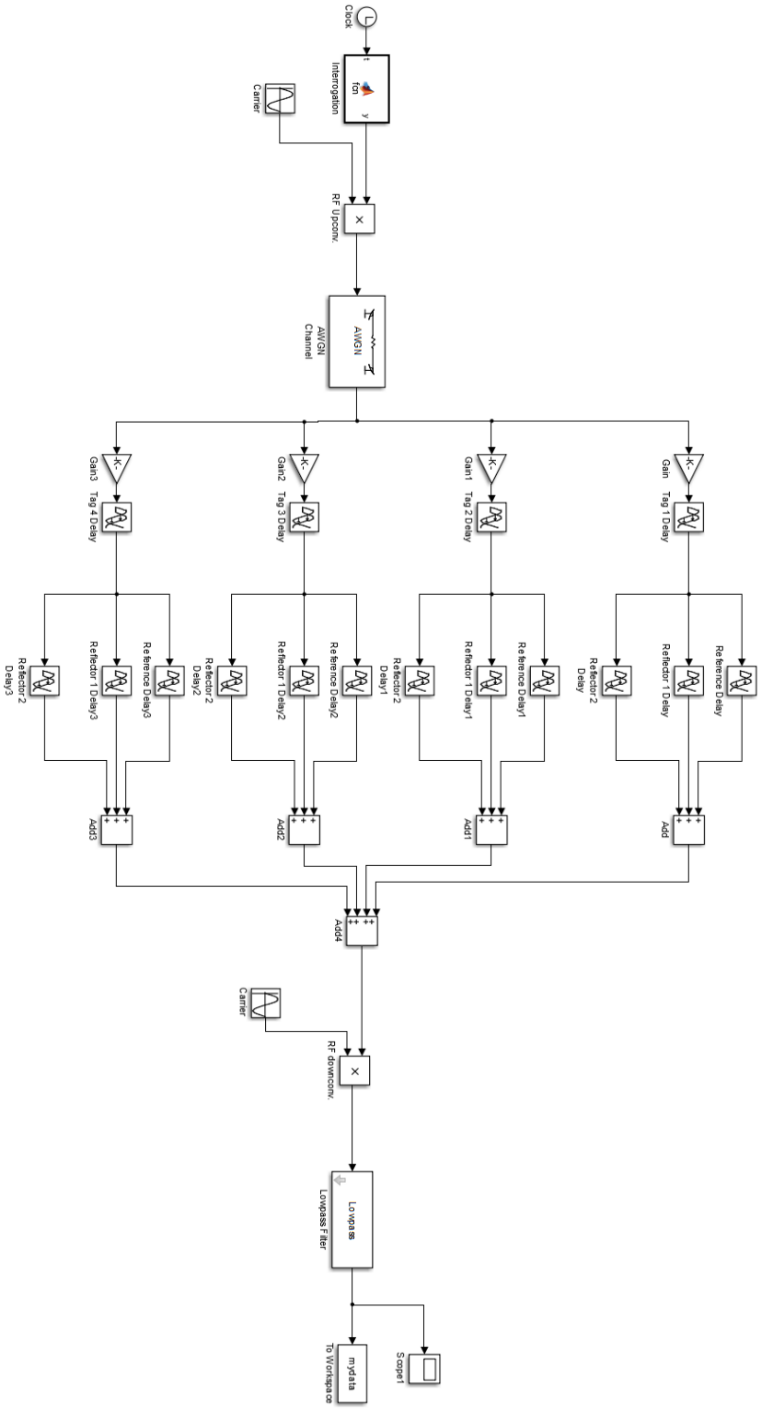


Figure 2: Simulink Model for the interrogation system

For deeper analysis, the simulated system can be divided into the following five stages:

1. Signal Generation
2. RF Up-conversion
3. SAW Tags
4. RF Down-conversion
5. Signal Processing

The first two stages are shown in this figure:

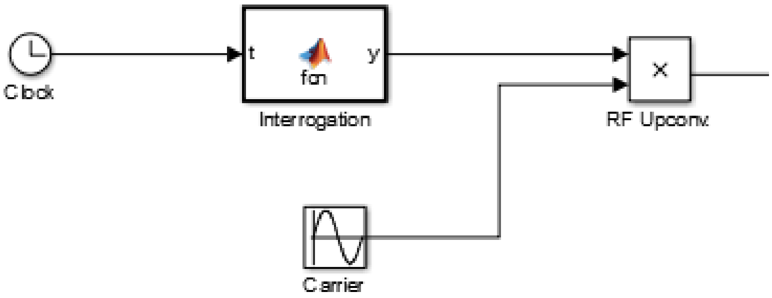


Figure 3: Signal Generation and RF up conversion

The interrogation signal is generated using MATLAB function block which will differ depending on our choice of the interrogation signal, while the carrier signal is generated using a sine wave block. RF up-conversion is achieved by multiplying the interrogation signal with the carrier signal.

The third stage, simulates the effect of the channel and the response of the tags. Therefore, it starts with the AWGN block, whose signal-to-noise-ratio is set to 50 dB. Each of the four SAW tag is represented by five blocks. Firstly, there is the gain block which simulates the attenuation in the signal power due to path loss. Since free-space path loss model is used, the gain constants K_1, K_2, $K_3$and K_4 can be calculated using the formulae:

$$K_x = \frac{P_{r,x}}{P_t} = \left[\frac{\sqrt{G_l}\lambda}{4\pi d_x}\right]^2$$

Where G_l is the antenna gain and is assumed to be have a unity value, λ is the wavelength of the radio wave which is $\lambda = \frac{c}{f} = \frac{3\times10^8}{2.45\times10^9} = 0.122\ m$, and d_x is the distance between the reader and the respective tag.

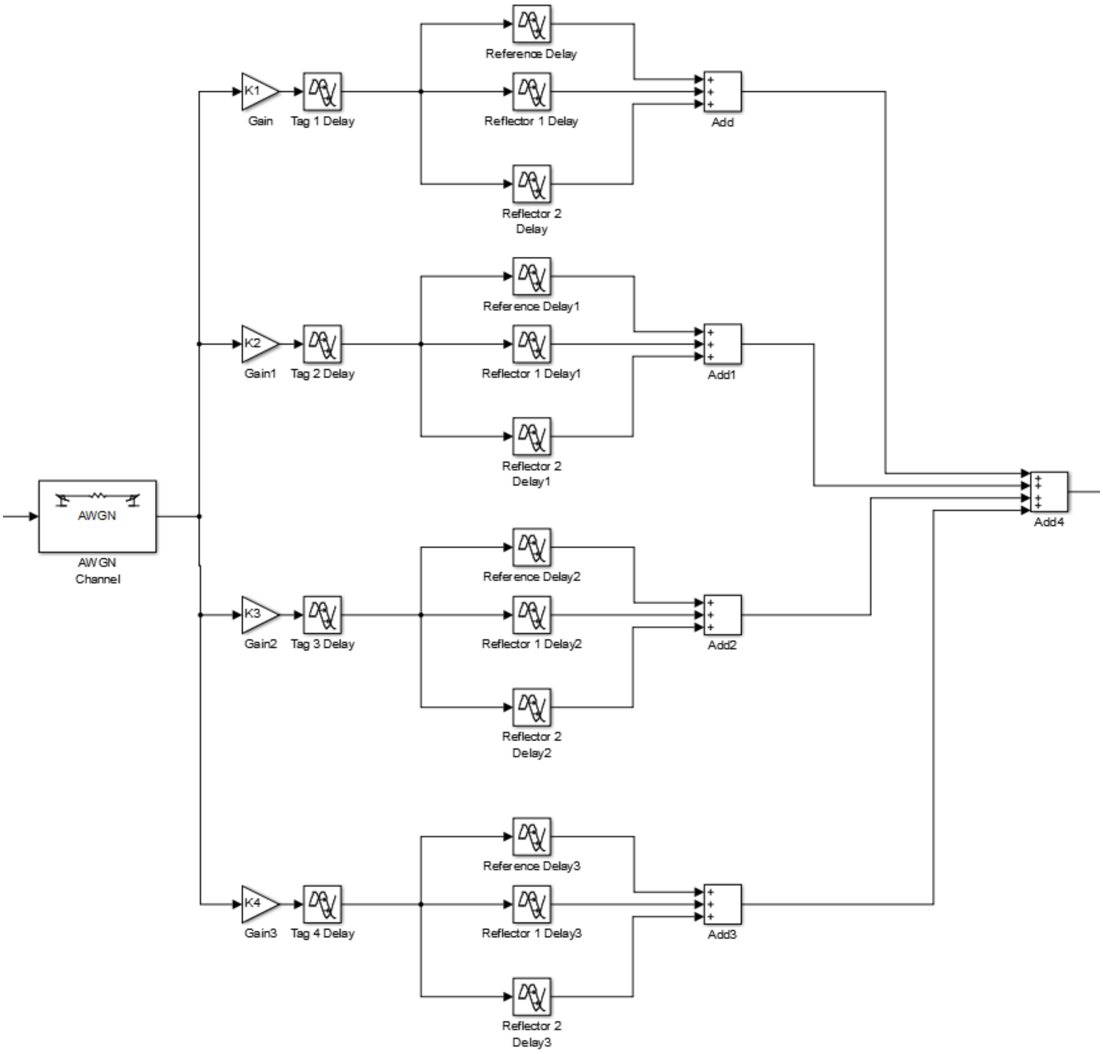


Figure 4: System model for the channel and SAW tags

From that we conclude that the values of the gain constants are:

$$K_1 = \left[\frac{0.122}{4\pi \times 1}\right]^2 = 94.95 \times 10^{-6}$$

$$K_2 = \left[\frac{0.122}{4\pi \times 2}\right]^2 = 23.74 \times 10^{-6}$$

$$K_3 = \left[\frac{0.122}{4\pi \times 3}\right]^2 = 10.55 \times 10^{-6}$$

$$K_4 = \left[\frac{0.122}{4\pi \times 4}\right]^2 = 5.93 \times 10^{-6}$$

After the gain, comes a delay block to simulate the time taken by the interrogation signal to reach the respective tag and back to the reader, which can be calculated from the equation:

$$t_x = \frac{2d_x}{c}$$

Hence

$$t_1 = \frac{2}{3 \times 10^8} = 6.67\ ns$$

$$t_2 = \frac{4}{3 \times 10^8} = 13.33\ ns$$

$$t_3 = \frac{6}{3 \times 10^8} = 20\ ns$$

$$t_4 = \frac{8}{3 \times 10^8} = 26.67\ ns$$

After that, comes three delay blocks in parallel to simulate the delays that occur within the SAW device where each block is supposed to simulate one of the tag's reflectors. Each tag has a reference delay of 1 μs, and two delays which depend on the tag as explained in the previous section. Finally, all these instances of the interrogation signal are summed together at the reader.

The next part is the RF down-conversion, which is achieved by multiplying the received signal with the carrier signal and applying a low pass filter to the product to extract the baseband signal.

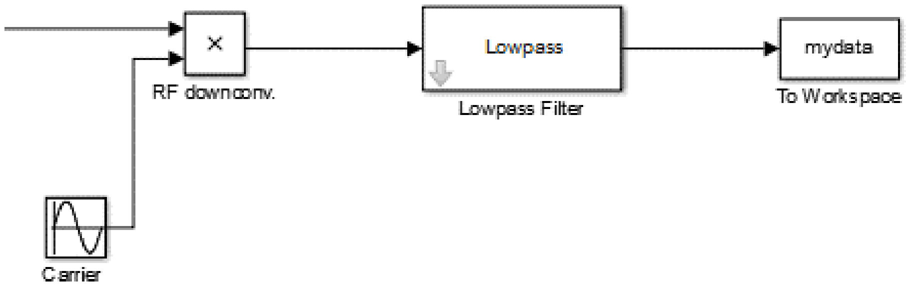


Figure 5: RF Down-conversion

The final stage of the reader system, which is the signal processing is done using MATLAB. Therefore, the output of the low pass filter is exported to MATLAB workspace where further analysis can be carried out.

As explained earlier, the MATLAB code for signal generation will depend on our choice of the interrogation signal. If we chose the pulsed interrogation, then we need the interrogation block to generate a narrow pulse. Since the minimum delay between the tags is $6.67\ ns$, then the pulse width needs to be smaller than that delay to avoid the interference between the reflectors' responses. The transmitted pulse in this simulation is only 2 ns wide. It is transmitted after 50 ns of the simulation start.

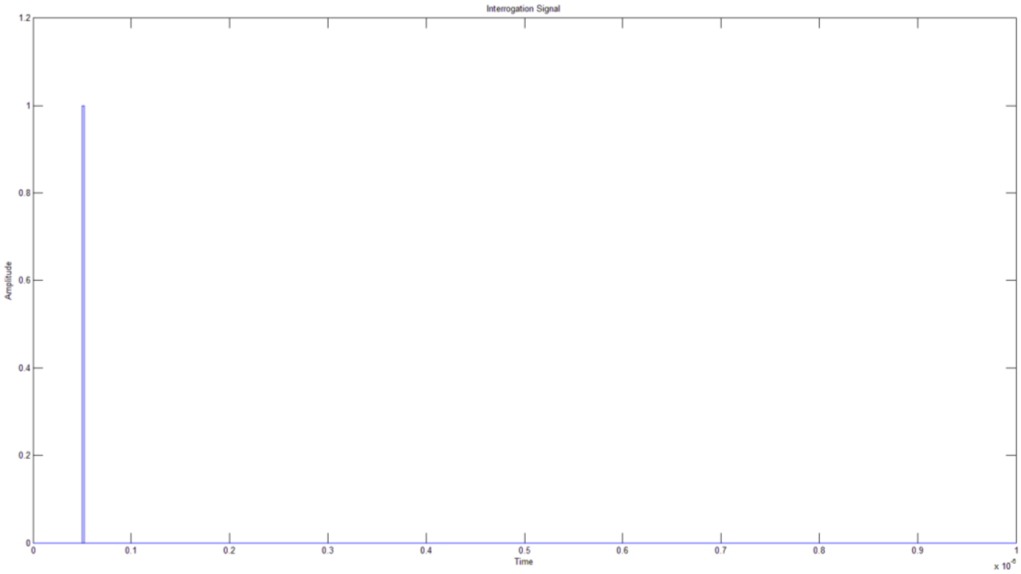


Figure 6: Pulsed-Interrogation Signal

The response obtained from the system contains the combined response of all the four tags as indicated by the following figure. It can be seen that the responses of each tag are distinct in their amplitude. It is also clear that the pulses do not overlap, which is the result of the correct choice of the interrogation pulse width

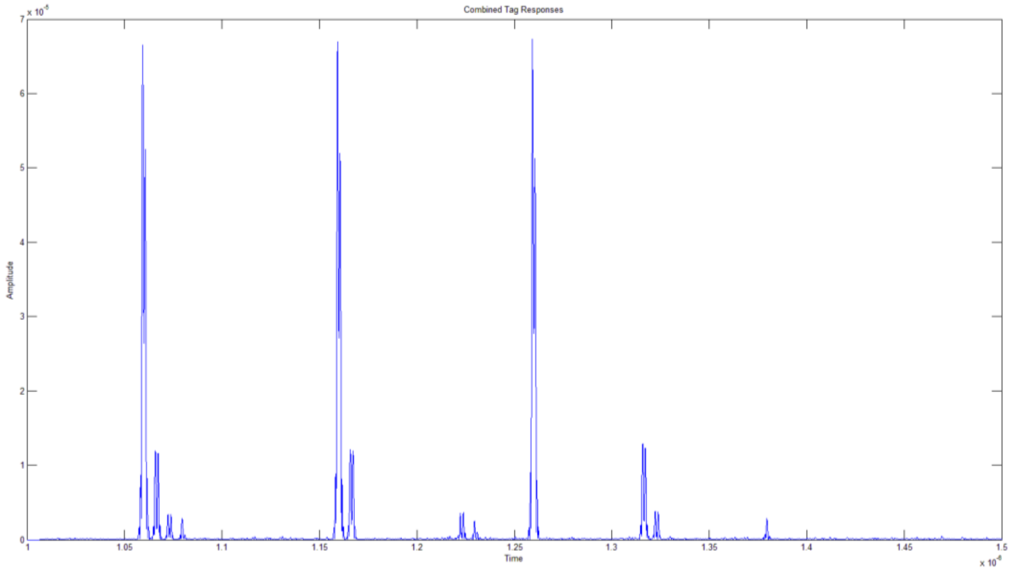


Figure 7: Overall system response

The extraction of information from this response is, by far, the most complicated task of all. In order to identify the location of each tag, for example, it is required to model each tag's response separately. Then these responses are each correlated with the overall response, and by searching for the autocorrelation peak at different time delays, one can identify the delay for the respective tag and use this information to determine the distance between each tag and the reader at the time of interrogation.

If the tag system is modelled properly, the impulse response of each tag is known in advance. This information can be used by the reader to separate the impulse response of each tag as indicated by this figure.

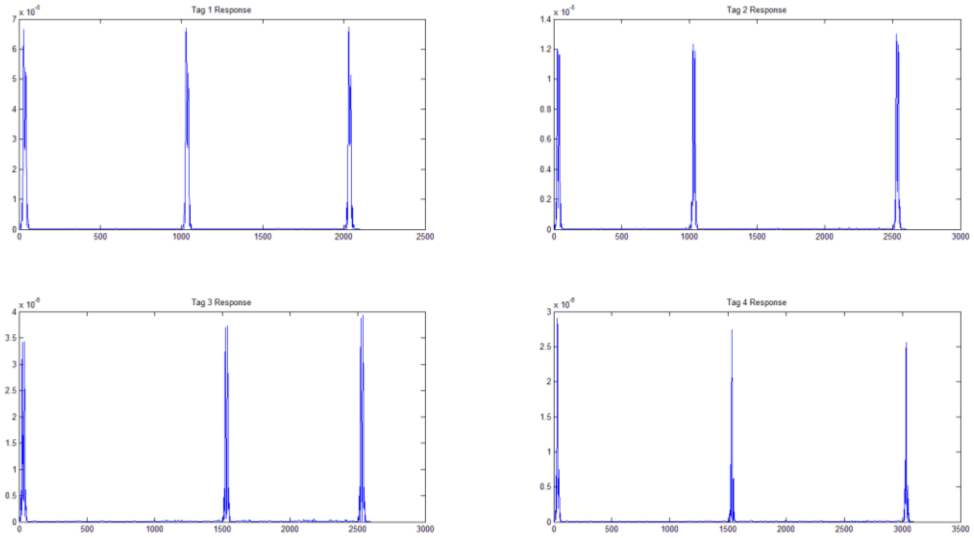


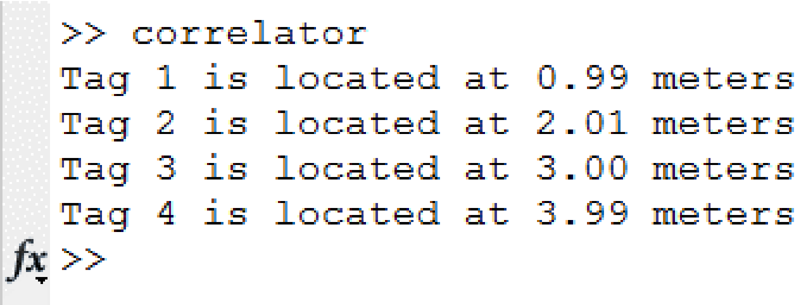
Figure 8: Modelling the response of each tag separately

The MATLAB code used to perform the correlation is stated below:

```
l1=length(tag1);
l2=length(tag2);
l3=length(tag3);
l4=length(tag4);
LX=length(combined);
i=1;
while(i<LX-l1)
   z=x(i:i+l1);
   zz=xcorr(tag1,z);
   CorrPeak(i)=zz(l1);
   i=i+1;
end
 [a,b]=max(CorrPeak);
delay(1)=(b-10499)*1e-10;
distance(1)=0.5*delay(1)*3e8;

CurrentTag=[zeros(1,b) tag1 zeros(1,(LX-l1-b))];
combined=combined-CurrentTag;
```

Note that the code above is only for identifying the location of the first tag, these operations have to be repeated for each of the remaining tags. The complete code will be provided in the appendix. The final results of the correlation is shown below. It is clear that these distances are in compliance with the actual distances used in the model.



```
>> correlator
Tag 1 is located at 0.99 meters
Tag 2 is located at 2.01 meters
Tag 3 is located at 3.00 meters
Tag 4 is located at 3.99 meters
>>
```

Figure 9: Correlation Result

In the case of choosing FSCW as our interrogation signal, our attention shifts to the frequency domain. So in order to avoid the interference between the reflectors responses, we must ensure that the bandwidth of the FSCW is greater than the inverse of the minimum time delay which is $\frac{1}{6.67ns} = 149.9\ MHz$. Therefore, the bandwidth chosen for our FSCW system modelling is 500 MHz, and the step size is 50 MHz and 0.01 μs.

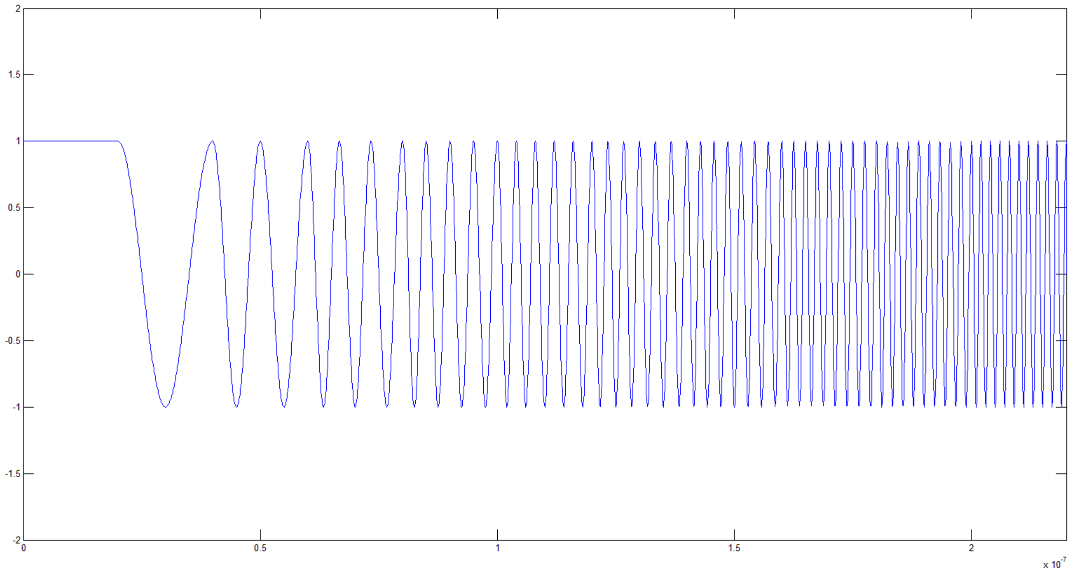


Figure 10: FSCW Interrogation Signal

The interrogation signal is not the only component affected when shifting from pulsed interrogation to FSCW, for the signal processing is also affected. Since the results are now in the frequency domain, Inverse Fourier Transform must be applied to the results in order to obtain the impulse response and be able to extract the required information from it.

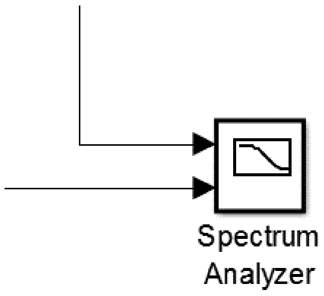


Figure 11: Spectrum Analyzer Block

The frequency response is measured by the Spectrum Analyzer block which compares the input and output of the system and calculates both the magnitude and phase of the frequency response of the channel.

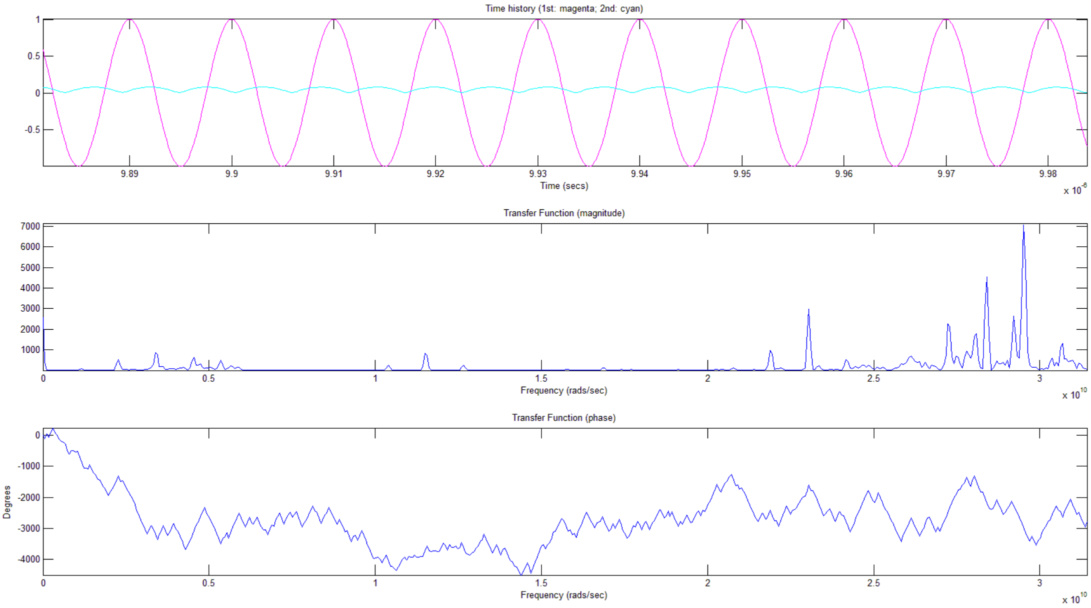


Figure 12: Frequency Response of the channel

As for the third alternative, The OFC, the generated signal is merely a narrow pulse, exactly like in pulsed interrogation. However, the model for the tag is much more complicated, which is why we only modelled the effect of a single tag.

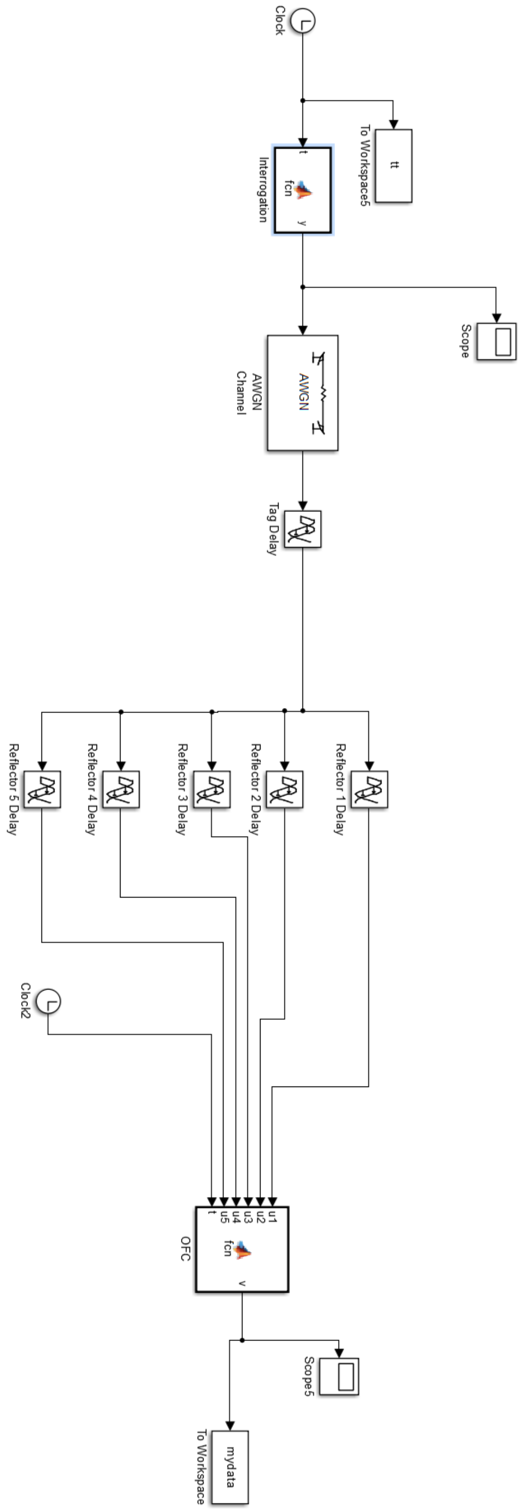


Figure 13: Simulink Model for OFC system

As indicated by the previous figure, each tag is modelled using several blocks. First of all, there is the initial delay that the RF signal encounters between the reader and the tag and vice versa. Since we chose to have five chips per tag, five instances of the initially delayed pulse are subjected to an additional delay dependent on the location of its respective reflector and then is amplitude modulated to the center frequency of the respective reflector. All five amplitude modulation operations are performed by the single MATLAB function block called “OFC” for simplicity. Then again, everything is summed up at the reader. In the case of OFC, the interrogation pulse is notably wider than the case of pulsed-interrogation, in order to accommodate the resonator’s response.

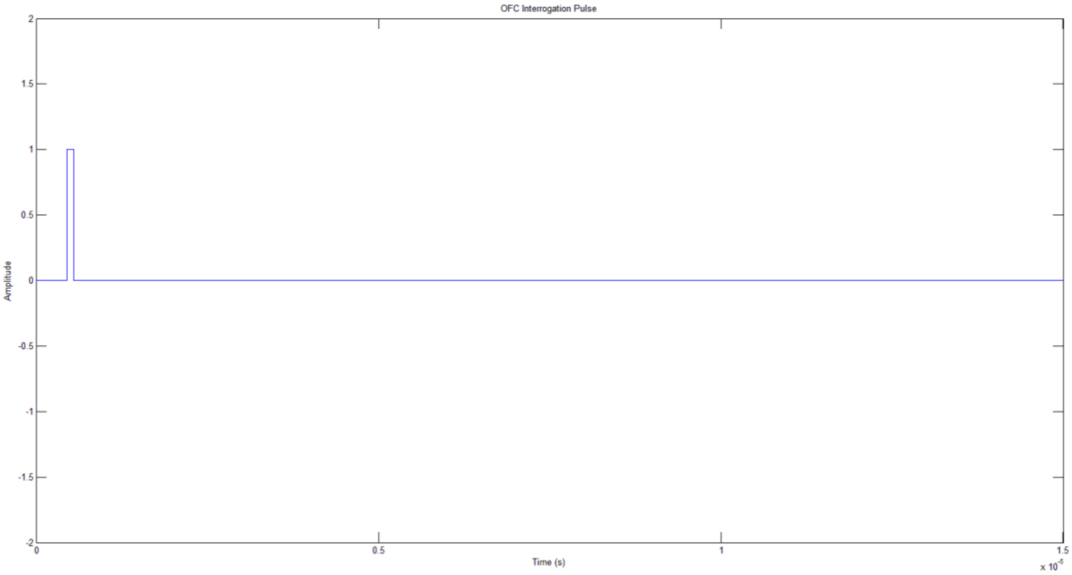


Figure 14: OFC Interrogation Pulse

The response of the OFC tag is shown below.

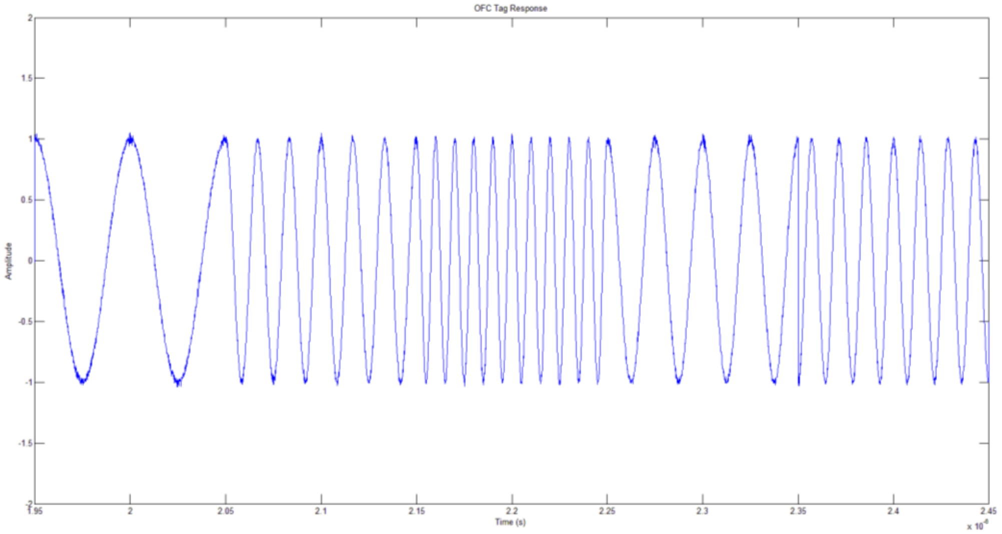


Figure 15: OFC Tag Response

4.2 VNA Training

The VNA training as merely a step in the path of VSG/VSA Training. Since the VNA combines the functions of both the VSG and the VSA in one device, but with significant limitations of course. These limitations will be discussed later in this section. The VNA at hand is an Agilent Technologies FieldFox RF Analyzer (N9912A 6 GHz) that was booked from the university’s laboratories.

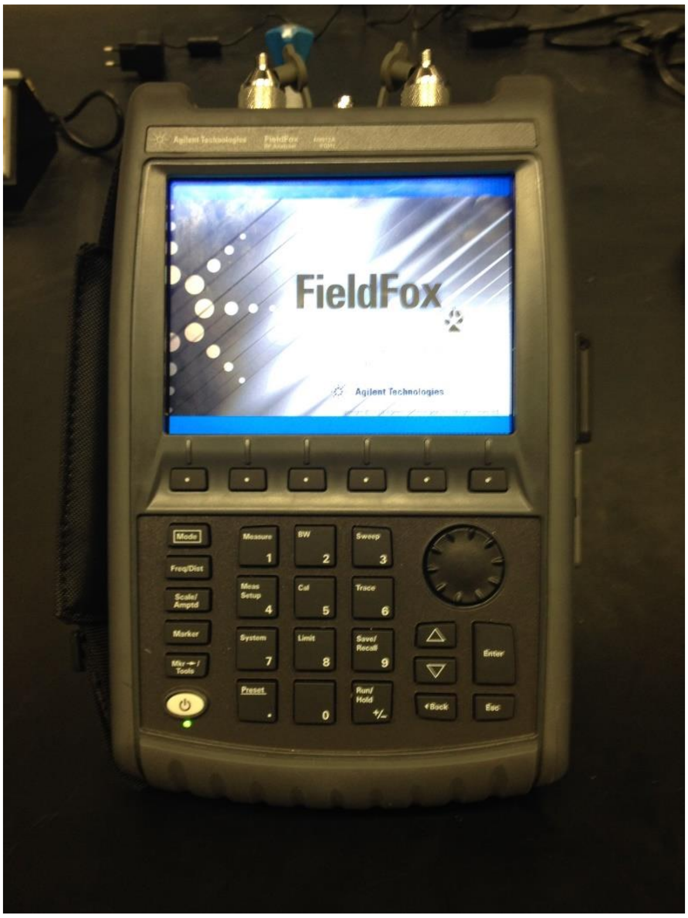


Figure 16: FieldFox RF Analyzer N9912A 6 GHz

This device is a device that combines the functions of three devices which are Network Analyzer, Spectrum Analyzer and Cable and Antenna Analyzer. The CAT is capable of performing return loss, insertion loss, cable loss, distance-to fault measurements. The NA is capable of measuring the S_{11} and S_{22} scattering parameters and transforming them into time domain analysis[2]. Finally, the SA is capable of measuring the channel power, occupied bandwidth and adjacent channel power ratio.

The author was trained to do simple calibration and channel measurements, and obtain the results using the device's user interface.

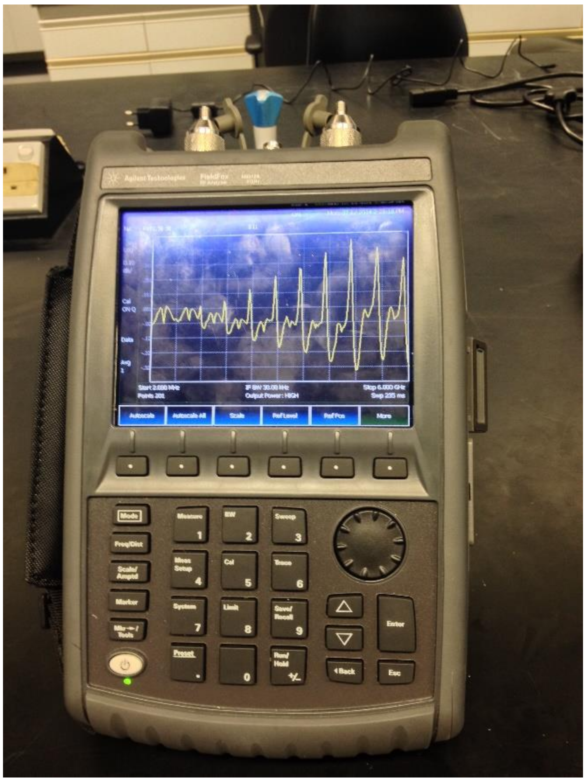


Figure 17: S_{11} measurements of the surroundings of the device

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[2] Time Domain analysis is an optional feature in the device that was not available in the acquired version

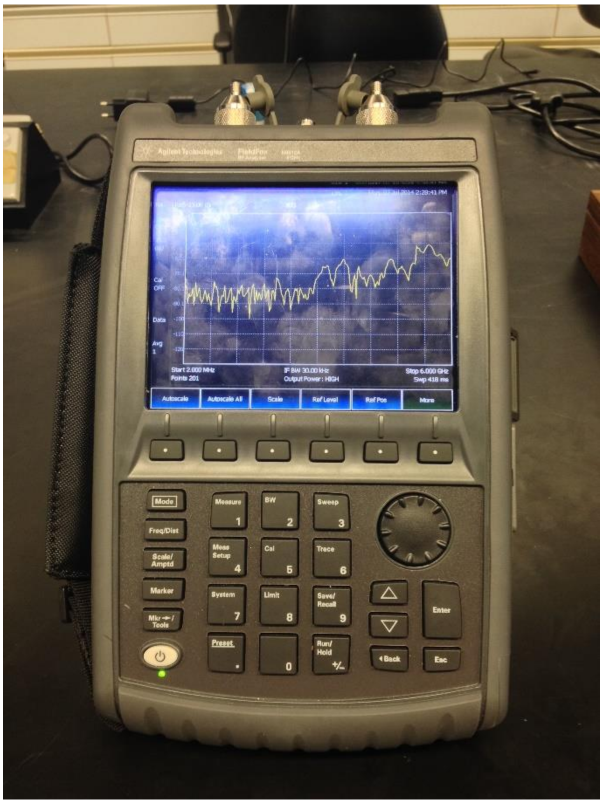


Figure 18: S_{22} measurements of the surroundings of the device

In order for the device to function properly it must be carefully calibrated. The device offers two modes of calibration; one is automatic calibration, while the other is the manual calibration using SOLT calibration kits. SOLT stands for (Short, Open, Load and Through), and the calibration kit contains standards with short circuit, open circuit, 50 Ohm loads and a through connection. After calibration, we started performing channel characterization using frequency sweeping of the channel.

Continue by attaching a load to the end of the cable, and pressing [Measure Load], or by leaving the cable end open and pressing [Skip Load].

Start: 2.000000 MHz
Stop: 6.000000 GHz
Points: 201

Figure 19: Calibration process for the VNA

The major limitation of the device however, is that this VNA is not a complete 2-port device, because it measures S_{11} in both magnitude and phase but only measures the magnitude of S_{21}. Which means that the extracted data cannot be converted into impulse response as was the original purpose of the training. That is why the VNA training was only a preparation for the VSG/VSA Training.

4.3 VSG/VSA Training

The purpose of this training is to get the author accustomed to measuring the frequency response and using it to obtain the impulse response. The VSG used in this training is The Agilent E8267D which is a fully synthesized signal generator with high output power, low phase noise, and I/Q modulation capability, while the VSA used is The Agilent M9018A PXIe.

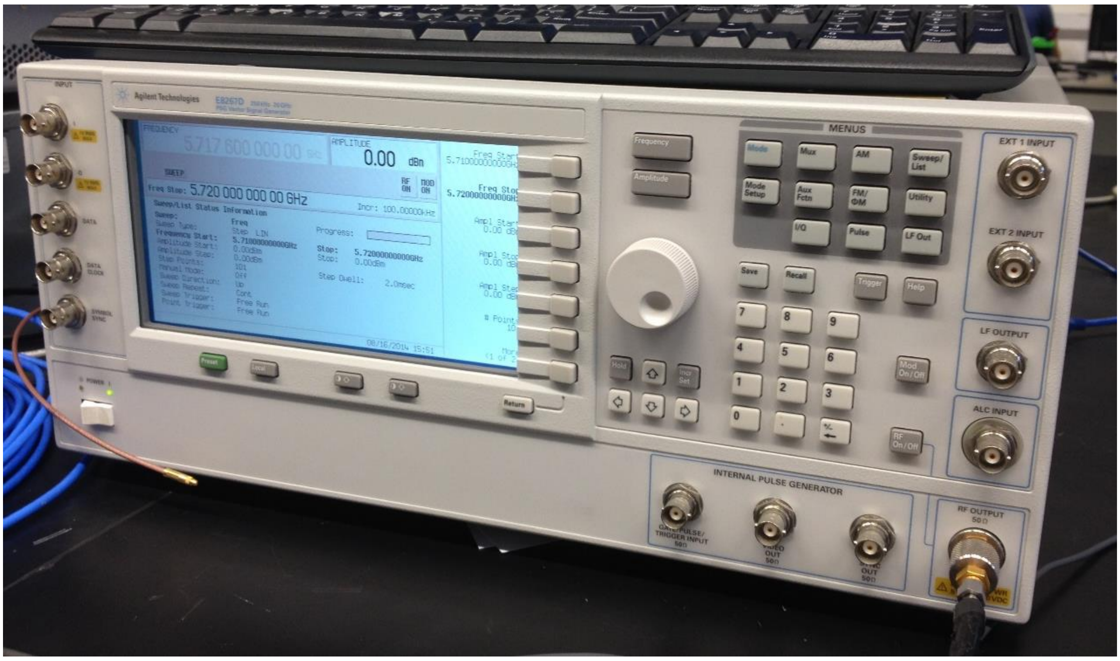


Figure 20: Agilent E8267D VSG

The VSG can generate a number of signals that are relevant to us, for example it can generate a mere carrier frequency at the pre-set amplitude, it is also capable of performing a frequency sweep of the channel according to the pre-set parameters. Moreover, it can generate any sequence using the I and Q information of that sequence which can be configured inside the VSG or directly fed to it using a hardware connection.

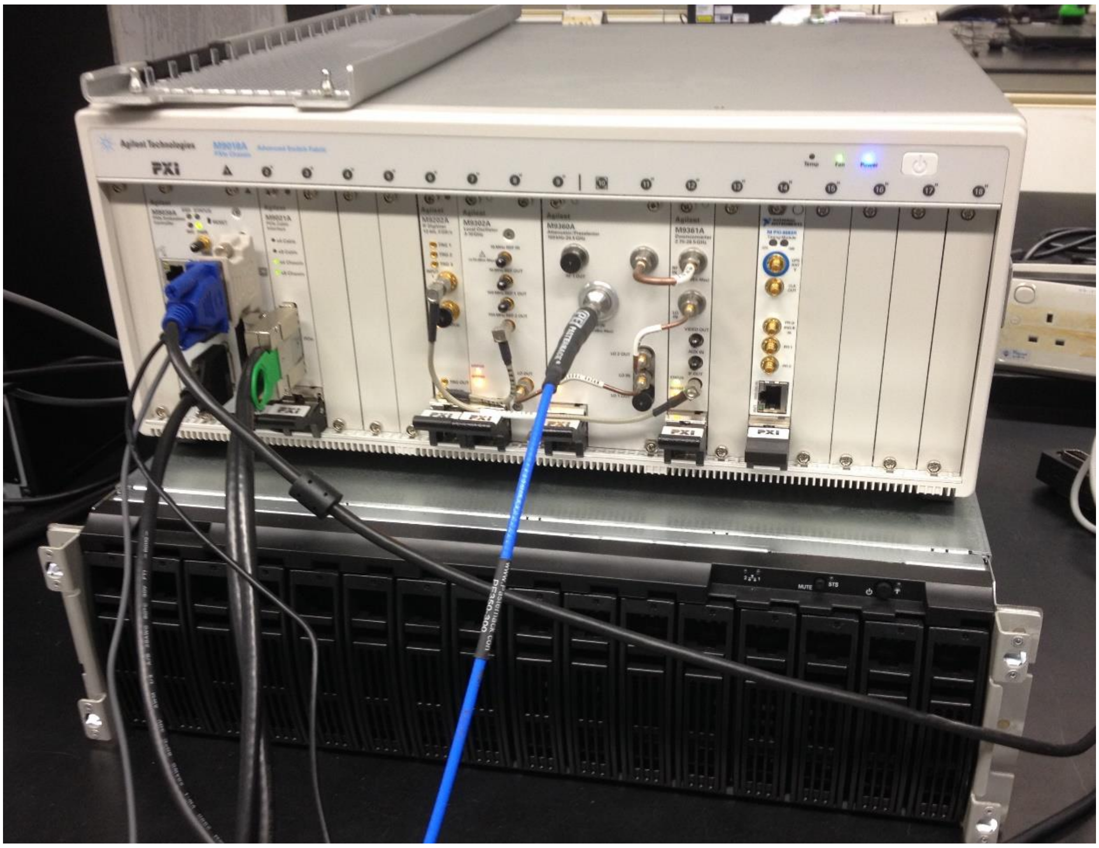


Figure 21: Agilent M9018A PXI VSA

After becoming familiar with the VSG and the VSA, we attempted to perform an experiment, where we will design a controlled environment, measure the frequency response of that environment and try to obtain the impulse response from it and see of that response is consistent with our expectations.

The experiment is to be carried out in the laboratory where the VSG and VSA are located. Two ES58-17 Echo series directional antennas are used. The I-Q sequence is to be generated using Agilent IQTools toolbox in MATLAB using a PC, the PC is connected via the LAN port to the VSG. The VSG is connected to the transmit antenna via the SMA connector, as it is for the receive antenna with the VSA. The two antennas are placed 5 meters apart. The experiment scenario is shown in the following figure.

Figure 22: Controlled environment experiment

The proposed signal would be a multi-tone square frequency pulse of 8MHz Bandwidth. It contains 257 different tones and the sampling rate is at 16 Msamples/s. The visualized signal is shown in this figure, while the iqtools toolbox is shown in the following one.

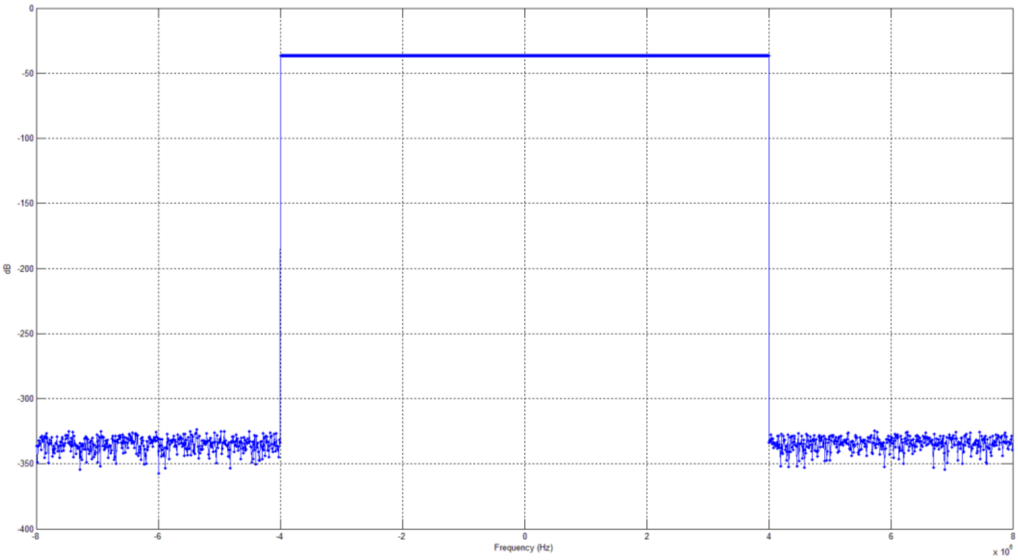
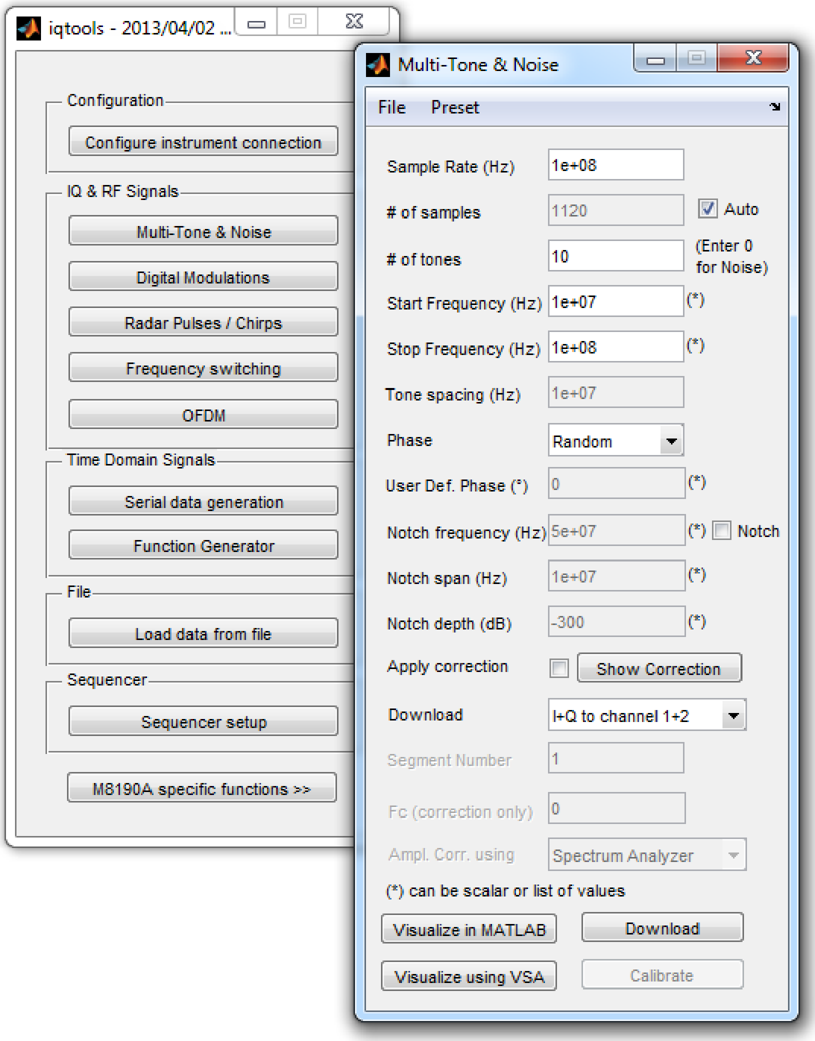


Figure 23: The signal used in the experiment as visualized by MATLAB

Since the transmitted value is a square wave in the frequency domain, its equivalent in the time domain should be a sinc function. So, we should keep that in mind when obtaining the results of the experiment.



Sample Rate (Hz) 1e+08
# of samples 1120 ☑ Auto
# of tones 10 (Enter 0 for Noise)
Start Frequency (Hz) 1e+07 (*)
Stop Frequency (Hz) 1e+08 (*)
Tone spacing (Hz) 1e+07
Phase Random
User Def. Phase (°) 0 (*)
Notch frequency (Hz) 5e+07 (*) ☐ Notch
Notch span (Hz) 1e+07 (*)
Notch depth (dB) -300 (*)
Apply correction ☐
Download I+Q to channel 1+2
Segment Number 1
Fc (correction only) 0
Ampl. Corr. using Spectrum Analyzer
(*) can be scalar or list of values

Figure 24: iqools toolbox and its multi-tone dialog box

Two parameters need to be set in the VSG itself, which are the carrier frequency and the signal amplitude. The frequency is chosen to comply with the antenna specifications, which operate in the 5.8 GHz band. The transmit power is chosen to be 10 dBm. The VSG settings are shown in the following figure.

FREQUENCY 5.800 000 000 000 GHz

AMPLITUDE 10.00 dBm

Hostname A-E8267D-500181

IP Address 192.168.1.2

Subnet Mask 255.255.255.0

Default Gateway 0.0.0.0

LAN Config Manual DHCP

Figure 25: VSG Settings

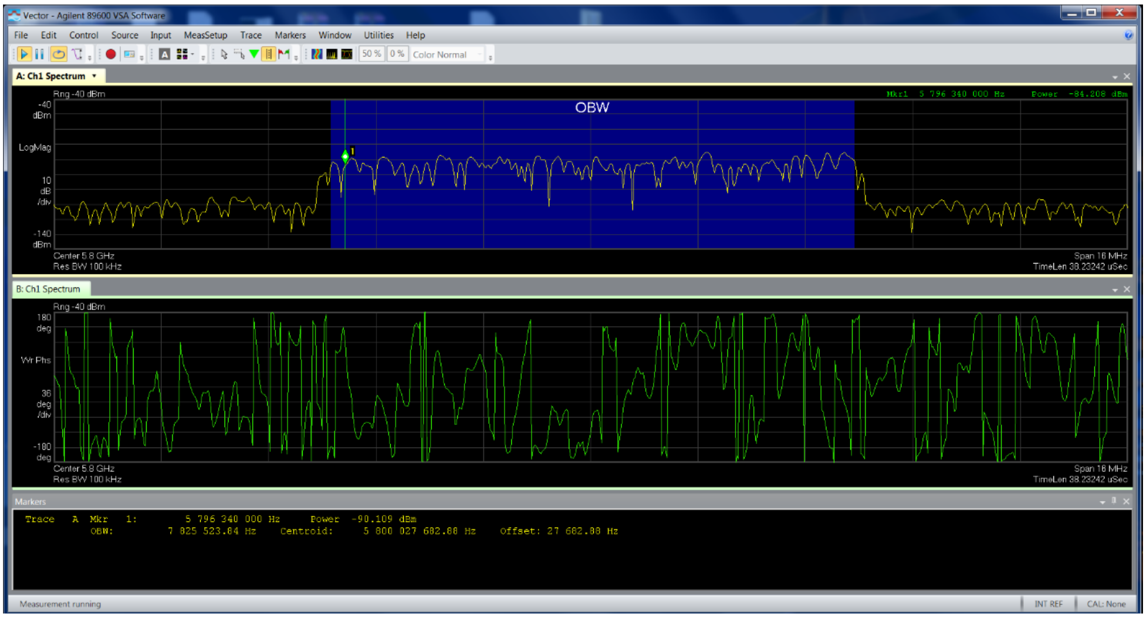
The transmitted signal encounters many losses and gains before arriving at the VSA. For example, the cables used to connect the VSG and the VSA to their antennas have 25 dB loss combined together. The distance of 5 meters between the antennas will result in a 65 dB loss assuming the simplified path loss model and a path loss exponent of 3. Antenna gains are 17 dB each. Therefore, the expected received power at the VSA should be:

$$P_{r,dB} = P_{t,dB} + P_{antenna} - P_{cable} - P_{path\ loss}$$

$$P_r = 10\ dBm + 34\ dB - 25\ dB - 65\ dB$$

$$P_r = -46\ dB$$

The following figure shows a screenshot from the VSA software which is used to view the data obtained by the VSA in real-time. The received signal power is in the range of -38 to -55 dB. Note that the whole plot is shifted by -40 dB as indicated on the top left side of the plot. It is also clear that the noise is very high, which is why, before being able to extract the impulse response, smoothing of these data must be done.



```
Trace  A  Mkr  1:        5 796 340 000 Hz    Power  -90.109 dBm
          OBW:        7 825 523.84 Hz    Centroid:     5 800 027 682.88 Hz    Offset: 27 682.88 Hz
```

Figure 26: Results from the VSA Software

The VSA measurements are extracted using this software and saved as .mat files which can be accessed using MATLAB. The first operation to take place is smoothing of the data in order to reduce the noise. After this, inverse fourier transform is applied to convert the data from the time domain to the frequency domain. The result is shown below.

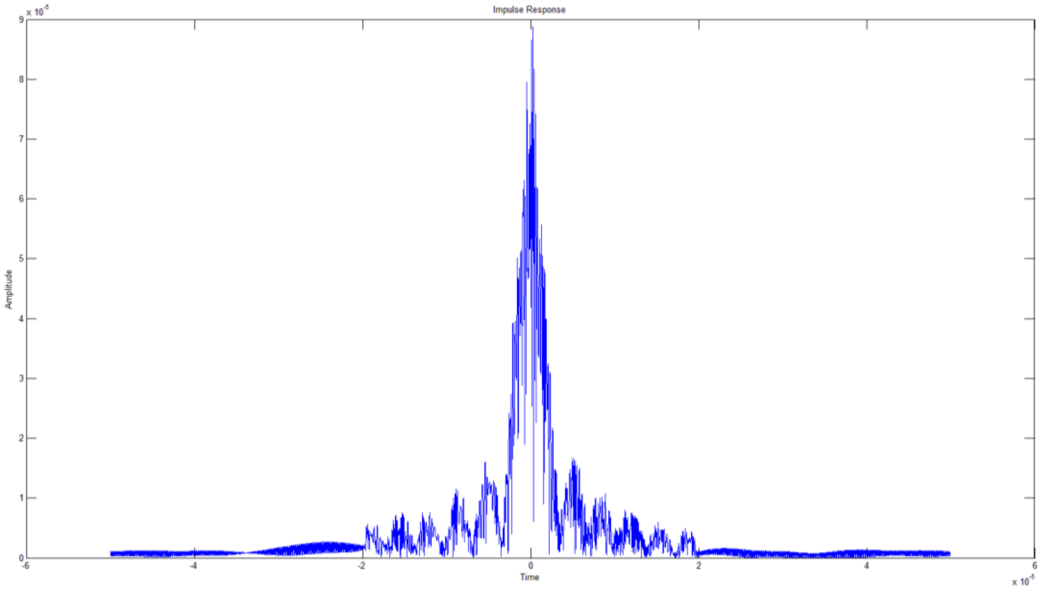


Figure 27: Impulse response

Even though it is clear that the response is a sinc function, the noise is still quite high. Further smoothing is performed to the time domain version of the response produces the following response where the sinc function is much clearer.

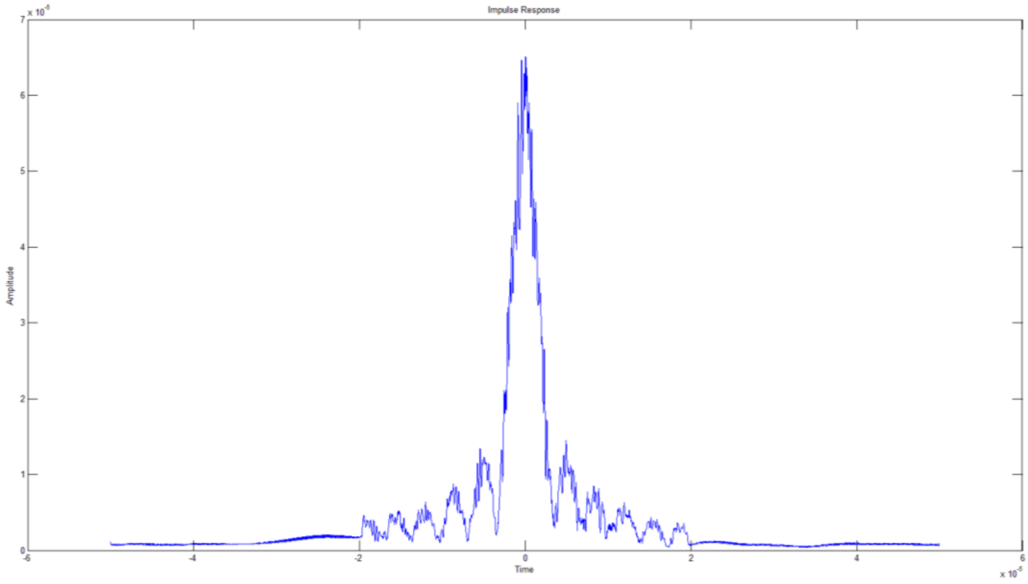


Figure 28: Smoothed impulse response

This concludes the VSG/VSA training phase. It was designed to acquaint the author with measuring the frequency response and using it to obtain the impulse response. The next stage of the project is to implement it on a MCU platform.

4.4 MCU Implementation

On the MCU front, an MCU development board (RIoTboard Development Board MCIMX6 SOLO) was purchased. It has the following specifications. The microcontroller is an ARM Cortex-A9 at 1 GHz, with a High-level Video Processing Unit and 1 GB of DDR3. It could be interfaced with external devices via the USB ports, the LAN port or the expansion port. The board supports Android or Linux as its operating system.

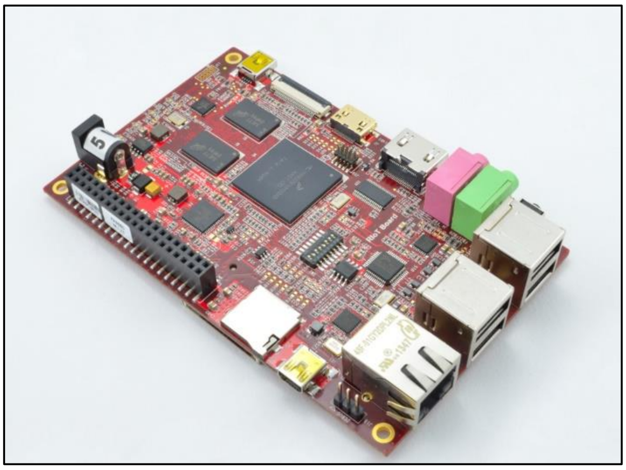


Figure 29: RIoTboard MCIMX6 SOLO

The author has spent a few weeks training in its use. Linux was chosen as the operating system because it is already equipped with the means for compiling and executing C code programs. The board has an HDMI port and an LVDS port through which and LCD can be connected. Alternatively, it can be connected using a debugging cable to a PC where certain software can be used to communicate with the Linux Terminal on the board. The third arrangement was mostly used as an HDMI monitor was not initially available.

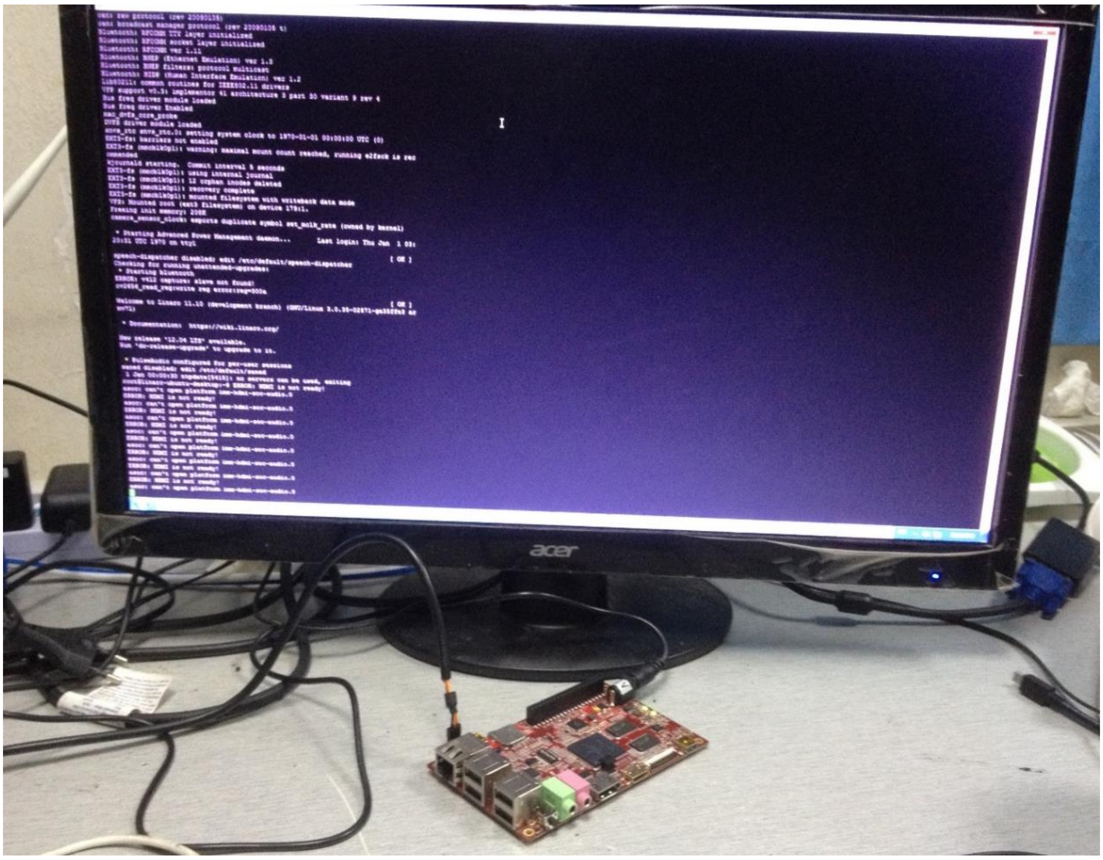
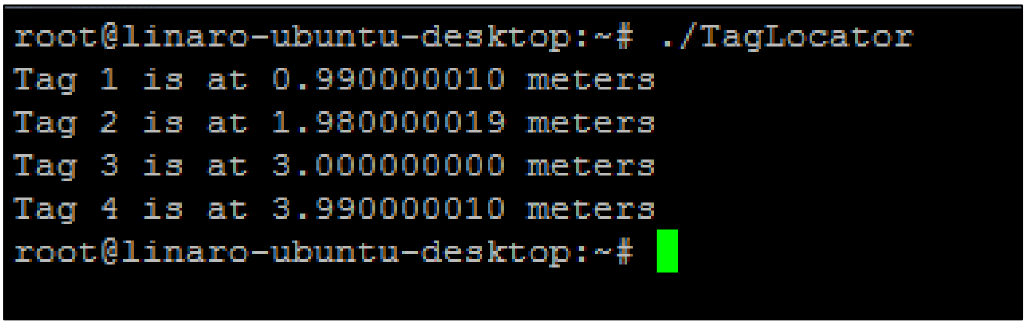


Figure 30: Communicating with the board through the PC

After the C correlation program has been designed, compiled and executed on the board here are the results.



```
root@linaro-ubuntu-desktop:~# ./TagLocator
Tag 1 is at 0.990000010 meters
Tag 2 is at 1.980000019 meters
Tag 3 is at 3.000000000 meters
Tag 4 is at 3.990000010 meters
root@linaro-ubuntu-desktop:~# 
```

Figure 31: Correlation results from the MCU board

4.5 Discussion

As shown in the simulation results, using a narrow pulse for interrogation produces positive results. The four tags' responses are separable. Since the narrow pulse contains little energy, the SNR required for an acceptable performance is relatively high (50 dB). If however we go lower to 20 dB, the task becomes very difficult. Therefore, if this method is to be implemented, signal to noise ratio of 50 dB or more is recommended.

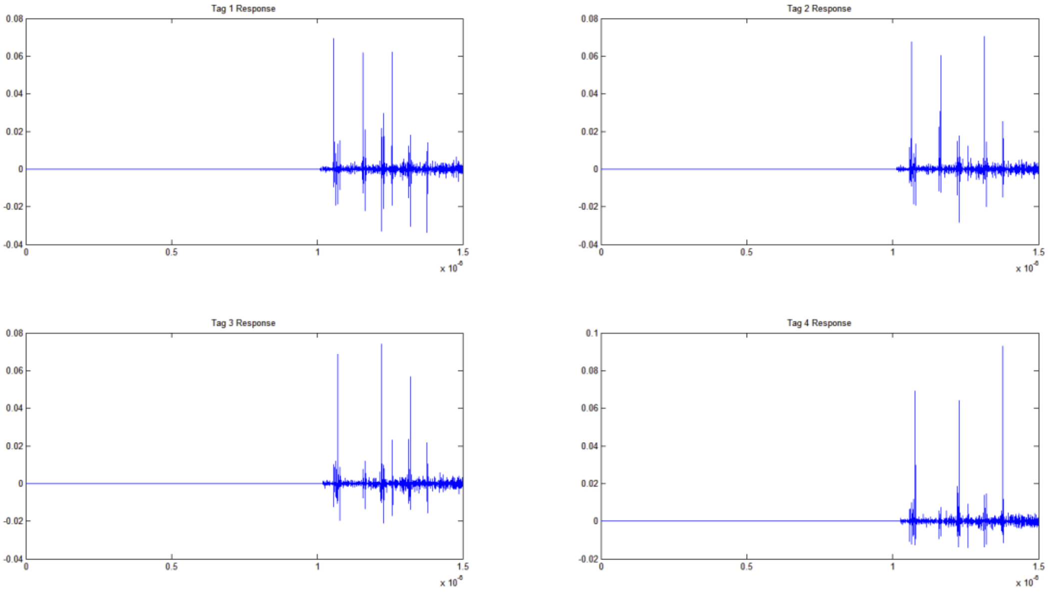


Figure 32: Individual Tags' response at 50 dB SNR

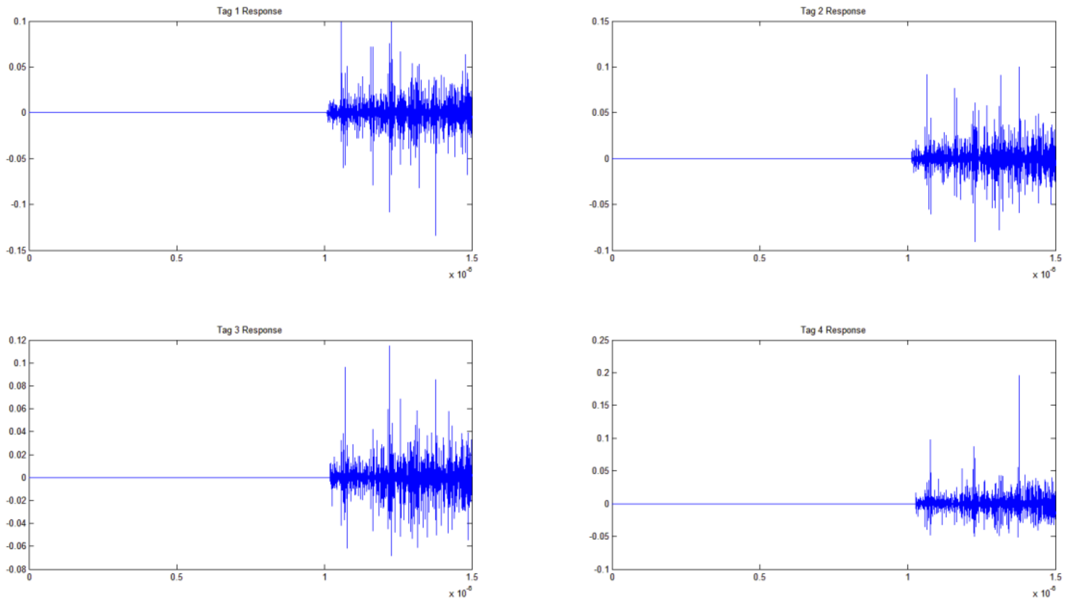


Figure 33: Individual Tags' response at 20 dB SNR

In practice, it is very difficult and costly to produce such a narrow pulse. It is more practical to use FSCW which is capable of producing narrow pulses by having a larger bandwidth. However, the bandwidth requirement are relatively high. In addition, the post-processing requirements of the reader greatly increase because it is required to perform DTFT on the received data before being able to extract useful information. Similarly for OFC, seeing that the reader is supposed to detect not only the signal’s amplitude and time delay, but its frequency as well. Moreover, designing OFC SAW tags is very expensive since each SAW device requires an individual mask in order to be synthesized on the piezoelectric substrate.

On the other hand, we notice that the correlation results from the microcontroller, though close to the actual values are less accurate than the MATLAB simulation results. This is because of two reasons. Firstly, MATLAB is mathematical tool whose programming is more focused and oriented on performing mathematical functions such as correlation, while programming in C or any other higher-level language programming language requires building these mathematical functions from scratch. Which makes it more difficult for us to design the same programs performed by MATLAB and for the MCU to execute them. In addition, the processing and memory capabilities of the MCU are far less than that of a personal computer.

Chapter 5

Conclusion and recommendation

The purpose of this project is to design a lab-scale prototype of a SAW reader that is able to interrogate passive SAW tags and differentiate between them based on their response. In order to obtain information about the technology and the advances in that field, broad research was carried out. After a general idea about the topic was obtained, a more focused research was done to understand the current trends and what other researchers have arrived at. Various alternatives to accomplish the project objectives were found, and to decide between these alternatives system simulation was carried out.

After system simulation, pulsed-interrogation seemed the simplest solution to achieve the desired outcomes. Moreover, in order to be able to do impulse response measurements using the reader, the author was trained on a Vector Network Analyzer, then a Vector signal Generator and a Vector Signal Analyzer. The last step was implementing the project partially on a microcontroller unit.

Our main recommendation is to acquire the SAW devices so that the suitable RF module can be designed and the complete prototype can be produced and practically evaluated.

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