Interrogation of Orthogonal Frequency Coded SAW Sensors Using the USRP

J.R. Humphries, M.W. Gallagher, D.R. Gallagher, A.R. Weeks, and D.C. Malocha
Department of Electrical Engineering and Computer Science
University of Central Florida, Orlando, FL

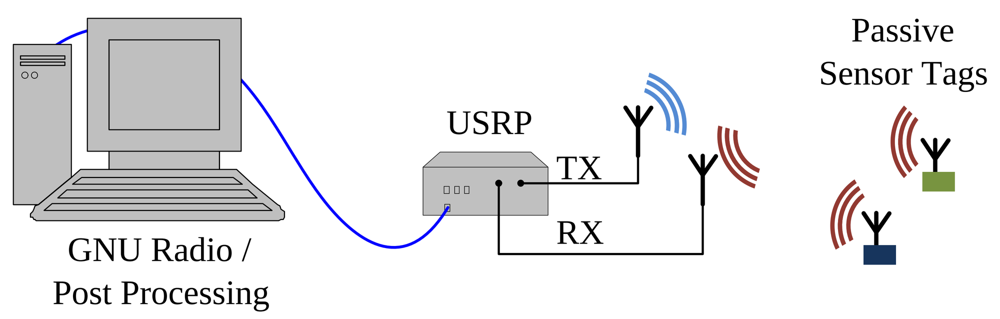
University of Central Florida

1 Introduction

Interrogation of passive sensor tags poses many unique challenges, particularly in a research environment. As sensor designs evolve, so too must the wireless sensor interrogation system (passive tag reader). Typical interrogator design requires many discrete components, many of which must be replaced or reconfigured manually to be compatible with the sensor specifications. One solution is to utilize a software defined radio (SDR) platform, such as the universal software radio peripheral (USRP), developed by Ettus Research.

Project Goals

- Modify USRP B200 FPGA for passive, wireless SAW sensor interrogation (passive tag reader)
- Port MATLAB matched filter correlator software to Python
- Interrogate orthogonal frequency coded (OFC) SAW sensors and extract temperature using the USRP B200
- Extract temperature sensor precision using the USRP



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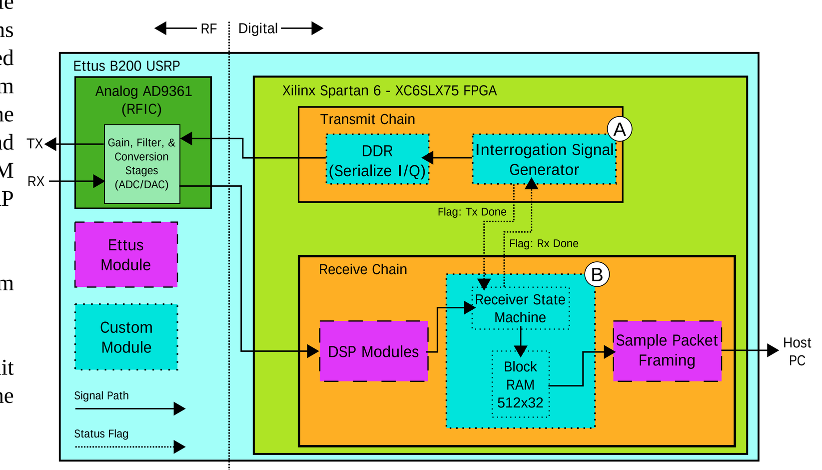
2 FPGA Modifications

The USRP FPGA was modified to synchronize the transmit and receive chains, implement an interrogation signal generator, and buffer a single data sweep in memory. The transmit modifications output a linear FM chirp, which can be customized for chirp bandwidth and time length. The custom receive modules synchronize to the end of the interrogation signal, define a listen window, and buffers one listen window worth of samples in RAM (9.15µs). These modifications allow the full USRP B200 bandwidth (56MHz) to be utilized.

A block diagram (right) shows how the custom modules were integrated into the FPGA.

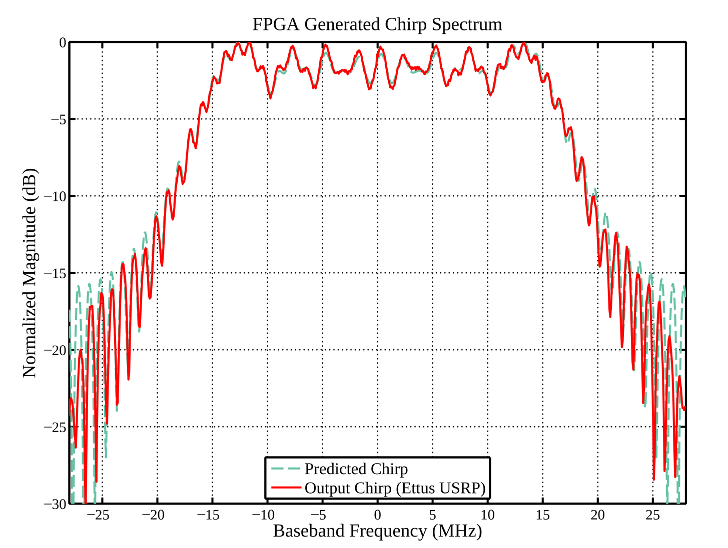
(A) The interrogation signal generator in the transmit chain. The samples are programmed directly on the FPGA

(B) The receiver state machine with RAM buffer. The RAM buffer stores 512 samples, equivalent to 9.15µs of data at a 56MHz sampling rate.



Transmit Chain Modification Characterization

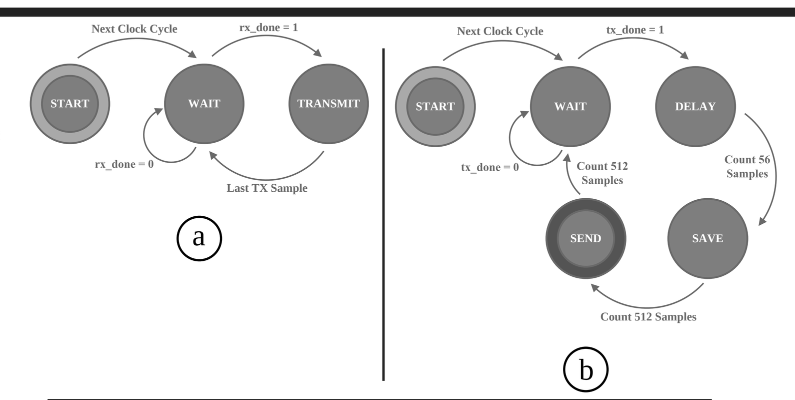
A linear FM chirp generator was implemented on the USRP FPGA. It outputs a chirp with 35MHz bandwidth and 1µs time length. The USRP output from the transmitter is compared to the predicted chirp spectrum below.

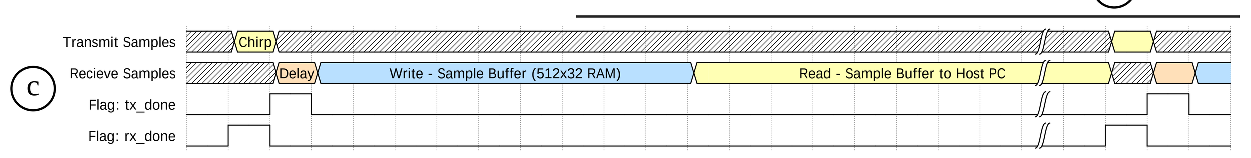


FPGA State Machines

The interrogator is controlled by custom state machines. The states control the synchronization between the transmit and receive modules.

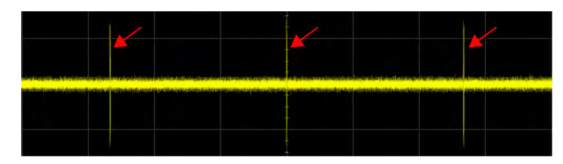
(a) Interrogation signal generator state diagram
(b) Receive window and buffer state diagram
(c) Timing diagram of a single interrogation cycle

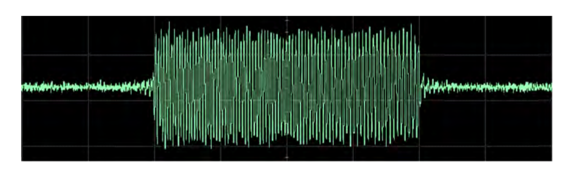




Receive Chain Modification Characterization

The receiver module controls the pulse repetition interval (PRI) of the USRP. The transmit output was measured on an oscilloscope to ensure the PRI was correct. (a) Three (3) pulses in time with 100µs / division. (b) A single (1) pulse with 250ns / division.

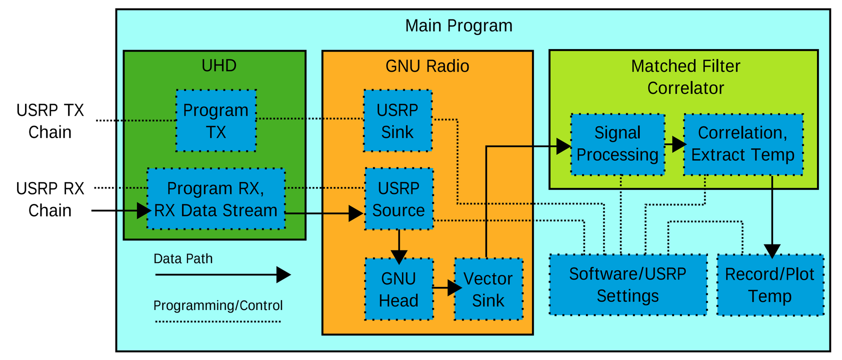




3 Software

Software running on the host computer has been implemented in Python to control the USRP and post-process the received SAW sensor data. A software matched filter correlator (previously developed at UCF in MATLAB) has been ported to Python and is compatible on a wide variety of systems. The USRP is controlled with the USRP hardware drivers (UHD) and GNU Radio.

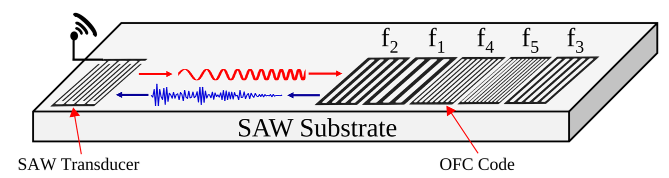
- Compatible with Windows & Linux and embedded platforms (RaspberryPi, Minnowboard, etc)
- USRP Automatic Gain Control (AGC) - Maximizes transmit output power and receiver gain to improve received SAW sensor signal SNR
- Integrates with USRP or vector network analyzer (VNA) to interrogate sensors
- Works with any number of sensors (Number of sensors limited by interrogator specifications such as listen window and bandwidth)

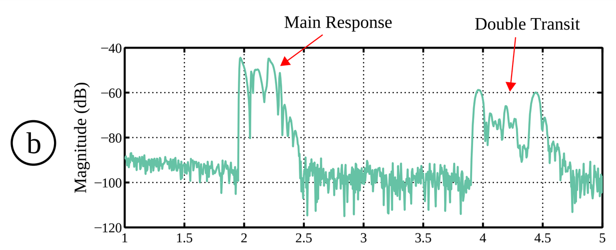


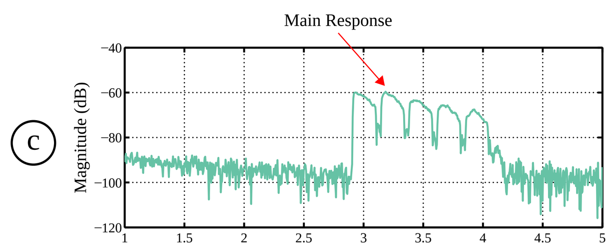
4 Sensor Design

A set of SAW sensors was designed to operate within the modified USRP specifications. Each sensor has a unique orthogonal frequency code (OFC). The sensors operate at 915MHz with a bandwidth of 30MHz and are fabricated on YZ-LiNbO3. Two (2) devices were fabricated and designed to operate simultaneously in the wireless system, usrp-m1-d1 and usrp-m1-d3.

(a) Schematic diagram of an OFC SAW sensor with 5 chips (reflectors)
(b) Time response of device usrp-m1-d1 (x-scale: µs)
(c) Time response of device usrp-m1-d3 (x-scale: µs)







5 Wireless Temperature Measurements

Each sensor was attached to a folded dipole antenna with approximately 2dBi gain. Two separate antennas were used for the transmit and receive ports on the USRP, which also has approximately 2dBi gain. The sensors were interrogated by the modified USRP and the received data was processed with the software matched filter correlator to extract temperature. The sensors were cooled (cold nitrogen gas) and heated (electric heat gun) randomly during each test. These wireless tests were performed at a range of 15cm (6in.), although, tests have been performed up to 1.6m (5.2ft.).

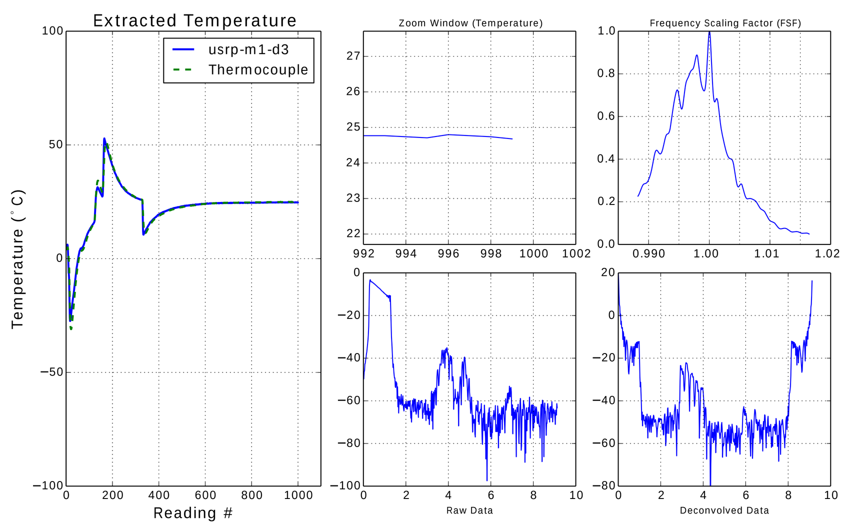
(a) Single SAW sensor (usrp-m1-d3, wireless) with a reference thermocouple (wired)

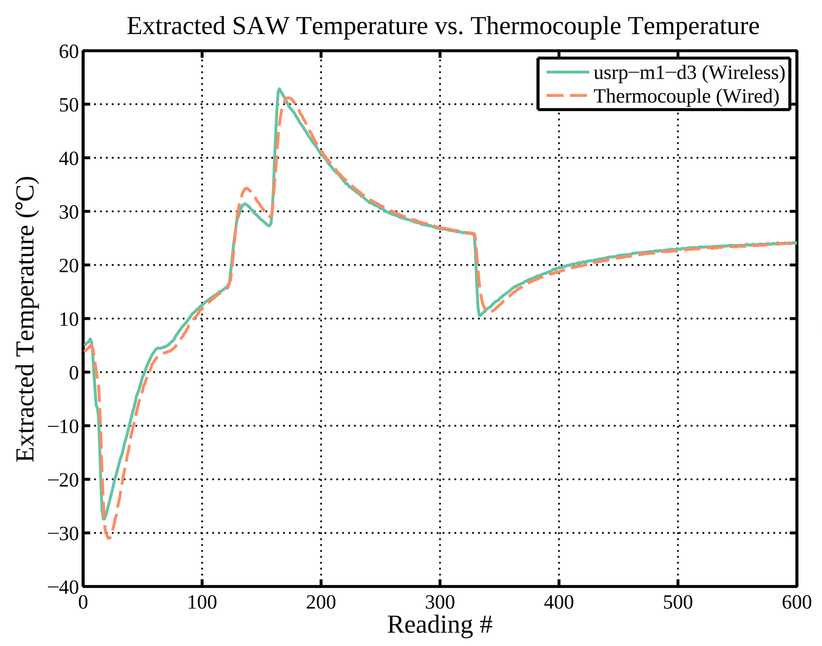
(b) Two SAW sensors (usrp-m1-d1 & usrp-m1-d3), interrogated simultaneously

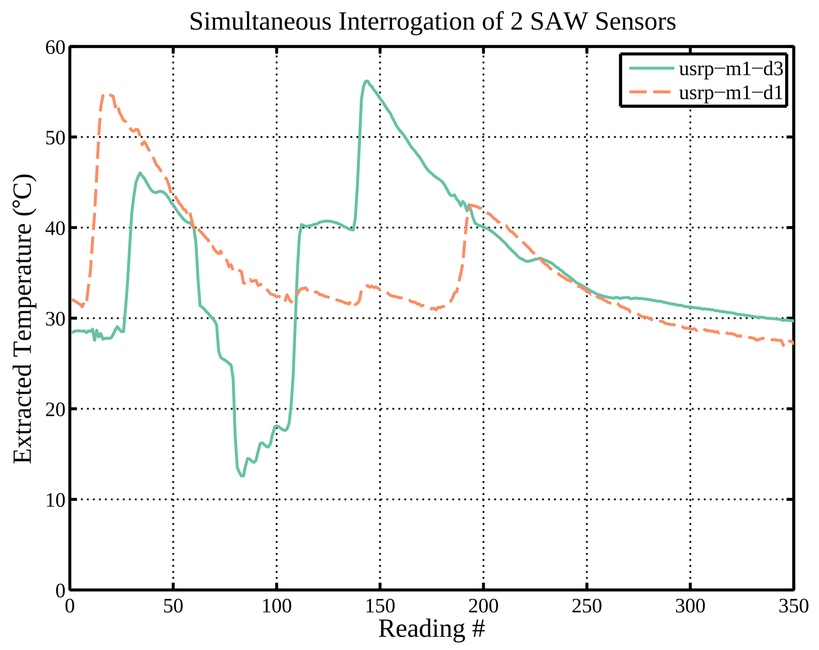
(c) Photograph of the SAW senor and antenna

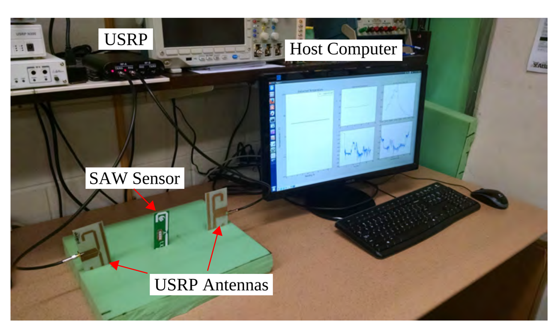
(d) Photograph of the wireless SAW sensor test setup

(e) Screenshot of Python correlation software output during a temperature run









6 Sensor Precision

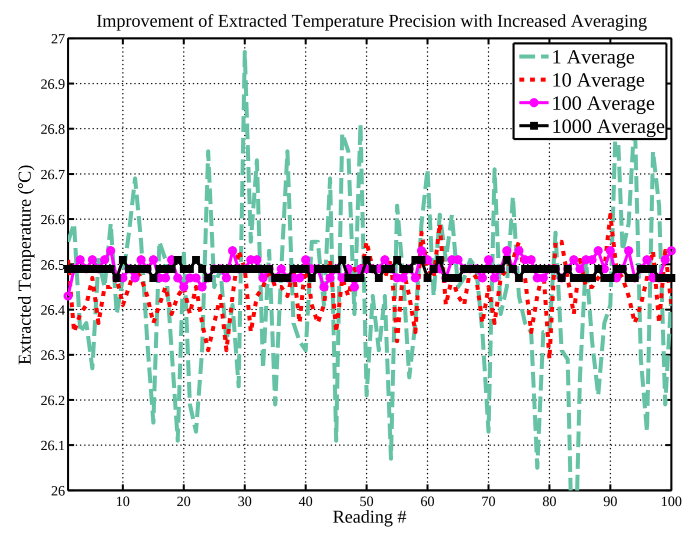
The precision of the extracted temperature from the SAW sensor can be improved by averaging multiple data sweeps. Averaging reduces the signal noise, improving the SNR. A test was performed by taking 100 measurements at constant temperature for 1, 10, 100, and 1000 averages. The measurements were taken at a wireless range of 15cm (6in.).

(a) Extracted temperature improvement by increasing the number of averages

(b) Standard deviation (STD) of each measurement run (log-log scale)

(c) Table of selected system performance

(d) Table of host computer hardware and software used in these experiments

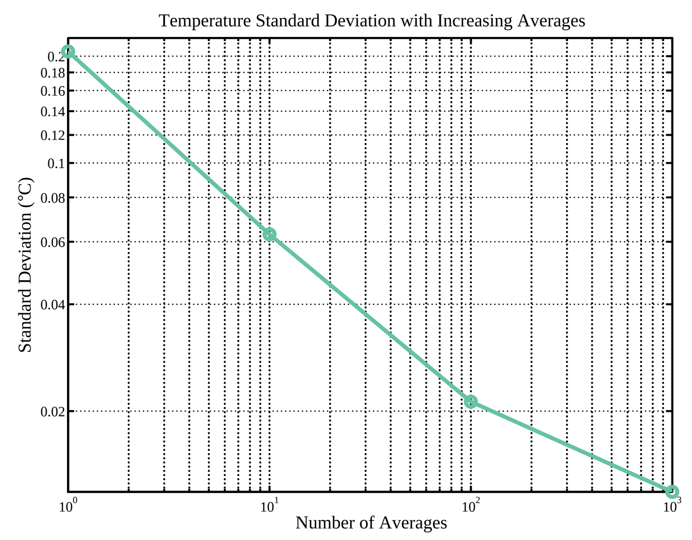


(c)

System Performance	
Max Peak Output Power (Measured)	+10.5 dBm (90dB Tx Gain)
Maximum Sensor Range (Can be increased with high gain antenna)	1.6m (5.2ft.)
Sweep Time – 1 Average (Get data and extract temperature)	0.25 sec.
Sweep Time – 1000 Averages (Get data and extract temperature)	1.0 sec.

(d)

Computer Hardware	
Processor	Intel Core-it-4690 (3.5GHz)
Memory	8GB
Chipset	Intel Z97 (USB3.0 Controller)
Software	
OS	Ubuntu 14.04 (Linux) – 64 bit
Python	2.7.6
UHD	003.008.000-52-g206af70
GNU Radio	3.7.5.1



7 Conclusion

The USRP has been demonstrated as a versatile interrogator for passive, wireless SAW OFC sensors. The USRP modifications that were implemented have unlocked the full 56MHz bandwidth potential of the B200 without depending on the USB3.0 throughput. The interrogation system is capable of tracking temperature wirelessly, with results comparable to a wired thermocouple. The extracted temperature precision can be controlled for each application by increasing the number of averages, controlling the USRP gain, or using high gain antennas. Future work will take advantage of new USRP models (such as the E310 embedded platform) to further improve the interrogation system performance and integration.

References

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James 'Trip' Humphries
James.Humphries@knights.ucf.edu
Orlando, FL, USA

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