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Re-configurable Completely Unpowered Wireless Sensors

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Abstract— **A methodology for remotely and wirelessly reading any type of unpowered impedance varying sensor is described. Unpowered wireless sensors, in existence for a number of years, have been limited to low impedance sensors. Techniques for reading high impedance sensors are introduced here. The resulting methodology can be used to measure a wide range of different sensors, including temperature, pressure, light level, mechanical switch, acoustic emission, and acceleration. These sensors report physically measurable data in the same manner as do similar conventional sensors, but they do it remotely and without any local power source. The sensors are measured remotely using a radar-like interrogation device, and the sensors and their related communication electronics draw all of the power needed for communicating from the radar pulse.**

***Index Terms*—**SAW correlator, sensors, wireless, passive.

I. Introduction

The specific focus of our work, described here, is passive remote sensing of physical properties. We define passive remote sensing as the ability to wirelessly measure some physical property by means of a sensor and its associated communication apparatus that both require no power source. They draw both their measurement and communication energy from a radar-like pulse sent by an external device referred to as an interrogator. The interrogator can be thought of as a radar transmitter and receiver, though it differs in some respects from aviation radars. The basic principle is that an interrogator sends an RF signal and then receives a modified response from an impedance-varying sensor tag. The response from the tag will be modified in a manner proportional to the physical property being measured by the tag, such as temperature, acceleration, or light level.

Passive wireless sensors enable the retrofitting of existing structures with sensors. For example, aircraft, transportation containers, buildings, or spacecraft can be loaded with health or environmental sensors to monitor structural parameters and determine hardiness or readiness. Modifying existing structures can be difficult both from a technical and logistics perspective, and passive wireless sensors can provide a means to circumvent the problem of routing wires or of replacing batteries. For most structural monitoring, a read-out range of 10 meters at FCC-approved power levels is adequate; this bounds the range requirement for wireless passive sensing.

For the purposes of creating a remotely readable sensor tag, surface acoustic wave (SAW) devices are often used. A variety of different tags and tag reading methodologies have been reported [1][2][3]. The SAW device is used all together as an energy storage medium, a delaying device, and a signal processing device. The SAW device receives energy from the radar interrogation pulse, delays any response until all radar echoes have died away, and then re-transmits a signal that has been modified proportionally to an attached impedance-varying sensor. The SAW device does all of this without the use of any power source other than the energy contained in the radar pulse.

SAW devices also enable the differentiation of different sensors by a variety of different methods. It is essential to differentiate one particular tag of interest from any other tags that might be within range of the interrogator. SAW devices can be differentiated in terms of frequency, coding, or time response. For frequency-based selectivity, tags are designed to respond to different narrow frequency bands, and the interrogator can select the tag of interest by changing the interrogation frequency. The narrow frequency selectivity is accomplished at the tag by means of a SAW filter. SAW filters provide narrow frequency separation and conversion of variable impedance information into RF signal modulation. Sensors that vary impedance with respect to some physical parameter can be measured remotely by measuring the proportional modulation in the RF return signal from the SAW filter.

For code-based selectivity, a SAW correlator is used at the tag. The tag can be made to only respond optimally if a correctly coded interrogation signal is sent. Similarly, for time-delay based selectivity, SAW filters with different acoustic path lengths are used. A single interrogation pulse will then read out all sensor tags which will respond in a pre-arranged order. The simplest approaches, suitable for a small array of sensors, use either frequency or time-based selectivity. Code-based selectivity can service a much larger constellation of sensors, but at the price of greater complexity and shorter range operation.

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II. SYSTEM OVERVIEW

Passive remote sensing using SAW devices has common elements regardless of the physical property begin measured. Each sensing arrangement consists of 1) a small radio transmitter sending out a short burst of radio frequency (RF) waves, 2) a SAW-based tag both receiving and modifying a portion of that signal, and 3) a receiver to pick up the transmitted and modified pulse (fig. 1). If the receiver and transmitter are in separate locations, the arrangement is described as being bi-static. If the receiver and transmitter are co-located, the arrangement is mono-static.

A SAW filter is a bandpass, frequency selective device that operates by converting electrical energy into acoustic energy in order to perform signal processing operations on the signal. The SAW filters used for remote sensing contain at least two ports. This means that they possess two electrical-to-acoustic transducers, designated arbitrarily as an input and an output port. The SAW-based sensor tag consists of a SAW filter with an antenna connected to its input port and an impedance varying sensor tied to its output port.

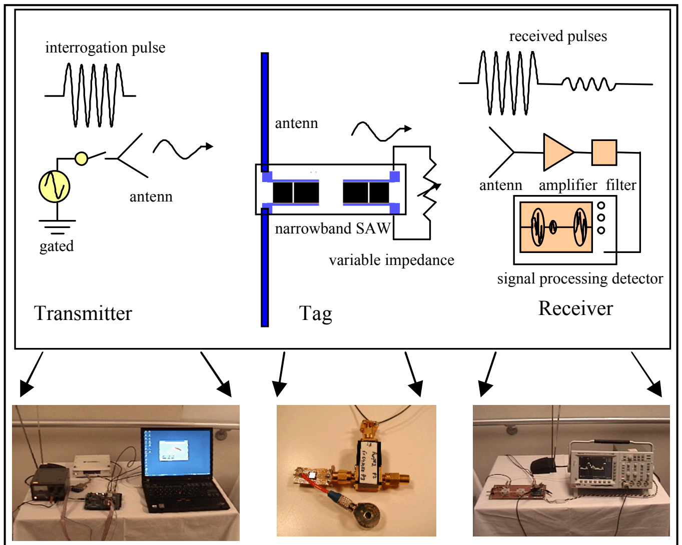


Figure 1: SAW Sensor System Configuration

The sensor tag varies its acoustically delayed radar cross section in proportion to the variable impedance load connected to the SAW's output port. Variations in sensor impedance are caused by variations in the physical property to be measured. For instance, a thermistor will vary its impedance as some function of temperature. If a thermistor is connected to the output port of a SAW device, its temperature induced impedance changes will, in turn, induce variations in the SAW filter's delayed acoustic impedance. The variations in the filter's acoustic impedance lead to variations in reflectance for a received RF wave.

The impedance induced variations are acoustically delayed and re-transmitted from the antenna at the input port of the SAW filter. That is, the RF pulse is first received by the tag's antenna. It is then converted into an acoustic wave by the input transducer of the SAW filter. The acoustic wave travels across the SAW device and is reflected off of the output transducer of the SAW. The reflectance of the acoustic wave is in proportion to the impedance of the sensor tied to that port. The reflected acoustic wave then travels back across the SAW, where it is re-transmitted by the antenna connected to the input port of the SAW. The variations in the sensor impedance can then be detected as delayed amplitude variations in a received RF signal. In this manner, the sensor impedance can be measured back at the receiver.

As will be discussed quantitatively in the next section, the SAW sensor must respond with great efficiency to a weak RF signal in order to be detected by the receiver. Each electronic transaction weakens the RF signal. However, a proper application of a narrowband SAW filter enables clear reception and measurement of the sensor impedance.

For SAW-based sensors, the tag modifies the signal that impinges on its antenna by two mechanisms. The first mechanism can be understood from conventional radar theory and is called backscatter modulation. Any reflector in the path of a radar beam can be thought of as an antenna. If an antenna within the path of that radar beam is tuned to the frequency of the radar, then that antenna will have a large scatter aperture (or radar cross section) for that radar. The scatter aperture is a measure of the power that is reflected from the antenna. The scatter aperture for an antenna will vary depending on the resonance characteristics of that antenna.

The resonance of the antenna varies with the impedance connected to the antenna. If the scatter aperture for an antenna connected to a 50Ω is given by A_{opt}, then the scatter aperture will vary from 0 to $4A_{opt}$ as the antenna's load impedance is changed from an open to a short. If the load impedance is varied by an impedance-changing sensor, then the sensor output can be detected back at the radar receiver. Using backscatter modulation variations alone to wirelessly sense impedance variations is prone to errors, as other changes within the scene can cause significant reflectance variations.

The SAW filter provides a second, much more dependable means of measuring the sensor variations. The SAW filter is an acoustic device that delays the reflected signal from its output port. This delayed signal contains the sensor measurement information. Since it is acoustically delayed with respect to the original RF excitation signal, it can be read after all radar reflections induced within the vicinity of the transmitter have dissipated.

III. THE SAW DEVICE

The key to the passive tag sensor is the SAW filter. A two-port SAW filter appears as two comb-like metal structures deposited on a piezoelectric crystal surface (fig. 2). The first comb-like structure, designated as the input port and called an interdigitated transducer (IDT), serves as a transducer to convert long wavelength radio waves to very short wavelength acoustic waves. The second comb-like structure, designated as the output port and also called an IDT, serves both as a signal-processing device and as a transducer to convert the acoustic waves back into an electromagnetic signal. The primary advantage of the SAW is its ability to perform signal processing in a physically compressed space. For instance, 3 GHz radio waves propagating in free space have wavelengths of 10cm, while 3 GHz acoustic waves propagating in lithium niobate, a suitable piezoelectric material, have wavelengths of 0.000116 cm. The SAW device takes advantage of this wavelength compression to perform signal processing on radio waves in a very small space.

The first signal processing function performed by the SAW is

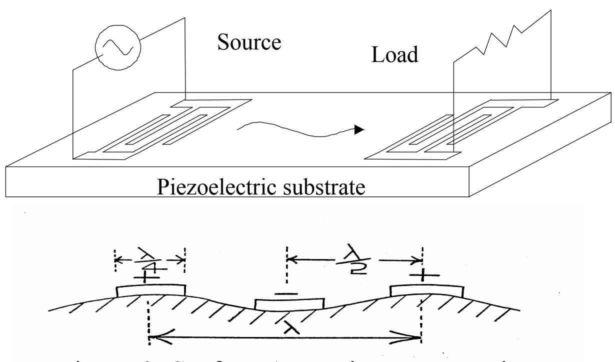


Figure 2: Surface Acoustic Wave Device

energy storage. It stores many cycles of the input RF wave in the form of acoustic waves. The second signal processing function is to provide a time delay that is long enough to enable radar echoes not associated with the tag to fade away. The third function performed by the SAW is to convert into acoustic variations the impedance variations of the sensor attached to its output IDT. The final signal processing function performed by the SAW is to re-convert and re-transmit the delayed and modified signal back out of the antenna.

IV. SIGNAL DETECTION AND RANGE

As discussed in the System Overview, the detection of a signal from a sensor tag is similar to any radar signal reception problem. The range of a passive SAW-based sensor is governed by the radar equation. The interrogator transmits a pulsed burst of narrowband RF energy and the receiver detects, processes, and interprets any return signals. Most of the return signals seen at the interrogator's receiver come from undesirable backscatter modulation from nearby surroundings. Any antenna tuned to the center frequency of the radar pulse will exhibit a large radar cross section and so may dominate the radar return signals. In varying degrees, all materials serve as radar reflectors and provide return signals. However, all conventional radar return signals quickly die away to below the noise level. Radar signals travel at about 1ft/nsec, so within about 600nsec, all signals within 100m have returned. Similarly, within 6 μsec, all radar reflections within about 1000m have returned. The expected maximum return time defines a time window during which the frequency band is cluttered and unusable. The acoustically delayed return signal from the SAW device can be set to be outside of this time window, when signal noise is at a minimum.

The SAW receives energy from the radar beam and temporarily stores it in the form of an acoustic wave. The acoustic wave travels across the SAW, reflects off of the back IDT, and then is re-transmitted by the antenna. The reflected signal finally re-emitted by the antenna is smaller than the initially received signal by 10-20dB, but it is re-transmitted after all other radar reflections have disappeared. As a consequence, the signal from the SAW stands out strongly. In addition, the magnitude and phase of the acoustic reflection are strong functions of the load impedance connected across the SAW back transducer. This means that a sensor variable load impedance will modulate the SAW's acoustic reflection coefficient. The modulations of the reflection coefficient then, in turn, modulate a re-transmitted signal out of the antenna that can be intercepted by the radar receiver.

The SAW's acoustic reflectivity, $P_{acoustic}$, is given as a function of load impedance Z_{load} by [4]

$$P_{acoustic}(Z_{load}) = P_{acoustic}(@Z_{load} = 0) + \frac{2K^2}{\left(\frac{1}{Z_{transducer}} + \frac{1}{_{load}}\right)}$$

where Z_{load} is the electrical impedance connected to the back transducer, $Z_{transducer}$ is the electrical impedance of the transducer alone, and K is the SAW electro-acoustic coupling coefficient. If P_{opt} is the reflectance for a matched transducer, the reflectivity can vary from 0 to $6P_{opt}$ as the back impedance changes. The result is that sensor impedance changes can be wirelessly measured at the receiver. This effect can be enhanced by use of a reference SAW attached to the same antenna but also attached to a reference load impedance in the same tag. The difference between the modulated load impedance and the reference load impedance will show up as a measurable difference in received signal amplitudes. Since the relative time delay between the reference and the modulated signals is a known constant, a precise measurement can be made.

By using acoustically delayed reflections at low frequencies one can measure sensors at a significant range. Some actual measured values are included below for reference. The range, r, at which the tag modulations can be measured, is given by the radar equation as

$$r := \frac{\lambda}{4 \cdot \pi} \cdot \sqrt[4]{\frac{P_o \cdot G_t \cdot G_r \cdot G_s^{\,2}}{S_{21}^{\,2} \cdot SNR \cdot kTBF}}$$

with λ being wavelength (= 4.3m at 69MHz), G_t being transmitter antenna gain (= 1.64 for a dipole), G_r being the receiver antenna gain (= 1.64 for a dipole), G_s being the tag antenna gain (= 1.64 for a dipole), S_{21} being the SAW filter insertion loss (= 13dB as measured), kT (= 4.14 e-21 J), B being the receiver bandwidth (= 600kHz as measured), F being the receiver noise figure (= 3dB), SNR being the minimum detection signal-to-noise ratio (= 50dB), and P_o

being the transmitted power. Note that the minimum detection SNR (50dB) is much higher for a sensing application than the SNR required for an identification application (6dB). The SNR chosen here is that required to obtain an 8-bit resolution of the received and detected sensor output. This choice is reasonable for many applications but is still somewhat arbitrary. Some applications may require greater SNR, many will require less. It is important to make an accurate and reasonable estimate of the required sensor resolution, as this will limit the range of detection.

For the actual measured values already given the detection ranges are as follows:

Transmitted power P_o	Detection range
1 mW	11 meters
100 mW	34 meters
10 W	108 meters

V. HIGH IMPEDANCE SENSORS

The impedance variations of the sensor create a measurable acoustic impedance mismatch at the SAW back port if the sensor impedance is close in value to the SAW impedance. For instance, if the SAW's IDT is designed to have an impedance of 50Ω, sensors with impedances that vary around 50Ω will be measurable. Directly coupling a sensor to the SAW is useful only for sensors with impedances close to the impedance of the SAW IDT. Sensors with impedances that are very different from the impedance of the SAW IDT appear as either a short or an open circuit. However, it is possible to use an interface device to passively measure sensors with very high impedances using low impedance SAW transducers.

The approach to measuring a high impedance sensor is shown in figure 3. The sensor, in this case a piezoelectric accelerometer, is connected to the gate of a field effect transistor (FET). The gate of a metal oxide semiconductor field effect transistor (MOSFET) has very high impedance, typically greater than 1 TΩ. This provides an impedance match to the highest impedance sensors, such as piezoelectric or pyroelectric sensors. The sensor impedance variations will then modulate the low output impedance of the FET channel. This variation is described by the standard FET r_{DS} vs. V_{GS} curve pertaining to the particular device. A standard enhancement or depletion mode MOSFET or junction field effect transistor (JFET) can be used as the impedance transforming device. These will need a battery to shift the sensor equilibrium voltage up or down to about the FET's V_T or threshold voltage. The battery will push a current equal to the gate leakage current of the FET, a very small value and much less than the battery's own internal leakage. A more desirable conversion device is to use a FET with a threshold shifted to $V_T = 0V$. Then, sensor voltage or charge variations will translate directly into variations of the channel resistance with a value close to that of the SAW IDT. Such as device will be entirely passive, drawing no DC power, but operating solely from radio signals transmitted to it from the SAW interrogator.

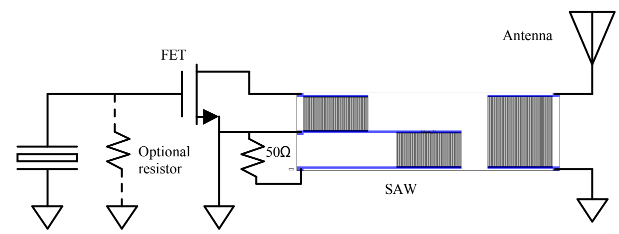


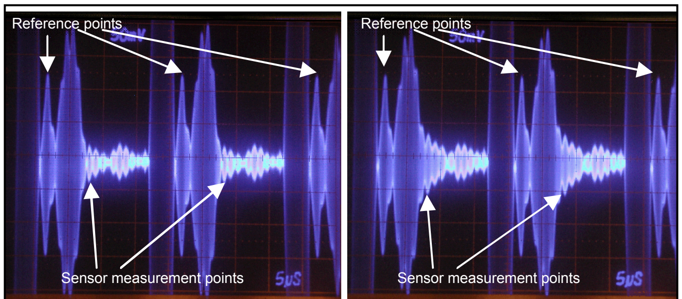
Figure 3: SAW Measurement Tag with a High Impedance Sensor

Using this approach, sensor impedance and time constant can also be tailored by adding or adjusting a shunt resistor, also shown. Very high impedance sensors, such as piezoelectric sensors, are a good impedance match for a MOSFET gate. The time constant can be as long as several seconds, as it is the product of the gate and sensor capacitance multiplied by the effective resistance represented by the charge leakage paths. To shorten this time constant, a shunt resistor is placed across the sensor output to ground. Such a resistor can also serve to match impedances for a sensor of somewhat lower impedance than a piezoelectric sensor. A long time constant can be useful if one wants to only interrogate every few seconds to detect events that happen in a millisecond, such as shock waves. The long time constant arrangement effectively integrates this information.

VI. RESULTS

The test-bed shown in figure 1 is sufficiently general to enable the testing of a wide variety of different sensors. Any sensor that varies its impedance in some relation to the physical quantity to be measured can be used as a wireless SAW sensor. Of course, to keep the entire set-up unpowered an unpowered sensor should be used. Then the entire SAW sensor configuration will be unpowered and can be permanently configured without batteries or a power source. For instance, a SAW sensor configuration can be embedded in the walls of a building, a transportation container, a vehicle, or a bridge or other structure. The sensor tag will then be available for monitoring that object indefinitely.

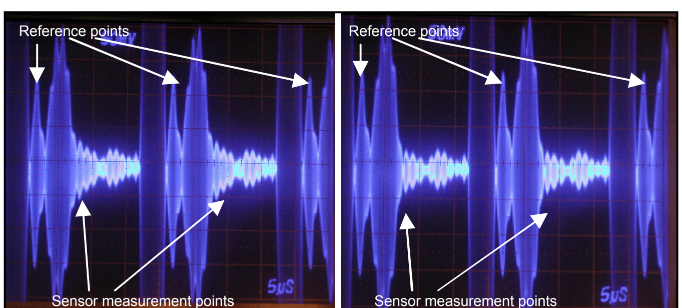
A total of 7 different classes of sensors were measured using the wireless SAW sensor test bed. These sensors were temperature, pressure, acceleration, mechanical switch, photoconductor, phototransistor, and acoustic emission. The simplest, and perhaps most useful, category of sensor is a switch. The raw signals received from a switch in the open and closed positions are shown in figure 4. The SAW filters used for this work contain 3 ports. One port is connected to the antenna and is referred to as the input port. A second port has an IDT with a short time delay and is connected to a reference impedance load that does not change. The third port with an IDT with a longer time delay is connected to the measurement impedance, which in this case is the switch. The magnitude of the reference signal is not dependent on the impedance seen at the third port, in this case the switch impedance. The delayed, re-transmitted measurement signal varies strongly with switch position, as can be seen by comparing the two photos. Many extraneous factors can cause both the reference and the measurement signals to vary in tandem, but only the switch position causes the relative difference in the two signals to change.



Received signal response with low sensor impedance. Received signal response with high sensor impedance.

Figure 4: Interrogator Received Signal Variations

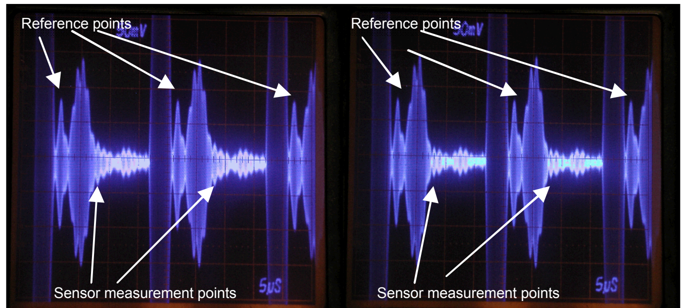
The results of measuring the accelerometer or acoustic emission sensor remotely are shown in figure 5. The measurement approach is similar to that used with the switch. The accelerometer used was an Endevco 2221F piezoelectric device. This is a high impedance device and the impedance transformer described in the previous section was used to interface the accelerometer to the low impedance SAW IDT. The delayed response has a peak magnitude of about 80mV, corresponding to an open circuit condition. The configuration provides signal integration, so that the charge from the shock acceleration is stored and made available for about 1 second. This time constant can be varied from a maximum of about 1 second to as fast as the time constant of the shock or the accelerometer, whichever is slower. As with the switch, an amplitude comparison between the reference and measurement signals gives a measurement of impedance that is independent of RF reflectance variations.



Received signal response with no shock. Received signal response under shock conditions.

Figure 5: Wireless Accelerometer Results

The results of remotely measuring a photodetector using the same methodology are shown in figure 6. The photodetector used here was a CdS photoconductor with an impedance that varies between 400Ω under dim light to 35Ω when placed directly under a 60W bulb. The results are similar to those described for the previous sensors, though the amplitude variation is not quite as large since the "short" condition is still closer to 50Ω than to 0Ω. Under dim light, the tag delayed response is about 60mV peak-to-peak. Under bright light, the tag delayed response decreases to about 40mV. More signal response can be obtained using a photodetector with lower impedance, or by using an impedance transforming device to interface to the detector. Results from tests of other sensors are similar to the three cases just presented. Impedance variations lead to variations in delayed responses in the received signals. These are easily detected using the approach outlined.



Received signal response with no illumination. Received signal response under high illumination.

Figure 6: Wireless Photosensor Results

All sensor responses must be calibrated as a wireless system. Original sensor calibrations will be rendered inaccurate by changing to the wireless readout. So, in order to obtain accurate measurement data, the sensor must be calibrated while it is embedded in the wireless measurement system.

VII. Conclusion

An overview of the basic physics and electronics behind passive remote sensing has been presented. With an extension, this becomes an approach to enable the wireless measurement of any passive impedance varying sensor. Measurements using a wide variety of sensors have been accomplished using FCC-approved power levels at 10m. The use of an impedance-transforming device has been shown to enable the use of high impedance sensors including piezo- and pyroelectric devices.

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