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RFID-enabled Temperature Sensing Devices: A Major Step Forward for Energy Efficiency in Home and Industrial Applications?

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***Abstract* — This paper presents the results of ongoing research in the area of autonomous RFID-enabled wireless sensors, focusing on low-power sensor nodes for use in temperature sensing applications. Low-power chipless RFID sensors operating in the 2.4 GHz band are utilized. The sensors are required to be completely autonomous, energy-independent, inexpensive, and easy to install.**
The compact design for both the sensors and reader will be considered, as well as the effects of operation/interference in the unlicensed frequency bands. Finally, the deployment of multiple sensors in benchmarking energy management application scenarios will be described accompanied by an assessment of the potential of this RFID-related technology for truly ubiquitous temperature measurement systems.

***Index Terms* — RF identification (RFID), SAW, Temperature, Sensor, Wireless.**

I. INTRODUCTION

This research is part of a longer term project within Georgia Tech Ireland to evaluate and develop wireless temperature sensors. The objective is to provide temperature sensing capabilities for indoor climate control, providing much more accurate thermal maps of indoor spaces therefore increasing energy efficiency compared to legacy systems. To this end, the system must have the following characteristics;

1) Energy autonomous;
2) Low maintenance, no batteries or other power sources to be replaced or replenished;
3) Easy installation, meaning no wiring for communications or provision of power;
4) Small size and form factor, to ensure unobtrusive deployment;
5) Inexpensive, so as to facilitate the deployment of multiple sensors to form a distributed wireless sensor network;
6) Low transmit power required to activate sensor tags;
7) Low complexity reader/access points so that multiple inexpensive readers can be deployed and interconnected to a central controller;
8) A wireless range of at least 7 meters;
9) Temperature accuracy of at least +/- 0.5 ^{o}C;
10) Temperature range to cover indoor ambient temperatures, +10^{o}C to +36^{o}C;
11) Resilient enough to withstand deployment and long-term operation when painted, wall-papered or plastered over.

II. OVERVIEW OF TECHNOLOGY

SAW RFID devices are entirely passive, and therefore fall into the category of chipless RFID. Traditional (chip-enabled) RFID tags require the transmit power of the reader to power up the tag circuitry, and the return path is formed by a reflected, or back-scattered signal. The transmit power from the reader therefore needs to be large enough to both power up the tag, and also reflect the signal back to the reader. The requirement to power up the tag is the limiting factor in terms of range for traditional passive RFID. In chipless RFID systems, the range is increased because the passive tag does not require any power, and therefore the range is limited by the back-scatter response only. This allows chipless RFID systems to achieve increased range compared to traditional passive RFID systems. Temperature sensors have been integrated with traditional passive RFID tags, as illustrated in [1] - [3]. The majority of the state of the art with regard to integration of sensors with RFID technology has been in relation to active RFID systems, where the sensor node and RFID tag are powered locally, typically from a battery source. A lot of research has been involved in reducing the power consumption of sensor nodes [4], and in using energy harvesting/scavenging technologies to recharge an onboard battery [5],[6]. The passive nature of the chipless SAW tags does introduce the following limitations when compared with their chip-enabled counterparts;

- The ID encoded on the tag is hard-coded at the time of manufacture, and is therefore read-only, and cannot be overwritten;
- Because there are no processing capabilities on the chipless tags, anti-collision techniques are entirely dependent upon the reader, resulting in a heavy signal processing burden on the reader.

For this particular wireless temperature sensing application, these limitations are irrelevant. Firstly, there is no requirement to update the ID and/or data that is encoded on the sensor tags.

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Secondly, unlike the typical RFID supply chain/inventory applications, the number of sensor tags to be decoded in a wireless sensor network is an order of magnitude smaller than the multiple millions of possible RFID ID's that are encountered in an RFID supply chain or inventory management system. Thus, the anti-collision requirements for this temperature sensor application are greatly reduced, resulting in a simpler reader design. These devices also have the following benefits, although these are not directly applicable in this application;

- Can operate in extremes of temperature compared to chip-based tags;
- Resilience to radiation, meaning that they can survive sterilizations processes such as gamma-ray and e-beam.

The system tested here is a prototype system provided by RF SAW Inc., as described in [7] – [8]. This system is primarily intended for RFID tracking applications, such as supply chain and inventory management, and as such is described as a Global SAW tag, as they operate in the unlicensed 2.4 GHz band which is available globally, unlike the EPC Gen2 tags which operate in different bands across the globe. The data format on these tags are compatible with EPC, in that they can hold EPC-64 and 96 bit data formats.

The RF SAW system also provides temperature sensing capabilities, however this application is the first time that these tags have been fully utilized for this purpose. This research is using this prototype system to evaluate and demonstrate the capabilities of chipless SAW RFID for the purpose described.

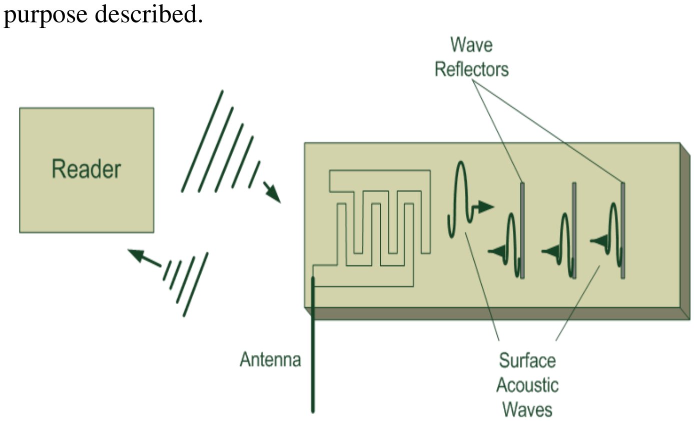

Fig. 1. System Overview.

A simplified illustration of how the information is encoded on the tag is shown in Figure 1.The number and position of the reflectors is used to encode a unique ID, and the distance between the reflected pulses varies according to the temperature of the piezoelectric substrate

III. RANGE MEASUREMENTS

The range of traditional passive RFID systems is of the order of 3-6 meters, with typical deployments achieving the lower end of the scale when the tag is adhered to various surfaces or materials. The range of chipless RFID systems has been shown to extend to 20m. The RF SAW system was also selected because it utilizes transmit powers of 0.5 mW. This means that this system fulfills the requirements set forth in section I in terms of both range and transmitted power.

Three types of passive RFID SAW tags were tested, with different sizes and antenna configurations. The tags will be classified as Type-A (largest), Type-B (midsize) and Type-C (smallest), and are illustrated in Figure 2. Type-A is a dual patch antenna, Type-B is a single patch antenna and Type-C is a single dipole.

Fig. 2. Three tag types, Type-A, Type-B and Type-C.

A summary of the results is given in Figure 3, which shows the range achieved as a function of read rate. The read rate is the number of times per second that the wireless sensor tag is read. There is an obvious drop in read rate as the distance between the tag and the reader increases, and in these tests, the maximum range achieved was 8 meters.

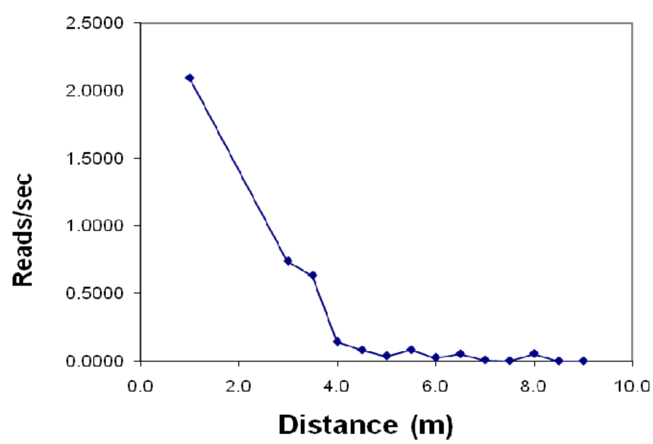

Fig. 3. Range versus read rate.

At this range, the average read rate was 0.054 reads/sec. This is a considerable decrease compared to the maximum achieved read rate of 2.6 reads/sec. However, this low read rate of 0.054 represents one read every 18.5 seconds, which for most temperature monitoring applications is more than sufficient.

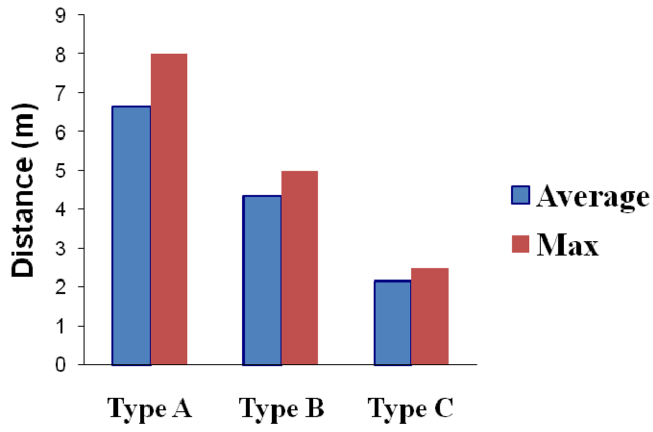

Fig. 4. Range for 3 different sensor tag types.

The results in Figure 4, illustrate the range results for the different tag types, which are shown earlier in Figure 2.

IV. Sensor Measurements

The sensor measurement setup consisted of a type-K thermocouple with an accuracy of +/- 0.1 °C. Initial measurements were undertaken for indoor ambient temperatures, ranging from +4 °C to +36 °C, and the results are illustrated in Figures 5 and 6. Figure 5 shows a snapshot of 3 different sensor measurements, and Figure 6 shows the average over all measurements. The average difference in measurement between the thermocouple and 20 SAW tags was -1.8 oC.

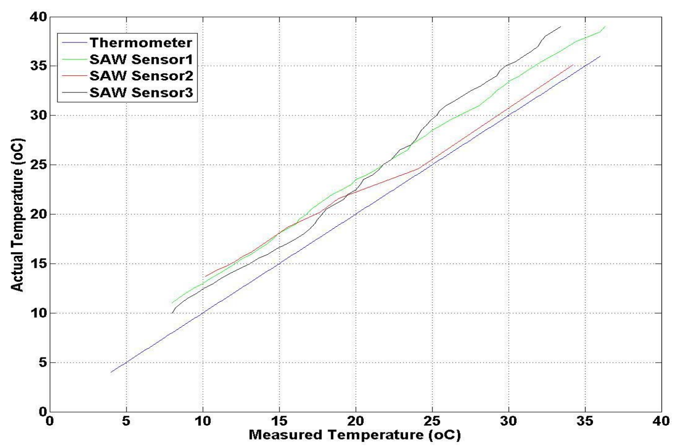

Fig. 5. Example temperature curves for 3 sensor samples.

The response time of the temperature sensor was also measured relative to the thermocouple and this is illustrated in Figure 7. This temperature change was achieved by removing the tag from the cool (10 °C) temperature chamber and placing in the relatively warm ambient environment.

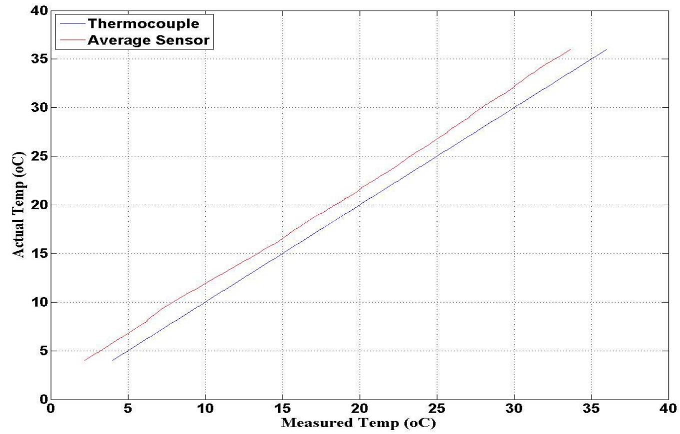

Fig. 6. Average temperature curve for multiple tags.

The temperature from both the accurate thermocouple and the sensor were measured periodically at 5 second intervals. As can be seen, the time constant for the sensor is over 60% longer than that of the thermocouple, and it takes over 3 minutes for it to track the approximately 17 °C change in temperature. The packaging of the RF SAW tags will have an impact on the time constant, as it will act as a layer of insulation around the piezoelectric material. This will affect the heat flow into the sensing surface, which is proportional to the temperature differential between the outside temperature, and the temperature of the sensing surface (the piezo material). The RF SAW tags are packaged to optimize their durability, and not with reference to their temperature sensing capabilities.

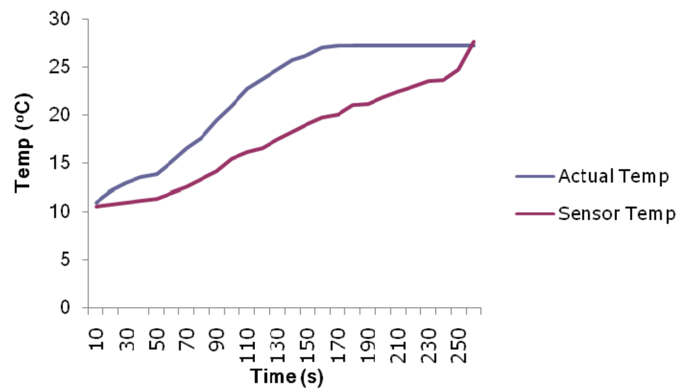

Fig. 7. Response Time of Sensor

V. SENSOR CALIBRATION

Based upon the measurements taken in section IV, a number of different calibration procedures were investigated to improve the accuracy of the temperature sensors. The 3 different schemes are categorized as follows;

- Fixed offset correction;
- Average Curve Correction;
- Individual Curve Correction.

The fixed offset is self explanatory, in that a fixed correction of +1.8 ^{o}C is applied to all sensor readings. As noted earlier, the average of all sensor readings was -1.8 ^{o}C away from actual. The average curve correction method involved creating a correction table, or curve, that applies a different correction for each 0.1 ^{o}C point on the temperature curve. This results in a table of length 320, with calibration points every 0.1 ^{o}C between +4 ^{o}C and +36 ^{o}C. This same table, which is based upon the plot shown in Figure 6, is used for all sensor tags. The final method is similar to the previous table method; however every tag has its own unique calibration table.

These calibration methods each represent an increase in accuracy; however they also represent an increase in complexity and cost. In this particular application, the cost is mainly associated with the additional steps required to calibrate tags at manufacture (and/or maintain a consistent temperature environment during manufacture), as opposed to the cost of storing the calibration tables. The wireless sensor network controller should have sufficient memory and processing requirements to hold tables for up to 50-100 sensor devices.

The average, mean squared error and accuracy for each of these methods is listed in Table I. The interesting finding is that the fixed offset and average curve schemes perform very similarly.

Table I
Calibration Results

	Average Error (^{o}C)	**Mean Squared Err**	**Accuracy (^{o}C)**
Raw data	2.296	7.15	-2.1 to +5.6
Fixed Offset	1.571	3.51	-4.0 to +3.7
Ave Curve	1.569	3.52	-3.9 to +3.4
Ind. Curve	0.358	0.17	-0.8 to +0.6

VI. FUTURE WORK

Future research in this area will look into other techniques for extending the range and utility of wireless sensors. In the area of chipless RFID based sensors, the use of phased array/beam-forming techniques to increase range will be investigated. Other possible areas of research will include energy harvesting and power scavenging of ambient energy sources such as light, vibration, RF, and heat. Finally, realizing these devices using inkjet printable technology on paper and other materials will be investigated.

VII. CONCLUSION

This initial study of RFID SAW based temperature sensors has shown it is feasible to use them in a wireless sensor network to monitor temperature. The system demonstrated achieves the desired range, however some work is needed to increase the coverage of multiple sensors using a wider beam reader antenna.

The temperature measurements can achieve reasonable accuracy after calibration, even with a development system which is not specifically designed for temperature measurement, rather for traditional RFID identification. This suggests that RF SAW sensors that are optimized for temperature sensing could achieve better than +/- 0.5 ^{o}C accuracy.

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REFERENCES

[1] S. Kim, J.H. Cho, H.S. Kim, H. Kim, H.B. Kang, and S.K. Hong, “An EPC Gen 2 compatible passive/semi-active UHF RFID transponder with embedded FeRAM and temperature sensor”,*Asian Solid State Circuits Conference*, Nov 2007.

[2] A.P. Sample, D.J. Yeager, P.S. Powledge, A.V. Mamishev, J.R. Smith, “Design of an RFID-Based Battery-Free Programmable Sensing Platform”, *IEEE Transactions on Instrumentation and Measurement*, vol. 57, NO. 11, Nov 2008.

[3] K. Opasjumruskit et al, “Self-powered wireless temperature sensors exploit RFID technology” , *Pervasive Computing*, IEEE Volume 5, Issue 1, Jan.-March 2006.

[4] N.M. Pletcher, et al, “Ultra-Low Power Wake-Up Receivers for Wireless Sensor Networks”, *PhD thesis*, University of California, Berkeley, 2008

[5] M. Marzencki, et al, “Integrated Power Harvesting System including a MEMS Generator and a Power Management Circuit”, *Transducers'07/Eurosensors XXI*, p 887-890, June 2007.

[6] S. Roundy, et al, “Study of Low Level Vibrations as a Power Source for Wireless Sensor Nodes”, *Computer Communications*, 2002.

[7] C.S. Hartmann, “Future high volume applications of SAW devices,” *IEEE Proceedings of 1985 IEEE Ultrasonics Symposium,* vol. 1, pp. 64-73, 1985.

[8] C.S. Hartmann, “A global SAW ID tag with large data capacity,” *Proceedings of 2002 IEEE Ultrasonics Symposium,* vol.1,pp.65-69,2002.