

RFID Tag Antenna Based Temperature Sensing

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Abstract—Temperature monitoring is important in a number of fields, particularly cold supply chain applications. Most commercial wireless temperature sensors consist of transceivers, memory and batteries to maintain a temperature time history but this is expensive and allows for limited sensor deployment. In this paper, we propose a low cost temperature sensor based on the paradigm of passive RFID tag antenna based sensing. A simple mechanical method to permanently induce changes in RFID tag power characteristics upon exposure to temperatures greater than a threshold is presented. Critical temperature threshold violations can then be detected by monitoring received backscatter signal strength at a reader. The feasibility of the proposed hypothesis is examined via theoretical and experimental means. It will be shown that this sensing paradigm has the potential to greatly increase the pervasiveness of temperature sensing nodes and improve supply chain visibility and performance.

I. INTRODUCTION

Temperature is an important environmental parameter in a diverse variety of fields such as infrastructure monitoring, chemistry, environmental engineering and cold supply chain management. Temperature monitoring in cold supply chain operations is particularly important as outlined by O'Connor [1] who points out that temperature within a transportation pallet itself varies by up to 35%. Fluctuations in ambient temperature have been known to affect the quality of perishable produce as outlined by Estrada-Flores [2] and Schuster et.al [3]. With an estimated 30% of perishable goods [4] spoiling in transit in supply chain operations, there is a dire need for increased visibility with optimal granularity using sensing devices.

Temperature sensors are required to monitor and record all critical temperature changes in the environment over the period of deployment. The wide variety of wireless temperature sensors deployed in commercial supply chain applications achieve this by including appropriate on board electronics like memory and battery which drives up the cost of the sensor unit. As a consequence, economic considerations often preclude the deployment of these sensors on a truly pervasive scale. Ambient temperature levels are inferred based on the output of a finite number of sensor nodes, rather than by monitoring each logistic unit passing through the supply chain. It would therefore be very useful to have a dedicated sensor monitoring at the logistic unit level so that critical temperature state changes can be monitored and recorded. However in order to meet this objective, the cost of this sensor must be significantly low. In this paper, we propose the design of an ultra-low cost temperature sensor based on

passive UHF RFID principles, which is capable of logging temperature changes above a critical temperature threshold for user specified tolerance intervals.

Section II discusses the requirements of temperature sensors and the impact of these requirements on the scale of deployment and measurement. In Section III we discuss our paradigm of RFID tag antenna based temperature sensing, how it would meet these requirements and describe the construction of a prototype sensor built to examine this hypothesis. Section IV then attempts to examine the feasibility of this principle by drawing comparisons to the behaviour of a dipole antenna in a multi-layered dielectric medium. Section V outlines the results of experimentation on the sensor prototype used to validate this hypothesis. Finally, in Section VI we summarize the contribution and outline the scope for future work.

II. CURRENT SUPPLY CHAIN TEMPERATURE SENSING ALTERNATIVES

Temperature monitoring is particularly important in the cold supply chain where temperatures have to be artificially maintained to optimize the shelf life of the transported goods. For example, orange juice typically produced and packaged in Florida is mobilized via transportation networks to different corners of the US. In order to prolong the life of the juice, the transportation medium is required to be appropriately refrigerated. Similarly vaccines and other perishable medical items may require to be constantly stored at sub-zero temperatures in order to remain potent.

It is crucial to log the critical temperature state changes during temperature monitoring of an environment. Most of the commercial sensors [5] [6] [7] available today are customized for precisely this functionality and are comprised of a series of discrete electronic components such as antennas, application processors, battery power units, signal conditioning units and memory. Unfortunately, the presence of discrete electronic components drives up the cost of the temperature sensor and this manifests in a reduction in the number of feasible sample points, due to monitoring budget constraints. Lack of adequate monitoring granularity, could inadequately represent the ambient temperature profile and therefore it is important to maintain an appropriate balance between sensor functionality and cost.

With this in mind, we highlight the most important factors required of temperature sensors in supply chain monitoring:

Low Cost: Most commercial temperature sensing options are

typically available in the price range of O(\$20) today. The price of these sensors prevent their pervasive deployment in supply chain applications. For example, it does not make any commercial sense to tag an orange juice carton priced at about \$3 with a dedicated sensor which costs O(\$20). Thus temperature measurements with this sensor is limited to inference measurements from a finite number of nodes deployed in the freezer or refrigerator storage unit which contains thousands of such cartons. The granularity of temperature measurements may not be sufficient to capture fluctuations in temperature across the freezer unit. In order to attain true ubiquity in supply chain operations, the sensors should be ultra-low cost so as to improve the scale of their deployment.

Ability to Maintain State: Most temperature sensors today log a time history of data so that threshold temperature exposure information can be recorded. The question of whether a critical exposure threshold was attained is more important than the time history itself. It is thus important that the sensors be able to log exposure information at minimum cost.

Standardization of Communication Protocols: There are numerous partners interacting in a supply chain. In order to facilitate seamless data transfer from one partner to another, the temperature sensor's communication protocol must be standardized. It is important to pick sensors that conform to a protocol that has the least setup cost in terms of hardware and software equipment.

RFID presents a well established, standardized wireless technology to leverage for sensor development. Some commercial alternatives have attempted to provide RFID based temperature sensing solutions. For example, KSW [8] has developed an RFID smart label with an integrated temperature sensor. Similarly, Gentag [9] has developed an RFID tag IC with an integrated temperature sensor. Both these approaches leverage the RFID Gen 2 Communication protocol [10] and thus conform to a standardized communication protocol. The KSW sensor however costs around \$3-\$10 and cannot be deployed for tagging cheaper items, such as perishable food products, which would account for a sizable fraction of the items passing through the supply chain. Similarly the design costs associated with the Gentag IC would drive up the cost of the composite sensor tag whenever the IC is integrated with a tag antenna. There is thus a need to drive the cost of a temperature sensor even lower in order to ensure its ubiquitous deployment and in this paper we examine the design of a temperature sensor using the RFID tag antenna based sensing paradigm. There has been some prior research work in using the RFID tag antenna as a sensor. For instance, Marrocco [11] present basic theory and simulations for the performance of multiport RFID tags on materials with different permittivities. Similarly, Bhattacharyya et.al [12] present a tag antenna based displacement sensor by relating displacement to a change in reader threshold transmitted power to power up the RFID tag IC and the differential backscatter power returned from an RFID tag, while Siden et.al [13] illustrate how ordinary RFID tags can be used as humidity sensors. In related work, Marrocco et.al [14] present experimental results for tag sensor designs along

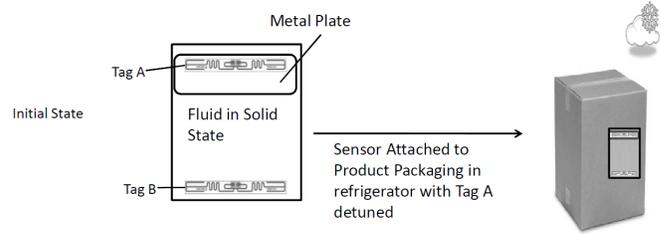


Fig. 1. Temperature Sensor Initialization

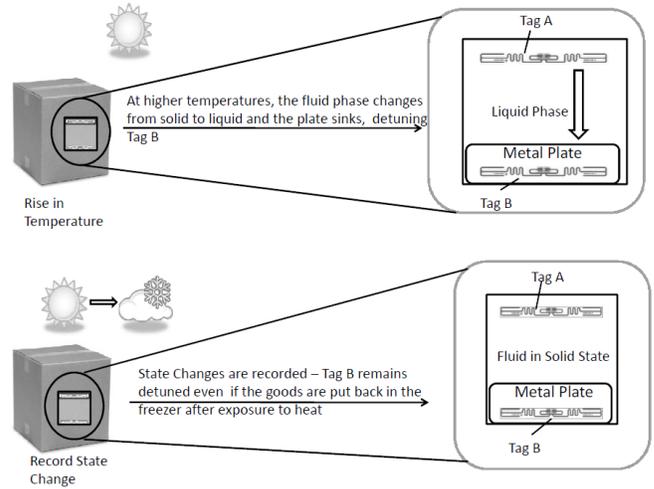


Fig. 2. Temperature Sensor Working

the lines of the theory and simulations presented in [11]. In the next section, we discuss the design of an RFID tag antenna based temperature sensor that has the advantage of being ultra-low cost and long lasting with an ability to maintain critical threshold temperature exposure information using non-electric memory.

III. TEMPERATURE SENSOR OPERATING PRINCIPLE

RFID tag antenna based sensing [12] is a paradigm for developing ultra low cost, long lasting, standardized and accurate sensors leveraging the UHF RFID infrastructure. This sensing approach relies on mapping a change in some physical parameter of interest to a calibrated change in RFID tag antenna characteristics and thus RFID tag power characteristics.

There has been prior research into the development of RFID Tag Antenna based sensors. For instance, Bhattacharyya et.al [15] discuss the development of a displacement sensor using the fact the RFID tag performance degrades in close proximity to metal, while Siden et.al [13] demonstrate how normal RFID tags can be used to detect relative humidity and moisture ingress, by making use of the fact that RFID tag performance degrades in proximity to water.

In this study, we design an RFID tag antenna based temperature sensor for supply chain scenarios where the temperature of the transported goods cannot exceed 0°C

for periods of time exceeding a chosen tolerance limit. If the temperature is maintained above 0°C for more than the tolerance, the sensor is capable of logging this and conveying this information to the next RFID reader unit that interrogates the temperature sensor. The operating principle of the sensor is summarized in Fig. 1 and Fig. 2.

The temperature sensor is designed as a compact cuboidal jacket made out of plexiglass with two RFID tag inlays pasted on the outer surface of the plastic jacket, separated by about 3-5 cm. The inside of the box is filled with an aqueous medium having a desired melting point - for the purposes of this study, we choose water having a melting point of 0°C. An aluminium plate, capable of vertical motion in the aqueous medium is located behind the two tags such that at any given instant one of the two tags is detuned due to the proximity of the metal plate. The sensor relies on changes in phase of the aqueous medium and vertical motion of the aluminium plate under the force of gravity to record changes in critical state as we shall illustrate.

A. Sensor Operating Principle

We now analyze in detail the operating principle of this sensor:

- *Initialization:* The temperature sensor is designed to monitor the temperature of goods in a freezer below 0°C. The sensor is thus initialized by freezing the ice with the metal plate directly behind the top tag - which we shall henceforth refer to as Tag A as seen in Fig. 1. Thus in the initialized state, we would expect better performance from Tag B, both in terms of differential backscatter power from Tag B as well as threshold transmitted power required to power up Tag B, since Tag A is detuned due to the metal plate directly behind it. If during supply chain transportation, the goods remain at or below 0°C for all times less than the tolerance limit, the metal plate remains frozen behind Tag A. Each reader unit interrogating the sensor would be able to verify that the goods were maintained at temperatures below 0°C throughout transit. Fig. 1 illustrates the attachment of the sensor to one of the items in the refrigerator prior to transportation.
- *Effect of High Ambient Temperature:* If the temperature sensor is placed at a temperature higher than the temperature of the freezer for periods greater than the tolerance interval, the ice would melt and the metal plate would descend under the influence of gravity to a position behind Tag B as seen in Fig. 2. The fact that the temperature sensor has undergone a state change can then be detected by the following observations:
 - *Reduction in Read Range:* The water molecule is highly polar and tends to orient itself so as to cancel out any incoming electric field, a phenomenon that is not as effective in the solid ice state. Thus about 80% of the incoming electric field would be reflected at the plexiglass-water interface [16]. This

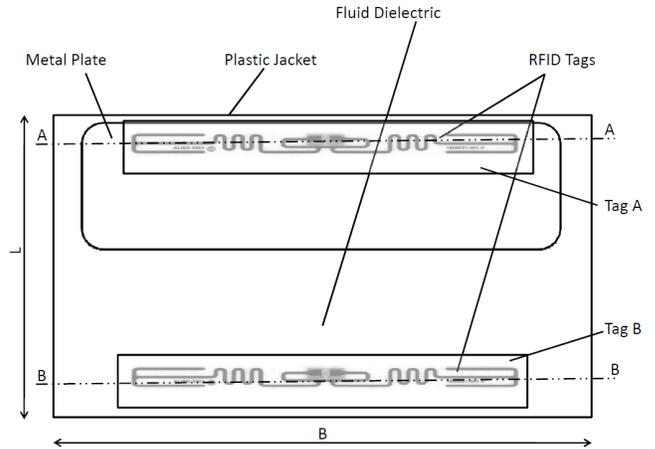


Fig. 3. Temperature Sensor in Elevation

is manifested in a reduction in sensor read range for tag power measurements from both tags. Thus if a sensor arrives at a distribution center with the aqueous medium in the liquid state, the read range for both tags is drastically reduced.

- *Detuning of Tag B:* Since the metal plate descends under gravity to detune Tag B instead of Tag A, a change of state can also be characterized by a degradation of performance of Tag B relative to Tag A - which is independent of whether the aqueous medium is in the liquid or solid state. In context of the supply chain, if a crate of frozen produce, tagged with this sensor, is kept out in the sun for a couple of hours, the ice in the sensor would melt and the metal plate would descend to detune Tag B. Even if the goods are placed back in the freezer, the metal plate continues to detune Tag B. Thus it is possible to permanently record the fact that the temperature sensor suffered a critical state change, irrespective of what state the aqueous medium assumes sometime after.

The plan and elevation of the sensor is described in Fig. 3 and Fig. 4 respectively.

B. Prototype Design

We examine the feasibility of this sensing approach via the development of a prototype sensor (c.f Fig. 5).

The plexiglass jacket which houses the metal plate and the aqueous medium is designed for the dual purpose of 1) testing the performance of different kinds of RFID tag inlays and 2) allowing for different volumes of water so that the ice-water transition time can be calibrated and controlled.

- *Selection of Jacket Surface Area:* RFID tag inlays vary significantly in dimensions, based on antenna geometry from about 10 cm X 2 cm in the case of an Alien Squiggle [17] to about 9 cm X 9 cm in the case of the Impinj Banjo [18]. Thus the surface area of the plastic jacket was set as $l=16$ cm and $b=10$ cm (Fig. 3) to be able to accommodate

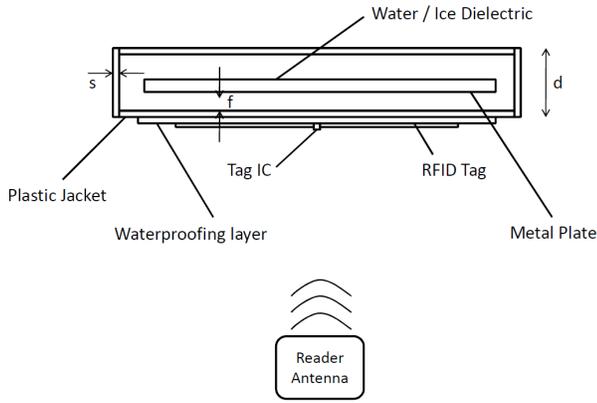


Fig. 4. Temperature Sensor in Plan



Fig. 5. The Sensor Prototype

most kinds of inlays. The complete list of dimensions is outlined in Table. I. References should be made to Fig. 3 and Fig. 4 to interpret the dimensions.

- *Effect of Volume of Water on Tolerance Interval:*

In Fig. 6 we plot observed time required for the ice to completely melt as a function of four different control volumes varying from 40ml to 100 ml of water as shown

TABLE I
DIMENSIONS OF THE PROTOTYPE

Dimension	Value (mm)
Jacket Length (l)	160
Jacket Breadth (b)	100
Jacket Depth (d)	6
Jacket Material Thickness (s)	1.3

TABLE II
VARIATION OF ICE MELT TIME WITH VOLUME OF WATER

Volume (ml)	Melt Time (min)
40	16
65	20
80	27
100	30

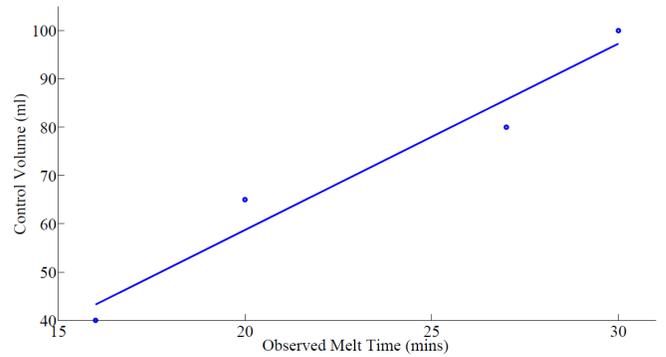


Fig. 6. Plot of Melt Time as a function of different control volumes

in Table. II for a constant outside temperature of 18°C. We find that a linear best-fit function adequately captures the relationship.

From Fig. 6 we observe that it is possible to draw a fairly accurate correspondence between the experimentally observed melt time and a control volume of water. For the purposes of experimentation, a control volume of 55 ml, corresponding to a tolerance interval of about 18 mins, is chosen. In general however, the volume of water can be varied so as to meet the specified tolerance interval by referring to Fig. 6.

IV. THEORETICAL ANALYSIS OF SENSOR PRINCIPLE

Changes in background dielectric material will certainly influence RFID tag performance both in terms of the power backscattered by the tag as well as the threshold transmitted power required to power up the tag. The sensor principle outlined in Section III relies on the difference in backscatter power levels due to the presence or absence of the metal plate being significant enough to be able to differentiate a state change. In this section, we propose a quick mathematical analysis to demonstrate whether this is indeed expected to be the case.

The net far field due to a dipole antenna on top of a dielectric substrate and assuming Transverse Electric (TE) radiation is due to the superposition of the electric field directly radiated from the dipole, $E(\theta, r)$ and the component of the electric field reflected by the dielectric substrate, $R^{TE}E(\theta, r)$. This superposition is given by:

$$|E_{eff}| = (1 + |R^{TE}|)E(\theta, r), \quad (1)$$

where R^{TE} is the effective reflection coefficient due to a system of dielectric layers and $E(\theta, r)$ is the far electric field

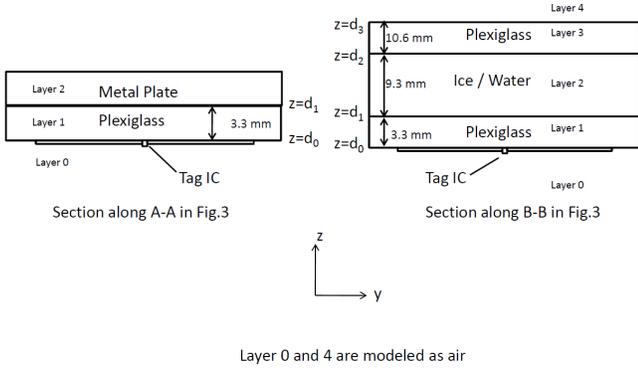


Fig. 7. Dielectric Layers in the model

of the dipole antenna with no background dielectric in free space.

We consider three cases here. In the first case, the background dielectric to the RFID tag is the plexiglass jacket followed by the metal plate. Since the metal plate is assumed to be perfectly reflecting, we do not consider any substrate beyond the plate. In the second case, the background material is plexiglass, followed by a layer of ice, followed by plexiglass as shown by taking sections at A-A and B-B in Fig. 3 and illustrated in Fig. 7. The third case, is the same as the second case except that the ice dielectric is replaced by water.

As outlined in Kong [19], the coefficient R^{TE} can be calculated for an n layer system by

$$\begin{aligned}
 R^{TE}_m = & \frac{e^{2ik_z d_0}}{R_{01}} + \frac{[1 - (1/R_{01}^2)]e^{2i(k_{1z} + k_z)d_0}}{(1/R_{01}e^{2ik_{1z}d_0})} + \dots \\
 & + \frac{e^{2ik_{(n-1)z}d_{(n-1)}}}{R_{(n-1)n}} + \frac{[1 - (1/R_{(n-1)n}^2)]e^{2i(k_{nz} + k_{(n-1)z})d_{(n-1)}}}{(1/R_{(n-1)n}e^{2ik_{nz}d_{(n-1)}})} \\
 & + R_{nt}e^{2ik_{nz}d_n}
 \end{aligned} \quad (2)$$

We define the terminology used in Eq. 2 below:

- Here R^{TE}_m is the effective reflection coefficient of the system of dielectrics corresponding to the three cases $m=1,2,3$ for metal, ice and water dielectric respectively.
- d_i relates to the thickness of the i^{th} layer in the dielectric system.
- k_{nz} is the z component of the wavenumber in layer n.
- R_{ij} is the reflection coefficient between the i^{th} and j^{th} layers and is given by :

$$R_{ij} = \frac{1 - \rho_{ij}}{1 + \rho_{ij}} \quad (3)$$

Here we have

$$\rho_{ij} = \frac{\mu_i k_{jz}}{\mu_j k_{iz}} \quad (4)$$

where μ_i relates to the magnetic permeability of layer i and k_{jz} is the component of the wavenumber in medium j. For normal incidence, k_{jz} relates to the electrical permittivity ϵ_j for the layer j.

TABLE III
RETURNED POWER LEVELS OF ICE AND WATER RELATIVE TO METAL

Dielectric	Power Relative to Metal
Ice	28.57 dB
Water	21.18 dB

Since the Poynting power density is $\propto |E|^2$, we have

$$|Power| = 0.5 * [A(1 + |R^{TE}|)^2] \quad (5)$$

where A is the constant of proportionality. Assuming R_i^{TE} is the reflection coefficients for case 1,2 and 3 we have the difference in power levels of the ice and water dielectric, relative to the metal plate dielectric as

$$P_{ice|metal} = 10 * \log\left(\frac{0.5 * [A(1 + |R_2^{TE}|)^2]}{0.5 * [A(1 + |R_1^{TE}|)^2]}\right) \quad (6)$$

and

$$P_{water|metal} = 10 * \log\left(\frac{0.5 * [A(1 + |R_3^{TE}|)^2]}{0.5 * [A(1 + |R_1^{TE}|)^2]}\right) \quad (7)$$

Plugging in the various values for d_i by referring to Fig. 7 and making appropriate assumptions for the relative dielectric constants for water, ice and metal we obtain results of power difference levels as summarized in Table III. We note from these computed values that the difference in power levels for ice and water are sufficiently large relative to metal as a background dielectric. Furthermore, there is a relative difference of about 7 dB between ice and water and thus all critical state and phase changes are clearly discernible. Thus the feasibility and validity of this sensor should certainly be investigated via experimentation and this is the focus of the next section.

V. EXPERIMENTATION AND RESULTS

In order to verify the sensing hypothesis, we subject the sensor to temperature cycles from the frozen state to the fully melted state. A control volume of 55 ml of water is selected for experimentation. Referring to Fig. 6, we expect the melt time to be about 19 minutes.

Tag read range is a key issue to be determined in this experiment since RFID tag performance dwindles significantly in the presence of water and metal. The sensor - RFID reader separation is varied from 0.5 m to 1.5 m in steps of 0.5 m. For each separation, the sensor is cycled from the frozen state to the melted state and the received backscatter power from Tags A and B (cf. Fig. 3) as a function of time is plotted. We expect the ice to completely melt in about 20 minutes, however the test is conducted for a 1 hour interval.

The Impinj RFID Reader System [18] is used in the experimentation. The reader transmitted power setting is set to the maximum of 4W EIRP. The temperature sensor in the initialized frozen state is placed before the reader antenna at an environment temperature of 18°C. The reader antenna measures the differential backscatter power from Tag A and B as a function of time for a 1 hour interval. Readings are

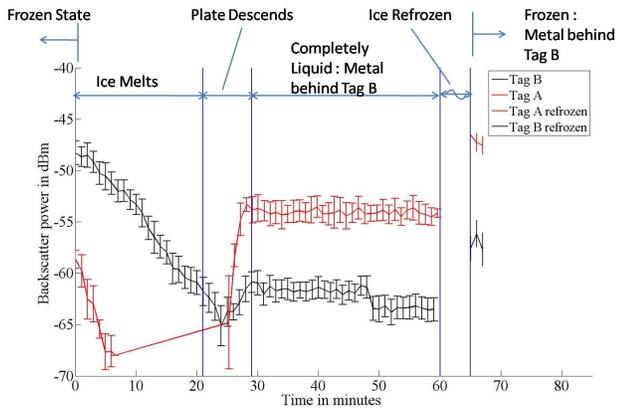


Fig. 8. Backscatter Power vs. time for sensor-reader separation of 0.5 m

taken at the rate of 2 per second, averaged over 60 seconds and reported on a per minute basis. We now discuss the sensor response as a function of time for the three different sensor-reader separations.

A. Reader-Sensor Separation of 0.5 m

Fig. 8 plots backscatter power response from the two tags as a function of time. Initially, Tag A has the metal piece behind it, which detunes the tag antenna, as a result of which Tag A gives a lower backscatter power response relative to Tag B. Tag B initially has ice as the background dielectric, which detunes the antenna less severely, as a result of which Tag B initially has a much better backscatter power response relative to Tag A (cf. Fig. 1).

As time passes, the ice starts to melt and the background dielectric for both tags involves increasing amount of water. Water molecules tend to orient themselves so as to cancel out incoming electric fields and thus water detunes the tag antenna and reflects most of the incoming electric field, thus affecting performance more severely than ice. Thus between 0 and 10 minutes, the performance of both tags starts reducing. Between 10 and 24 minutes we see that there is no observed response from Tag A. We observe during experimentation that water vapour has a tendency to condense on the surface of the cold plexiglass jacket and arbitrarily detune the tags. The condensed water now presents one additional layer in front of the tag where 80% of the incoming field is scattered. It is possible that this condensation together with the proximity of the metal plate, detunes Tag A to the extent that the tag IC chip fails to power up.

In order to verify this hypothesis, we repeat the experiment removing moisture due to condensation as soon as it builds up. The results are seen in Fig. 9. From the figure, we observe that Tag A always gives a clear response over 24 minutes, illustrating that moisture condensation must be accounted for while taking measurements from the sensor system.

Referring back to Fig. 8, it is observed that the ice completely melts and the plate descends to detune Tag B at about 24 minutes which is reasonably close to the predicted 19 minutes.

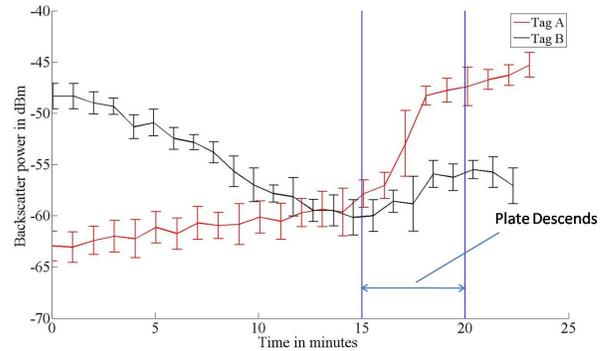


Fig. 9. Backscatter Power vs. time accounting for condensation moisture buildup

Thus after 24 minutes, Tag B gives a worse performance than Tag A. We note an interesting observation here. After 24 minutes Tag A is no longer detuned by the metal, but its performance is worse than that of Tag B at $t=0$, since the background dielectric for Tag A is water, which detunes the tag antenna more severely, rather than ice. To verify this, we refreeze the sensor with the metal plate behind Tag B. As seen from Fig. 9, the response of Tag A then improves to levels comparable with Tag B at $t=0$.

If we attempt to corroborate the experimental results with our theoretical analysis, we observe that the trends predicted by the theoretical analysis are confirmed via experimentation. The power levels with dielectric backdrop of ice is on an average about 7dBm better than with a backdrop of water as seen by comparing the power levels of Tag B at $t=0$ with those of Tag A beyond $t=30$ in Fig. 8. Similarly, there is a significant difference of about 10 dBm between a backdrop of metal vis-a-vis ice. Although not as high as the theoretically computed 28dBm, the assumption of there being a significant difference in power level between the states is certainly verified in practice.

In order to validate the repeatability of the observations, the temperature cycle test was repeated three times and in each run, repeatable results were obtained.

B. Reader-Sensor Separation of 1 and 1.5 m

Fig. 8 shows the response of the sensor as a function of time when the separation was increased to 1m. The trends of the curves remain the same although the absolute values of the power levels decrease slightly due to the increased distance between reader and tag. It is interesting to note that at 1m distances, once the metal plate descends, Tag B does not get picked up by the reader. The power density reaching the tag over the increased distance after mismatch losses due to the water and the metal is insufficient to power up Tag B's IC. Similar trends were observed when the reader-tag separation was increased to 1.5 m as shown in Fig. 11. As we observe from the figure, there are several missed observations, indicating that the backscatter power readings from the sensor are difficult to detect at that range.

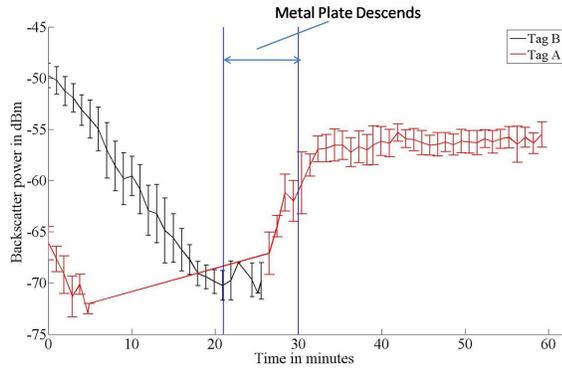


Fig. 10. Backscatter Power vs. time for sensor-reader separation of 1 m

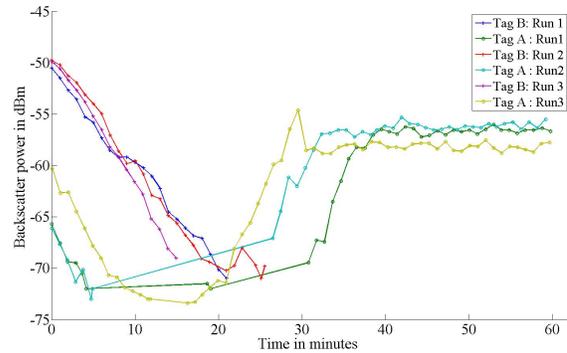


Fig. 12. Three Runs for Reader-Sensor Separation of 1m

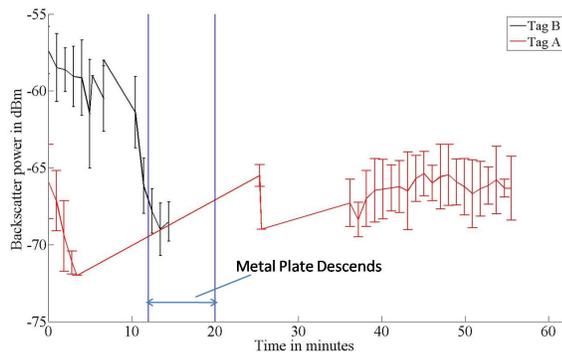


Fig. 11. Backscatter Power vs. time for sensor-reader separation of 1.5 m

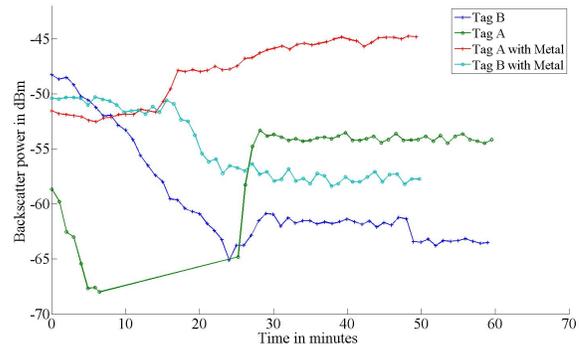


Fig. 13. Effect of different material of deployment

As in the previous case, these tests were run three times as well and consistent results were obtained. Fig. 12 for instance demonstrates three runs when the sensor-reader separation is 1m.

C. Effect of Material of Deployment

It is also important to consider the electromagnetic influence of the material on which the sensor is deployed. The experiments were conducted by attaching the sensor to a hollow cardboard box, however it is necessary to consider the effect of other materials - particularly the so called RF unfriendly materials. A lot of packing crates and containers are metallic and in order to simulate this the sensor is attached to a metallic plate and the experiment is repeated for a 0.5 m sensor-reader separation. The results are shown in Fig. 13. As we can see the presence of metal significantly alters the relative power differences between the two tags. In fact, the metal seems to boost the strength of the backscatter power signal. We note that the metal plate is located at a distance of about 2 cm from the tags. It is possible that the backscatter power from the tag and the reflected signal from the plate are interfering constructively at the reader and this may account for the boost in signal. Thus material of deployment is an important factor to be considered and will be addressed in future work to enhance the sensor performance.

VI. CONCLUSIONS

In this paper, we propose a design methodology and verify the working feasibility of an ultra low cost wireless temperature sensor which leverages the RFID infrastructure. While many of the sensors commercially available in the cold supply chain, boast high precision and accuracy of measurement with features such as memory logging, their relatively high cost precludes their pervasive deployment in cold supply chain applications.

Our approach emphasizes the ultra-low cost of manufacture but recognizes the associated trade-offs this would entail. Tag antenna based temperature sensing will not provide real time updates or log a time history of temperature measurements. However this sensor will provide the user with binary state information indicating whether critical temperature thresholds were reached during transportation allowing the user to make a decision of whether to keep or discard the goods. Since the state of most goods are examined at the distribution centers in a supply chain, rather than in transit, we argue that this kind of sensing might in fact be adequate for monitoring most items such as orange juice cartons, milk and meat products in supply chain applications, since the state of the products will be automatically monitored as soon as the products pass past an RFID reader at the dock door of a distribution center. Furthermore, since many supply chains have an RFID infrastructure already in place, this sensing

paradigm has the advantage of leveraging an already well established communication infrastructure. Thus with its ultra low cost and ability to convey critical state change information upon interrogation, we expect RFID tag antenna based sensing to be very relevant to a large market share of cold supply chain applications.

While the design methodology was demonstrated in this paper, there is significant research that requires to be done in this area to extend the technology. We note that the lower Tag B is consistently not read for reader-tag separations of more than 0.5 m. It is difficult to differentiate this from a failure of Tag B. A relative response from both tags A and B would be a much better indicator of state change. It is thus necessary to design a tag with custom antenna geometry that is optimized for performance near water and metal so that the read range of the sensor is boosted to more than 0.5 m.

The current prototype implicitly assumes that the sensor would be deployed on packaging material that is RF friendly. In practice, many transportation pallets are metallic and the performance of the sensor is affected by this. Modifying the sensor design, perhaps by including a metal backplane, would make the performance independent of the material of deployment.

Condensation of moisture on the surface of the sensor is another issue that must be tackled. Even for reader-sensor separations of about 0.5m, the build up of moisture can detune the tag and reflect incident electric fields to the extent that the tag is no longer picked up. Elimination of moisture buildup by use of appropriate hydrophobic surfaces that shed water on contact is another avenue that must be explored in the sensor design.

The requirement that this sensor be initialized by freezing the metal plate in position behind the top tag is one potential impediment to the commercial deployment of this sensor. Although it is not difficult for supply chain partners to initialize batches of these sensors in industrial freezers, it is one additional step that detracts from the low-cost, pervasive appeal of this sensor. Furthermore, since the memory effect is triggered by gravity, it is necessary to place the sensor on the side of the shipping container. Thus an underlying assumption is that the goods are not rotated or turned by 180 degrees during transit. Furthermore, this current version of the temperature sensor is not tamper proof and the memory mechanism breaks down should the sensor be rotated by 180 degrees and refrozen. Our research efforts are currently looking into developing a low-cost solid state sensor that is independent of sensor placement orientation and which does not require to be initialized before deployment.

Extending the sensor to detect the violation of several thresholds is another important step perhaps via the use of composite dielectrics having different melting points. It might be useful to design a sensor that detects not only a upper bound critical temperature but a lower bound as well. For example most organic produce would be optimized for transport for temperatures between 0 and 10 C. The food would spoil if maintained for a long time above 10 C but would also spoil if frozen below

0 C. Developing an RFID based temperature sensor having an optimized range, with extensions for monitoring different temperature range thresholds and which is independent of the packaging material of deployment would thus be a significant boost to the proposed technology and is thus the focus of future research.

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