Low-Cost, Ubiquitous RFID-Tag-Antenna-Based Sensing

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CONTRIBUTED PAPER

Low-Cost, Ubiquitous RFID-Tag-Antenna-Based Sensing

The authors of this paper propose a means for providing low-cost, long-lifetime temperature-threshold sensing, displacement sensing, and fluid level sensing for RFID systems.

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ABSTRACT | Radio-frequency identification (RFID) has been well established as an effective technology for track and trace applications. In this paper, we go beyond the ID in RFID, and discuss the potential for RFID tags to be used as low-cost sensors by mapping a change in some physical parameter of interest to a controlled change in RFID tag antenna electrical properties. We will also show that it is possible to design the tag antenna to suffer a permanent change in case of violation of a critical threshold in the parameter of interest thereby creating a low-cost threshold sensing mechanism. This can be achieved by inducing controlled changes to the tag antenna geometry parameters or to the antenna boundary conditions, in effect creating a nonelectric memory to monitor state. After identifying the application space for which this class of sensing is well suited, we present details into the design and testing of three different kinds of sensors based on this sensing paradigm. We demonstrate how we use this concept to sense displacements, temperature thresholds, and fluid levels. We will show that RFID-tag-antenna-based sensing has the potential to revolutionize application domains in which there is a need for low-cost, long-lasting, ubiquitous sensors.

KEYWORDS | Low-cost sensing; radio-frequency identification (RFID); tag antenna impedance changes; ubiquitous sensing

I. INTRODUCTION TO SENSING IN RFID

Radio-frequency identification (RFID) is gaining a lot of traction as an effective technique in track and trace applications [1], since it offers several advantages over well-established optical technologies such as barcodes in terms of range and non-line-of-sight operations [2]. There has been much research into addressing the challenges to RFID adoption such as lowering transponder cost [3], standardizing RFID communication protocols [4], and implementing security measures [5]. The net result of this research is a mature standardized wireless communication protocol for object identification.

An interesting research proposition is to extend this well-developed infrastructure for applications that have a need for low-cost, ubiquitous wireless sensing. Current wireless sensing applications make use of battery-powered sensors, but these sensors are at least two orders of magnitude more expensive than their simpler passive counterparts, which limits the granularity of their deployment. For example, it is not possible to sense the temperature of every crate carrying a couple of \$3 orange juice cartons passing through the supply chain with a \$20 temperature sensor. Battery-powered sensors have limited battery life [6] and conform to one of several communication standards available. Seamless communication can thus be problematic in a multientity business model such as supply chain logistics if there is no one standard which is agreed upon and if one or more of the partners in the chain do not have the infrastructure in place to interrogate these sensing units.

In this paper, we propose a technique for using changes in the response of an RFID tag antenna as a sensing mechanism by correlating a change in some physical

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parameter of interest to a calibrated change in RFID tag performance. Furthermore, we will show that it is possible to build in nonelectric memory into these sensing devices by having the tag antenna suffer some kind of permanent change upon violation of a threshold, even if the event occurs when the tag sensor was not in range of reader interrogation equipment—which is useful when the question of whether a threshold was violated is more important than the precise time at which it was violated. The event of critical threshold violation can then be detected the next time the sensor is interrogated by an RFID reader unit. This kind of sensing paradigm allows us to design sensors that leverage low-cost RFID tags which are passive and thus long lasting, which conform to a standardized communication protocol and which have the potential for pervasive deployment. Of course, we do have tradeoffs in terms of sensor range, lack of time history data storage, and nonreal-time data communication.

A brief overview of wireless sensing is provided in Section II and Section III describes the principle of RFID-tag-antenna-based sensing. Section IV then describes the construction and experimental results from three different kinds of sensors that exploit these principles. Finally, Section V summarizes the advantages of this sensing technique and scope for application while pointing out the associated tradeoffs.

II. RELATED WORK IN WIRELESS SENSING

Wireless sensors can be broadly classified into active and passive depending upon whether there is an on-board battery supply. There are a host of instances of each of these sensor classifications, each of which is catered towards a particular class of applications and which comes with its own set of tradeoffs in terms of functionality, life, and cost [6]. Active sensor platforms come in many flavors such as Berkeley Motes [7] or BTnodes [8]. In addition to the on-board power supply, these sensors tend to have more sophisticated electronics for data processing and storage. These kinds of sensor nodes typically tend to be rather expensive and thus their application is best suited to monitor dedicated cost-intensive operations in which features like time history of data, real-time updates, and alarm triggering are of importance. The spatial granularity of deployment is frequently governed by budget considerations [9]. Being more power intensive, these sensing units tend to have lower service life and research efforts continue in trying to optimize this [10].

Passive sensors on the other hand need an external power source to power their on-board electronics. There is a selection of passive wireless sensors commercially available such as surface acoustic wave (SAW)-based sensors [11] that use power supplied from an external interrogation unit or modules that work on the principle of piezoelectric or vibration power scavenging [12], [13]. The on-board electronics thus tend to be more simplistic and have low-power consumption. Sensors of this type are more limited in terms of data storage and processing and data transmission range. The advantage of these sensors, however, is that they are lower cost and thus can be deployed at far greater spatial granularity than active wireless sensing units. In order for these sensors to be capable of ubiquitous deployment, they have to be manufactured at high volumes at minimal cost. Fig. 1 outlines the tradeoffs associated with the different types of wireless sensing paradigms.

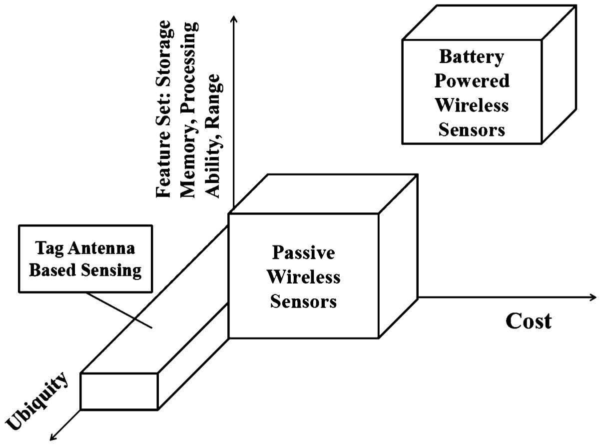

Fig. 1. ***Wireless sensing tradeoffs.***

The mature low-cost passive RFID tag manufacturing and standardized communication infrastructure presents us with a perfect medium to design low-cost passive sensors. Prior research efforts have looked into using RFID-based sensing. For example, KSW Microtec (Germany) has developed a battery-assisted temperature tag for use in supply chain applications [14]. Similarly, the Intel WISP (Seattle, WA) serves as a radio-frequency (RF) front end to sensor electronics [15].Although these sensor alternatives do drive down the cost of the sensor nodes significantly, the presence of an on-board battery in the case of the KSW tag and the discrete components of the Intel WISP do add a cost overhead to the sensor unit.

As mentioned in Section I, the RFID infrastructure has been well established as a low-cost, standardized communication infrastructure. RFID tags, which are mass produced today at a cost of \$0.07–0.15 present an excellent platform on which to fabricate sensors that are low cost and which have the potential for pervasive deployment. Sensors, which make minimalistic changes to the RFID tag design itself, truly lower the cost envelope to the best extent and thus lend themselves well to applications in which there is a need for pervasive, low-cost sensing in which the sensor response can be simplistic.

RFID sensors that calibrate a change in some physical phenomenon of interest to a change in RFID tag antenna electrical properties have been studied before. For instance, Marrocco *et al.* [16] present a multiport RFID sensor that exploits this principle. Similarly, Siden *et al.* [17] present a humidity sensor based on this technique while Bhattacharyya *et al.* [18]–[20] present a displacement, temperature threshold, and fluid level sensor. Bhattacharyya *et al.* [19] also introduce the concept of utilizing nonelectric memory to induce permanent changes to the tag antenna electrical properties upon violation of critical thresholds in the parameter of interest.

III. TAG ANTENNA SENSING PRINCIPLE

As mentioned in the previous section, RFID-tag-antenna-based sensing works on the principle of relating a change in some physical parameter of interest to a controlled change in RFID tag electrical properties. There are two different power parameters that can be leveraged for sensing:

- *Reader threshold transmitted power*: An RFID tag is optimized for performance when the tag integrated circuit (IC) impedance is complex conjugately matched to the tag antenna impedance. In the tag antenna sensing paradigm, a change in the physical parameter of interest induces a mismatch and this manifests itself in the reader requiring to transmit additional power in order to just turn the tag IC on. This difference in transmitted power can be used as one sensing mechanism.
- *Tag backscatter power*: For a given transmitted power, an induced mismatch causes less power to be transmitted to the RFID tag IC for its operations and this manifests itself as a reduced backscatter power response of the tag when subject to reader interrogation. Thus, differential backscatter power can be used as a sensing mechanism as well.

In the following sections, we outline the details of how each power parameter can be exploited as a sensing mechanism.

A. Tag-Antenna-Based Sensing Principle

In this section, we outline the theoretical analysis governing the use of reader threshold transmitted power and tag differential backscatter power as a sensing mechanism.

1) Threshold Transmitted Power as a Sensing Mechanism: The reader transmitting antenna transmits a power of P_{trans} and this results in a power density W_{trans} [21] of

$$W_{\text{trans}}(\theta_{\text{trans}}, \phi_{\text{trans}}) = \frac{P_{\text{trans}} G_{\text{reader}}(\theta_{\text{trans}}, \phi_{\text{trans}})}{4\pi d^2} \tag{1}$$

where $G_{\text{reader}}(\theta_{\text{trans}}, \phi_{\text{trans}})$ is the directional gain of the reader transmitting antenna and d is the distance of the tag from the reader transmitting antenna. The RFID tag antenna intercepts power given by the expression

$$P_{\text{tag}} = \frac{W_{\text{trans}} G_{\text{tag}}(\widehat{\theta}_{\text{trans}}, \widehat{\phi}_{\text{trans}}) \lambda^2 |\widehat{\rho}_{\text{trans}} \widehat{\rho}_{\text{tag}}|^2}{4\pi} \tag{2}$$

where W_{trans} is the transmitted power density in (1), and $\hat{\theta}_{\text{trans}}$ and $\hat{\phi}_{\text{trans}}$ are polar measures in the tag's coordinate system. $|\widehat{\rho}_{\text{trans}} \widehat{\rho}_{\text{tag}}|^2$ is the polarization loss factor and λ is the wavelength of reader operations.

The amount of this power that is received by the RFID chip P_{chip} depends upon the power reflection coefficient Γ_{tag} and is given by [21]

$$P_{\text{chip}} = \left(1 - |\Gamma_{\text{tag}}|^2\right) P_{\text{tag}} \tag{3}$$

where Γ_{tag} is given by

$$\Gamma_{\text{tag}} = \frac{Z_c - Z_a^*}{Z_c + Z_a} \tag{4}$$

where Z_c is the RFID IC impedance and Z_a is the RFID tag antenna impedance.

For ease of representation, we now drop the polar coordinate angular notation and manipulate (1)–(3) to give

$$P_{\text{chip}} = \left(1 - |\Gamma_{\text{tag}}|^2\right) G_{\text{tag}} G_{\text{reader}} P_{\text{trans}} |\widehat{\rho}_{\text{trans}} \widehat{\rho}_{\text{tag}}|^2 \left(\frac{\lambda}{4\pi d}\right)^2. \tag{5}$$

This implies that

$$P_{\text{chip}} \propto \left(1 - |\Gamma_{\text{tag}}|^2\right) G_{\text{tag}} P_{\text{trans}} \tag{6}$$

all other factors being equal. A sensing mechanism can be designed by inducing a calibrated relationship between the change in the physical parameter of interest (Δ) and a change in the antenna impedance. Due to this, a gradual mismatch is induced between the microchip and tag antenna impedance. This manifests itself as a increase in the reflection coefficient Γ_{tag} resulting in a reduction in power available to the chip. The tag antenna gain G_{tag}, radiation pattern, and efficiency are also affected. Thus, Γ_{tag} and G_{tag} are both nonlinear functions of the change in the physical parameter of interest. Equation (6) can be expressed as

$$P_{\text{threshold}} \propto \left(1 - \left|\Gamma_{\text{tag}}(\Delta)\right|^2\right) G_{\text{tag}}(\Delta) P_{\text{trans}}. \tag{7}$$

2) Use of RFID Tag Backscatter Power Strength as a Sensing Mechanism: RFID tag-reader communication relies on the tag modulating a signal response which is intercepted by the reader. The tag IC is assumed to have two impedance states Z_1 and Z_2. The tag antenna is typically well matched to state Z_1 resulting in a reflection coefficient Γ_1 close to zero where state Z_2 is typically a shorted state where there is great impedance mismatch between the tag antenna and IC impedance resulting in a higher reflection coefficient Γ_2. This differential power reflected from the tag is what results in a signal modulation which the reader can interpret as the tag response. Note that there are other ways to choose Z_1 and Z_2 and thus Γ_1 and Γ_2 as outlined by Karthaus *et al.* [22]. We now present the relevant mathematical expressions required for the derivation of change in backscatter power received at the reader as a function of change in the physical parameter of interest (Δ). Note that these mathematical models are idealized for a tag-reader system in *free space*. The differential power backscattered by the tag is directly proportional to the impedance matching between the tag antenna and chip, given by the power wave reflection coefficients $\Gamma_{1,2}$ [23]. Thus, the differential tag radar cross section (RCS), which is directly related to the backscatter power can be given by [23]

$$\delta\sigma = \frac{\lambda^2 G_{\text{tag}}^2 |\Gamma_1 - \Gamma_2|^2}{4\pi} \tag{8}$$

where G_{tag} is the tag antenna gain, λ is the wavelength of reader operations, and $\Gamma_{i=1,2}$ is the power wave reflection coefficient for chip impedance state i. Alternatively, in terms of the power received at the reader, the RCS is given by [23]

$$\delta\sigma = \frac{\delta(P_{\text{rec}})(4\pi)^3 d^4}{P_{\text{trans}} G_{\text{reader}}^2 \lambda^2} \tag{9}$$

where P_{rec} is the power received at the reader from the tag, P_{trans} is the power transmitted by the reader, G_{reader} is the reader gain, and d is the distance to the tag.

Equating (8) and (9) the following result is obtained:

$$\delta P_{\text{rec}} = \frac{\lambda^4 G_{\text{reader}}^2 G_{\text{tag}}^2 P_{\text{reader}} |\Gamma_1 - \Gamma_2|^2}{(4d\pi)^4}. \tag{10}$$

Now we note that both G_{tag} as well as Γ_1 and Γ_2 are functions of Δ. Thus, the above equation may be expressed as

$$\delta P_{\text{rec}} = \frac{\lambda^4 G_{\text{reader}}^2 G_{\text{tag}}(\Delta)^2 P_{\text{reader}} |\Gamma_1(\Delta) - \Gamma_2(\Delta)|^2}{(4d\pi)^4}. \tag{11}$$

It is thus possible to observe that a change in backscatter power received at the reader can be related to a nonlinear function of Δ.

B. Electromagnetic Modeling Techniques

RFID tag antenna impedance changes or changes in the antenna gain and radiation pattern can be triggered by a controlled change in the electrical properties of the background dielectric material surrounding the RFID tag antenna. A tag-antenna-based sensor could be built by placing an RFID tag on top of a system of dielectric layers, one or more of which suffer a change in electrical properties with change in the physical parameter of interest. Providing a theoretical interpretation of this phenomenon is the focus of this section.

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 $R^{\text{TE}}E(\theta, r)$. This superposition is given by

$$|E_{\text{eff}}| = \left(1 + |R^{\text{TE}}|\right)E(\theta, r) \tag{12}$$

where R^{TE} is the effective reflection coefficient due to a system of dielectric layers and $E(\theta, r)$ is the far electric field of the dipole antenna with no background dielectric in free space.

As outlined in [24], and as shown in Fig. 2, the effective reflection coefficient for an n-layered dielectric system is

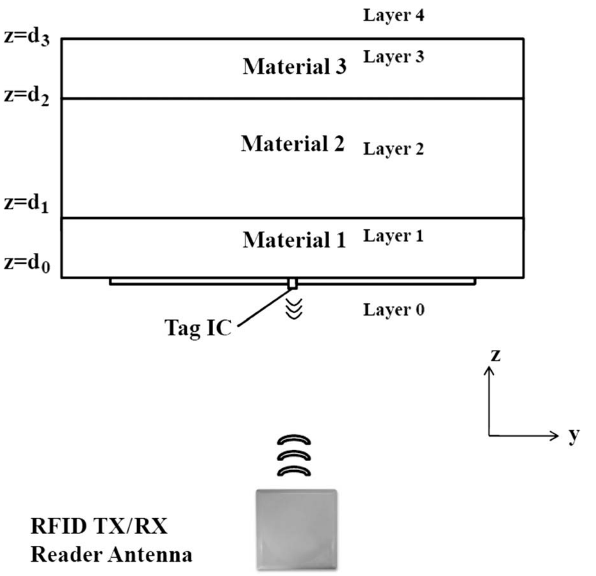

Fig. 2. *RFID antenna on a three-layer dielectric medium.*

given by

$$R_m^{\mathrm{TE}} = g(d_i, \epsilon_{ri}, \mu_i, f, \ \forall i) \tag{13}$$

where d_i is the depth of medium i from the antenna, ϵ_{ri} is the relative electrical permittivity of medium i, μ_i is the magnetic permeability of medium i, and f is the operating frequency. By having some of these layers undergo changes in electrical properties that are triggered by a change in the physical parameter of interest, it is possible to change R_{ij} and thus R^{TE}. Thus, the change in the resultant electric field due to a change in the physical parameter of interest (Δ) is given by

$$|\delta E_{\mathrm{eff}}(\Delta)| = g\left(|\Delta R^{\mathrm{TE}}|\right). \tag{14}$$

This manifests itself as a change in Poynting power which can be interpreted physically at the reader as change in backscatter power signal strength received from the RFID tag and in a change in threshold reader transmitted power needed to power up the RFID tag.

IV. RESULTS

The principle of tag-antenna-based sensing is illustrated via the construction of three different types of sensors. In this section, we examine the design principle and representative results from each of them in turn.

A. Temperature Threshold Sensing

Fluctuations in ambient temperature are known to affect the quality of perishable produce [25], and with an estimated 30% perishable goods spoiling in transit [26], there is a dire need for improved supply chain visibility and increased spatial temperature sensing granularity. The principles of RFID-tag-antenna-based sensing are utilized to design a low-cost temperature threshold sensor that detects whether goods passing through the cold supply chain were ever subject to temperatures above 0 °C for unacceptably long periods of time.

Fig. 3 illustrates the design of the temperature sensor. The apparatus consists of two RFID tags separated by a small distance. The sensor is initialized by freezing a metal plate in aqueous solution behind the tag A in Fig. 3 and placing it on the item passing through the cold supply chain. Thus, tag A is detuned due to the metal plate and gives worse performance relative to tag B.

If the products are maintained at subzero temperatures throughout the transportation process, the metal plate remains frozen behind tag A. If, however, the products are subjected to unacceptably high temperatures for more than a tolerance interval, the ice melts and the plate descends detuning tag B. The working of the temperature sensor is illustrated in Fig. 4. The violation of a temperature threshold can be detected by noting an improvement of power response of tag A relative to tag B. In this application, change in tag backscatter power detected at the reader is used as a state change indicator. Fig. 5 describes the response of the sensor when it is subjected to a cold–hot temperature cycle. The construction material of the sensor and volume of water is chosen so that the tolerance interval for which the sensor may be exposed to high temperatures is set to be about 20 min. It is important to note that the metal plate induces a nonelectrical memory effect. Even if the goods to which the temperature sensor is attached are refrozen, the tag remains frozen behind tag B. Furthermore, it is possible to use relativistic measurements from the two tags to eliminate the dependence on reader-tag separation and effects such as fading in the environment of deployment.

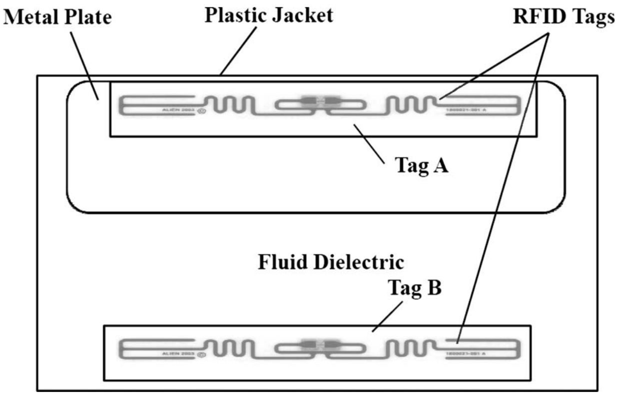

Fig. 3. *Design of the temperature threshold sensor.*

B. Displacement Sensing

Displacement is one of the most perceivable physical parameters used to assess structural health [27]. In large

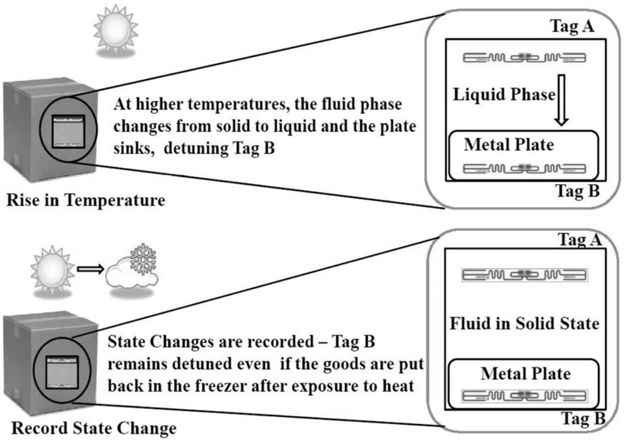

Fig. 4. *Functional states of the temperature sensor.*

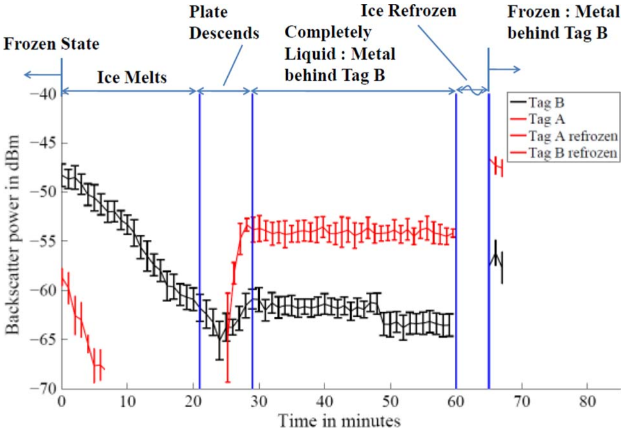

Fig. 5. ***Change in tag response with threshold violation for a reader-tag separation of 0.5 m.***

infrastructure projects such as bridges made up of heterogeneous construction materials like concrete, fine spatial sampling granularity is crucial to accurately assess structural health. For this, it is important to design and manufacture wireless sensors which are not only capable of detecting instantaneous structural response and violation of design thresholds, but which are also low cost. In this section, we present the design and functioning of a low-cost displacement sensor.

The technique makes use of the fact that RFID tag performance deteriorates in close proximity to metals. A change in structural displacement manifests itself as a change in RFID tag backscatter response and threshold reader transmitted power required to power up the tag as explained in Section III.

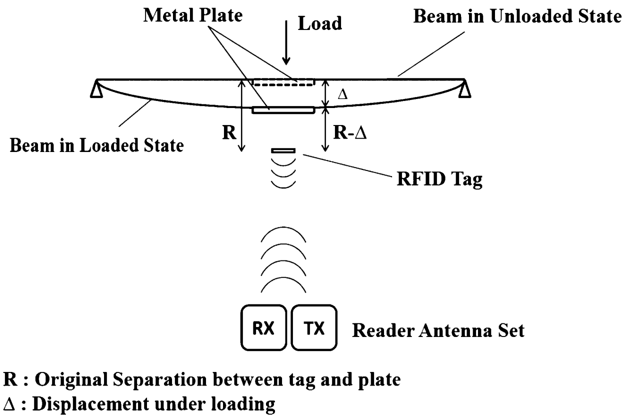

Fig. 6. ***Displacement sensor design.***

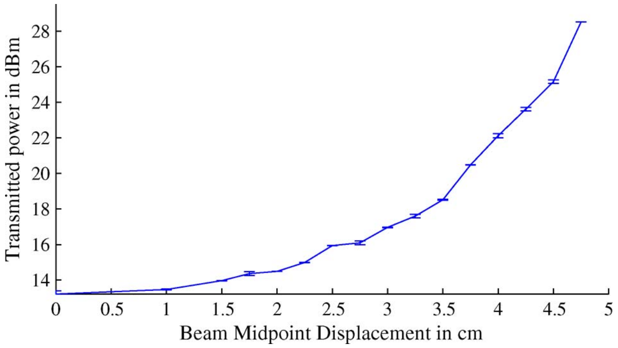

Fig. 7. ***Displacement versus threshold TX power.***

Fig. 6 highlights the design of the displacement sensor. Fig. 7 illustrates how a change in the RFID tag threshold transmitted power response can be used to measure a change in the physical parameter of interest—in this case, displacement. As we observe from Fig. 6 as the displacement increases, the metal plate comes closer to the RFID tag. Thus, the trend in Fig. 7 makes logical sense—as the metal plate comes closer and closer to the tag, the reader needs to put out more power in order to just turn on the tag IC. It is important to note that obtaining relativistic measurements from two RFID tags in close proximity to one another, one which is subject to the metal plate displacement and the other which is not, can eliminate the dependence on reader position and the effects of fading.

C. RFID-Based Fluid Level Sensing

There is potential for using RFID in detecting empty beverage glasses in need of a refill, by exploiting the fact that RFID tag performance decreases in proximity to fluids. As seen in Fig. 8(a), an RFID tag is pasted on the bottom quarter of the glass. When the water in the glass is above the quarter level mark, the water detunes the RFID tag to the point where it can no longer be detected by nearby reader antennas. When the water level falls below this mark the background material to the tag is air and the tag responds with a signal strength strong enough to be detected by nearby reader antennas. The efficiency of this technique is examined in a real-life restaurant-like scenario as shown in Fig. 8(b) where there is ample scope for multipath and absorption of RF radiation by human bodies.


(a) (b)

Fig. 8. ***Beverage refill experiments. (a) RFID enabled glass. (b) Empty glass detection in a crowded environment.***

It was observed that the empty glasses were detected with an accuracy of about 80%, which is very encouraging considering that the experiment was run with off-the-shelf RFID tags in real-life settings. Those glasses which were not detected contained ice in the bottom quarter and failed to be detected due to the change of the ice to water which detuned the tag antenna to the point where it could be no longer detected. It is possible to utilize this technique to sense the level of fluids in plastic overhead tanks or in bars for liquor inventory.

V. CONCLUSION

The tag-antenna-based sensing paradigm discussed in this paper has several advantages including low cost, theoretically infinite lifetime, and is based on standardized communication protocols, all of which are very desirable properties in applications requiring ubiquitous monitoring. Instantaneous measurement values at the time of query can be obtained, as in the case of the displacement sensor, however, by inducing permanent physical changes, we can potentially convert these sensors into reliable threshold sensors that can even monitor their environment when not powered by an RFID reader as seen in the case of the temperature sensor. Furthermore, by utilizing relativistic measurements between two tags close to one another, one which is influenced by changes in the physical parameter of interest and one which is not, it is possible to eliminate dependencies such as reader-sensor separation distance and environment specific fading effects. Besides the case examples of displacement, temperature, and liquid level sensing, research efforts are currently underway to extend this paradigm of sensing to different modalities.

Finally, while the prospects of this sensing paradigm are exciting, it is important to realize that this technology comes with its own set of limitations and we need to recognize these tradeoffs. This sensing paradigm cannot provide end users with real-time monitoring updates or with a time history of data. Furthermore, since these sensors are passive, the range over which they can be read is limited. Tag-antenna-based sensing does not provide a silver bullet solution to all sensing applications, but can certainly be considered as a viable technology for those application domains in which there is a need for low-cost, ubiquitous sensing in which the sensor response can afford to be simplistic. ■

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