

Wireless Ice Detection and Monitoring using Flexible UHF RFID Tags

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Abstract—Owing to its low relative permittivity, very few microwave sensors have been developed for monitoring ice deposition. This paper presents the first use of UHF RFID tags for wireless RF ice sensing applications. Despite its low permittivity, the existence of ice as a superstrate on a planar ultra-thin dipole antenna can lower the resonance frequency of the antenna significantly. The RFID tags, having a measured unloaded range of 9.4 m, were evaluated for remotely detecting the formation of ice in various scenarios and up to 10 m from the reader, as well as monitoring the ice thawing, based on the Relative Signal Strength (RSS) in a phase-free approach. Unlike conventional RSS-based sensing approaches where the tag's read-range is reduced as the RSS decreases in response to the stimulant, the ice superstrate improves the impedance matching of the tags, maintaining a 10 m loaded read-range with over 12 dB ice-sensitivity, in an echoic multi-path environment. The long range and high sensitivity show that UHF RFID is a promising method of detecting and monitoring ice formation and thawing in future smart cities.

Index Terms—Antennas, RFID, Materials, Relative Permittivity Measurement, Wireless Sensing

I. INTRODUCTION

LONG-range Ultra High Frequency (UHF) radio frequency Identification (RFID) tags have been widely used for a variety of battery-less on-demand sensing applications [1], [2]. The ability to interrogate a varying number of tags and reconstruct information about their surroundings has enabled a variety of applications. For example, localization [3], electricity metering [4], moisture sensing [5]–[7], mechanical deformation sensing [8], structural monitoring [9], in addition to fluids characterization [10] are among the various applications of RFID-based sensing. With UHF RFID readers becoming ubiquitous in various domains, RFID sensing can be considered a low-cost and low-maintenance approach to battery-less wireless sensing.

The detection of ice accumulation on various surfaces such as roads, air crafts, power cables, and pipe-works is of paramount importance. For example, ice formation on wind turbines could lead to up to a 20% loss in the power production [11], requiring regular helicopter deicing. In addition, in the US alone, over 250,000 households experienced property damage due to freezing water pipes resulting in 10 billion

dollars insurance payments over a decade [12]. Moreover, ice-related injuries in a workplace are a main cause of lost work days with over 2,900 ice-caused hospital admissions in the U.K. alone in 2014/15, and over 42,000 work absences in the U.S. [13]. This has motivated research into ice detection mechanisms such as near infrared (NIR) cameras and image processing [14]. While a plethora of RF-based approaches were investigated for remote ice and snow monitoring using GPS signals and satellites [15], the use of wireless RF sensing for ice detection in urban and smart cities applications has not been reported.

Despite its ubiquity in a variety of applications, UHF RFID sensing has not been applied for detecting ice accumulation or deposition. This is attributed to the very low permittivity of frozen particles compared to their liquid form, where the immobility of charge carriers reduces the ionic conductivity of water leading to ice being commonly described as being “almost transparent to microwaves” [16]. Recently, a two-port microstrip resonator, implemented on a low-loss RF PCB, was proposed for freeze and thaw detection [17]. A ground plane-integrated heater was later proposed based on the same resonator showing a solution for detecting and removing the ice [18]. However, owing to the resonator design, the sensors, [17], [18] can only be sampled using complex lab instruments such as a Vector Network Analyzer (VNA) due to the high (3.5–4.5 GHz) frequency of operation, and the low forward transmission S_{21} amplitude (−20 to −50 dB). A low-frequency capacitive sensor was also proposed for ice detection [19]. However, the sensor still requires active sampling circuitry, adding to the cost, complexity and maintenance overhead of the approach. Therefore, a need exists for a wireless, compact, battery/maintenance-free and low-cost solution to enable detection and monitoring of ice formation and thawing.

In this paper, the use of ultra-thin and compact RFID tags is proposed for wireless ice detection and sensing applications. The key novel findings in this work can be summarized as:

- 1) Demonstrating the first use of wireless RF sensing for ice detection and low-permittivity stimulants;
- 2) Relying on an increase in the tag's relative signal strength (RSS) to detect the stimulant for improved sensitivity without sacrificing the read-range;

In Section II, the RF ice sensing phenomenon is introduced through the simulated antenna parameters. Section III presents the experimental setup including the antenna and reader design, as well as the example test use-cases, with the measured results and discussion in Section IV.

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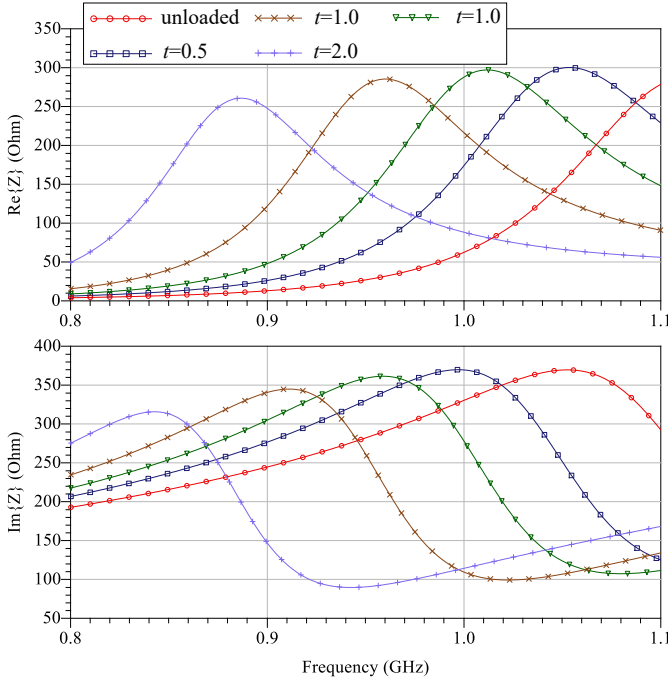


Fig. 1. Simulated input impedance of the RFID antenna under varying thickness ice loading.

II. RFID ANTENNAS AS ICE SENSORS

Ice possesses one of the lowest relative permittivities ($\epsilon_r=3.2$) and dissipation factors ($\tan\delta=0.0009$) compared to other stimulants such as moisture [6], or food products [16]. Therefore, for an RF sensor to detect the presence and the formation of thin ice layers, the RF resonator needs to be highly sensitivity to very small changes on its surface.

Most of the reported magnitude-based RFID sensing tags detect the stimulant through a reduction in the RSS, i.e. through detuning or additional losses in the tag [5]. This will result in a reduced read-range when the tag is measured under loading, reducing its applicability for remote wireless sensing. Recently, a tag was shown operating with an 8 m-range at 868 MHz, despite being tuned for 915 MHz and having an S_{11} around -2 dB [20]. Thus, it is possible to operate the sensing tag at a lower frequency than its unloaded resonance while maintaining a medium read-range. When loaded with the stimulant, the antenna's resonance will shift to a lower frequency resulting in an increase in the RSS in response to the stimulant, owing to an increase in the RFID antenna's realized gain.

To verify the anticipated shift in an antenna's resonance in response to ice-loading, a loop-fed dipole antenna, discussed in detail in the next section, was simulated in CST Microwave Studio (frequency domain solver with 0.2 mm maximum mesh step) for varying ice thicknesses. The thin ice layer added on the antenna model is 21×9 cm and variable thickness t , with $\epsilon_r=3.2$ and $\tan\delta=0.0009$ based on the microwave properties measured in [16]. Fig. 1 shows the simulated input impedance of the antenna for different ice thicknesses t .

From Fig. 2, it can be verified that the 75 μm -thick dipole exhibits a high sensitivity to sub-mm thick ice-loading.

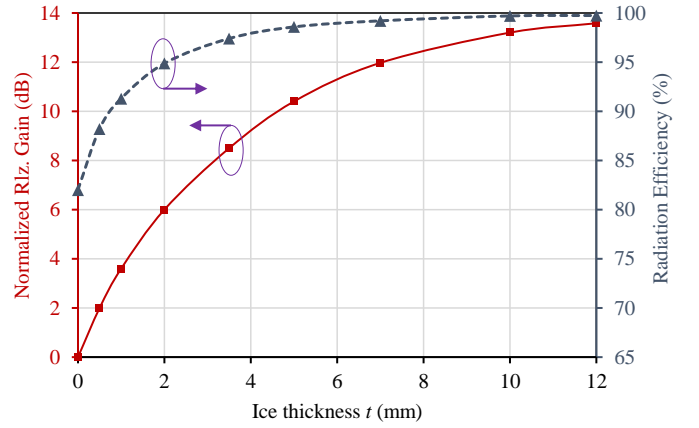


Fig. 2. Simulated realized gain and radiation efficiency of the RFID antenna as a function of the ice superstrate thickness.

Furthermore, the resonance shift to a lower frequency not only improves the impedance matching in the 868 MHz band for a fixed- Z source but also improves the antenna's radiation efficiency. To explain, the additional low-loss superstrate, i.e. ice, increases the antenna's electrical size increasing its radiation resistance and subsequently efficiency. The antenna's far-fields were simulated for varying t to investigate the ice influence on the radiation properties. Fig. 2 shows the increase in the antenna's radiation efficiency (exclusive of mismatch) at 850 MHz under ice-loading.

While the additional ice superstrate results in up to 2 dB increase in the radiation efficiency (from 80% to 99% in Fig. 2), the impedance matching effect has the most significant influence on the sensory response. This is observed in the antenna's realized gain, normalized to the unloaded antenna's gain, showing an improvement of over 10 dB for 5 mm ice-loading. Therefore, the simulated results show that an antenna can act as a highly sensitive detector for the formation of ice, with a response that could be detected wirelessly using an off-the-shelf receiver, e.g. an RFID reader.

The read-range of an RFID tag can be estimated using

$$\text{Read range} = \frac{\lambda}{4\pi} \sqrt{\frac{P_t G_t G_r}{P_{th}}} \times (1 - |S_{11}|^2), \quad (1)$$

where G_t and G_r are the transmitter (reader) and receiver (tag) antenna gains, respectively, P_{th} is the RFID IC's sensitivity, and P_t is the transmitter power [21]. The improved matching of the antenna (lower S_{11}) will allow the loaded tag's range to exceed its unloaded counterpart, preserving its range in a realistic lossy multi-path environment. When the ID is back-scattered, the RSS is given by

$$\text{RSS} = \Gamma_{\text{Ref.}} P_t G_t^2 G_r^2 \left(\frac{\lambda}{4\pi d} \right)^4 \quad (2)$$

where $\Gamma_{\text{Ref.}}$ is the reflection coefficient when the antenna is shorted for modulation, and d is the distance between the reader and the tag, assuming an ideal and linear switching response by the RFID IC. Therefore, the increase in the tag's gain G_r will be directly detected at the reader through the RSS, provided that $P_{RX} > P_{th}$ for the tag to turn-on.

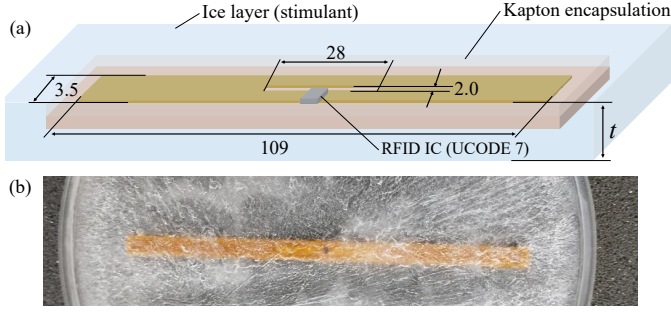


Fig. 3. Top: 3D layout and dimensions (in mm) of the encapsulated RFID tag inside the ice loading; bottom: photograph of the tag in ice.

III. EXPERIMENTAL SETUP AND TAG CHARACTERIZATION

A. Antenna Design and Characteristics

The RFID tags used in this work are based on thin and flexible dipole antennas with an inductive tuning loop. The antenna is designed to directly match the RFID IC with a complex impedance and is fabricated using standard photolithography. The details of the antenna tuning, in addition to the tag fabrication and encapsulation, for mechanical robustness and waterproofing, are detailed in [20].

Fig. 3 shows the layout and dimensions of the antenna used in this work. The RFID Gen-2 IC is the NXP U-CODE 7. Having a -21 dBm read-sensitivity, the expected read-range is up to 15 m from a reader equivalent isotropic radiated power (EIRP) of 33 dBm and a 0 dBi tag antenna using based on the free space path loss (FSPL). Unloaded, the RFID tags achieve a measured read-range of 9.4 metres at 860 MHz, where their optimum matching to the datasheet's input impedance is at 915 MHz. The tags were only characterized around 868 MHz due to the EU reader frequency limits.

B. RFID Ice-Sensing Test Setups

The proposed RFID-based sensors are characterized to investigate their performance in three use-cases: (a) detecting the formation of ice during the freezing process; (b) remotely detecting the existence of an ice layer on the sensing tag in a variety of environments and read-ranges; (c) remotely observing thawing ice. This section describes the test setups used to evaluate the tags for these use-cases.

A commercial hand-held Gen-2 RFID reader (Zebra RFD-8500) is used to interrogate the tags. The reader has an equivalent isotropic radiated power (EIRP) of 3 W and operates in the EU 868 MHz license-free band. Connected to a smartphone via Bluetooth, the reader reports the RSS of up to 200 tags with a 1 dB resolution. By operating at a single frequency and relying entirely on the RSS for sensing, the proposed RFID-based ice sensor is compliant with regional frequency regulations where the stimulant can be detected without the need for a frequency sweep spanning the full bandwidth between 860 and 940 MHz, often found in several RFID sensing applications [22].

To investigate the tags' freezing response, the RFID tags were placed inside a TEFCOLD SE10-45 freezer at -20°C . The reader was placed outside the freezer to interrogate the

TABLE I
ICE-LOADED RFID TAG TEST SETUPS.

	Test setup	Unloaded RSS	Loaded RSS
A	Indoor, $d=7.4$ m and tag/reader $h=1.85$ (Fig. 5-a)	-70	-62.5
B	Indoor, $D=5.1$, reader $h=1.85$ and tag on-ground (Fig. 5-b)	-67.7	-57.7
C	Indoor, $d=7.7$, reader/tag $h=1.7$ (Fig. 5-d)	-57	-53
D	Outdoor, $d=6.5$ m and tag/reader $h=0.8$ (Fig. 5-e)	-61	-57

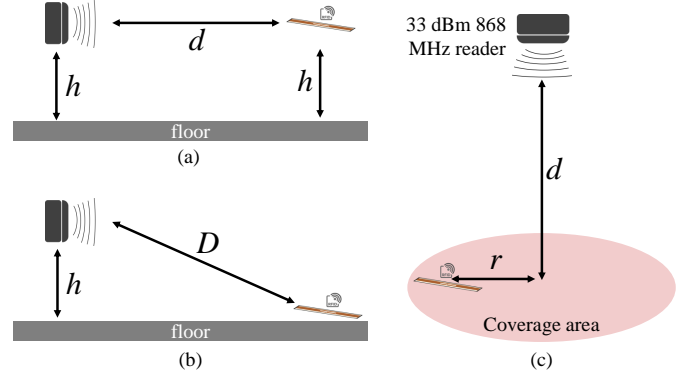


Fig. 4. Measurements setups of the RFID ice sensor: (a) Off-ground tag and reader; (b) Off-ground reader and on-ground tag; (c) vertical off-ground reader and on-ground tag

tags intermittently. Due to the high RF shielding caused by the freezer's walls, and the additional reflections inside the freezer, the measurements were performed at 50 cm from the freezer, with 10 cm between the tag and the freezer's inner wall.

Following the formation of full ice layer on the tag's surface, the input impedance of the antenna is measured using a two-port Rohde and Schwarz ZVB4 VNA to understand the ice influence on the tag's matching, and for validating the simulated results in Section II. The differential input impedance was measured using a balanced coaxial jig connected to the VNA's imbalanced ports using a widely known method detailed in [23], widely used for complex impedance antennas for RFID and Schottky-base rectennas [24]. The balanced jig is soldered on the tag prior to freezing with the coaxial connector protruding from the ice to enable VNA measurements post-freezing.

The ice-loaded RFID tags were then interrogated in various test conditions to show that the change between the unloaded and loaded tag RSS (ΔRSS) is maintained in real-world use-cases, summarized in Table I. Fig. 4 shows the measurement setups and separations of the ice-loaded RFID tags. The photographs of selected test setups are shown in Fig. 5.

The final test carried out is to assess the sensor's response for detecting thawing events. Multiple tags with varying ice thicknesses are then used to assess the tags' sensitivity to thawing. The ice-loaded tags are left at room temperature (24°C) where they were interrogated periodically every 30 s. The measurements were performed using the setup in Fig. 4-a, at $d=3$ m. The experimental results of the fore-mentioned test setups are presented and discussed in the next section.

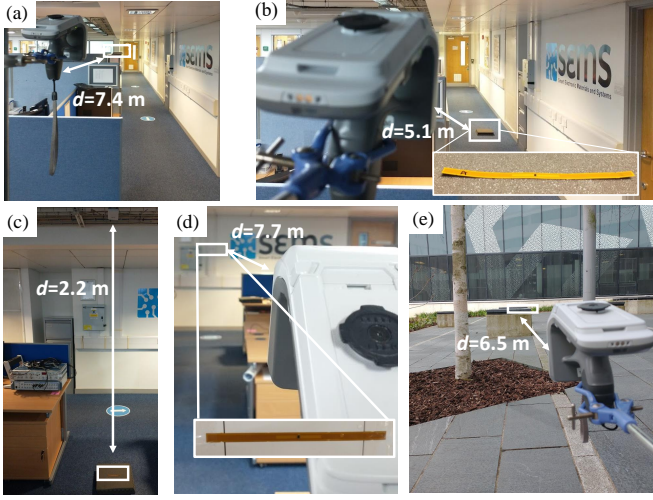


Fig. 5. Photographs of the antenna measurement setups: (a) off-ground tag from Fig. 4-a; (b) on-ground tag from Fig. 4-b; (c) ceiling reader from Fig. 4-c; (d) wall-mounted tag.

IV. MEASUREMENT RESULTS AND DISCUSSION

A. Ice-Formation and Detection

The ice-loaded RFID antenna was characterized following a complete freeze. The ice thickness was measured to be approximately 7 mm over the antenna's surface. The antenna's input impedance, measured using a coaxial jig connected to the two-port VNA is shown in Fig. 6, before and after the antenna is covered by ice. The resonance shift of approximately 200 MHz ($0.79 \times f_0$) caused by the ice superstrate shows a very close agreement between the CST simulation and measurements. The slight discrepancy observed in the ice-loaded case is attributed to variations between the uniform rectangular ice layer in simulation, and the tapered ice layer shown in the inset in Fig. 6, in addition to the possible impurities in the tap water resulting in a higher $\tan\delta$. Nevertheless, the observed sensory response will result in improving the realized gain and the radiation efficiency $\eta_{\text{Rad.}}$, given by

$$\eta_{\text{Rad.}} = \frac{R_{\text{Rad.}}}{R_{\text{Rad.}} + R_{\text{Loss}}} \quad (3)$$

for a wire antenna where $R_{\text{Rad.}}$ and R_{Loss} are the radiation and loss resistances, respectively. Therefore, the increase in the radiation resistance $R_{\text{Rad.}}$ at resonance maximizes the antenna's $\eta_{\text{Rad.}}$, as well as improves the RF voltage available at the RFID rectifier's input [25]. In addition, the higher $\Re\{Z\}$ will increase the observed RSS, owing to a larger change in the reflection coefficient between the short circuit condition (introduced by back-scattering) and the antenna-IC matched case.

Observing the measured RSS in Table I, it can be observed that once the ice layer is formed on the antenna, the RSS exhibits a clear change of at least 4 dB. Therefore, the approach of detecting ice presence through an increase in the tag's RSS is validated. For example, case C shows that despite mounting the tags on a composite electric works enclosure (shown in Fig. 5-d) the ice presence can still be detected in spite of the added thick plastic substrate.

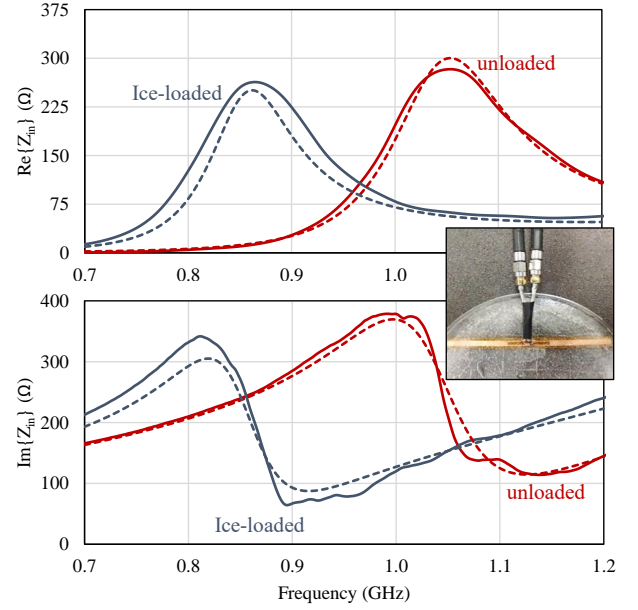


Fig. 6. Simulated (dashed) and measured (solid) Z_{in} before and after 7 mm-thick ice-loading; inset shows the loaded measurement setup.

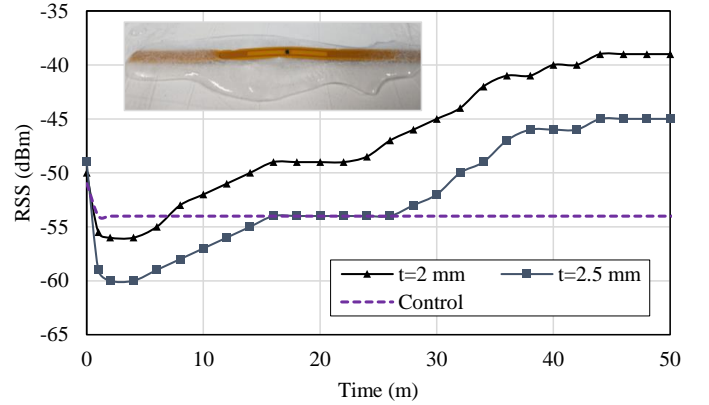


Fig. 7. Measured RSS of the freezing tags with water-droplets loading inside a -20°C freezer; inset shows the non-uniform $t=2.5$ ice layer on the tag.

B. Ice Detection and Sensing Read-Range

The measured RSS of the tags placed inside the freezer is shown in Fig. 7. Water droplets were added on top of the tag-under-test to mimic dew prior to frost formation. An additional tag was measured inside the freezer without humidity or added water droplets, shown as the control RSS in Fig. 7.

After about 2 minutes at -20°C , the control tag suffers from a 4 dB decline in the RSS, this is attributed to the temperature effect on the RFID IC, where a low temperature results in variations in the transistors threshold voltage [26], increasing the parasitic losses inside the tag's rectifier and modulating switch. However, as the unloaded tag's RSS stabilizes at -54 dBm, it can be confirmed that the influence of temperature does not interfere with the tags ability to detect the presence of ice, as observed in the two ice-loaded samples, where their ΔRSS exceeds 6 dB, and stabilizes after the water has frozen completely in about 45 minutes.

For the icing tags, initial sharp decline in the RSS is

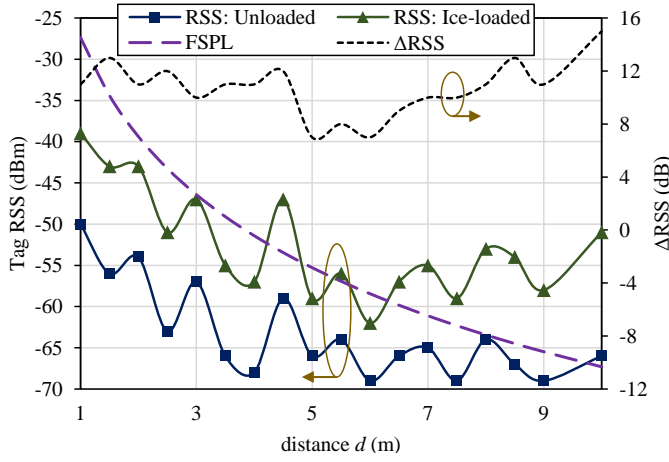


Fig. 8. Measured RSS of the sensor tags before and after ice loading for varying distance (setup-a).

attributed to both the temperature effect, observed on the dry control sample, and the high $\tan\delta$ of water. As ice forms, the RSS improves as previously observed in Table I, explained by the measured input impedance shown in Fig. 6 and the sensing phenomenon introduced in Section II.

Following the demonstration of the tag's sensing capability through the VNA Z measurements and the RSS measurements inside a freezer, Fig. 8 shows the measured RSS of the loaded and unloaded tags at varying separations d , from a reader at the same height $h=1.85$ (Fig. 1-a). The measurements were performed indoors as in Fig. 5-a, to demonstrate the sensor's response in a highly echoic environment. Several application domains such as monitoring pipe-works, electric transformers, and staircases in public spaces will expect the RFID tags to operate in confined indoor spaces, where multi-path effects are more omnipresent than outdoor environments or anechoic chamber lab demonstrations.

From Fig. 8, it can be observed that the tags maintain at least 6 dB Δ RSS sensitivity. At 10 m from the reader, the tag's Δ RSS is 14 dB, showing that the proposed sensor can be used at a longer range than the tag's unloaded read-range. This highlights the advantage of designing the tags to improve their Z matching under loading. The observed increase in the RSS at 4.5 m is attributed to the interference caused by multi-path reflections, as the test was carried out in an echoic indoor environment. However, it can be observed from Δ RSS that the tag maintains its high sensitivity and the presence of ice can still be detected regardless of the multi-path reflections. It is also observed that the measured RSS follows the expected $1/d^2$ relation caused by the FSPL, calculated using (2) for EIRP=33 dBm and $G_r=2.1$ dBi. As for Δ RSS, the 8-14 dB RSS gain agrees with the simulated increase in the antenna's gain, in Fig. 2, in response to the 9 mm-thick ice layer.

As ice forms a major slip hazard [13], the tags sensory response when placed on the ground is important for public safety applications. Fig. 9 shows the measured RSS for varying distance D , based on the setup in Fig. 1-b and 5-b. From the measured results, it can be observed that the tag's read-range is reduced to 4.5 m, owing to the additional destructive

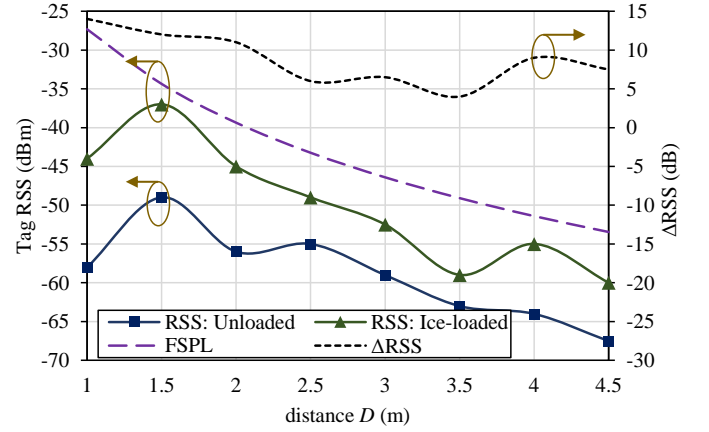


Fig. 9. Measured RSS of the sensor tags before and after ice loading for varying distance where the tag is placed on the ground and interrogated by a reader at $h=1.2$ (setup-b).

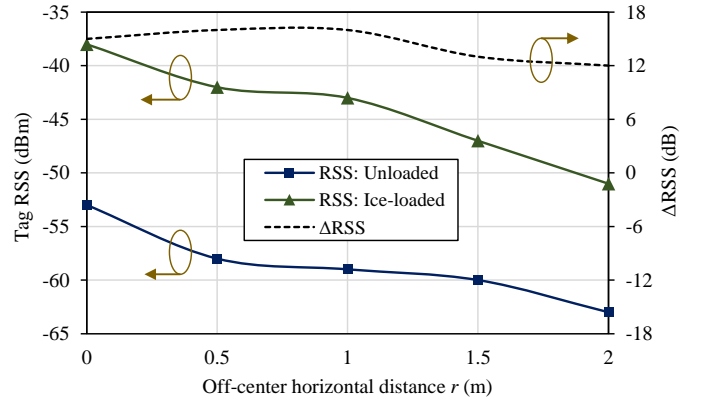


Fig. 10. Measured RSS of the sensor tags before and after ice loading for varying off-axis radii from a ceiling receiver at $d=2.2$ (setup-c).

interference between the transmitted signals from the reader. Nevertheless, the ice-sensitivity still exceeds 4 dB at all distances considered, with the measured RSS following closely the analytical RSS based on the FSPL from (2). Therefore, a handheld reader, for example carried by a maintenance personnel, can detect the formation of ice on the ground with an RFID sensor up to 4.5 m away.

Similarly, a ceiling-mounted reader can be used to cover a circular spot whose size is controlled by the antenna's main lobe beamwidth. The RSS results for the ceiling mounted reader (Fig. 4-c) are shown in Fig. 10. This setup resembles a highly-likely deployment scenario for monitoring surfaces such as pavements or platforms with the readers mounted on light-posts or shelters. $d \approx r = 2.2$ m, the tags maintain a very consistent and high Δ RSS between 12 and 16 dB. For $r > d$, the tags were not readable (both loaded and unloaded) which is attributed to the relatively more directional radiation pattern of the reader's antenna, which typically maintain a half-power (-3 dB) beamwidth of 60° , typical for a broadside patch antenna.

The final test carried out is for assessing the sensor's response for thawing detection and monitoring. Fig. 11 shows the measured tag RSS for four different ice thicknesses at 3

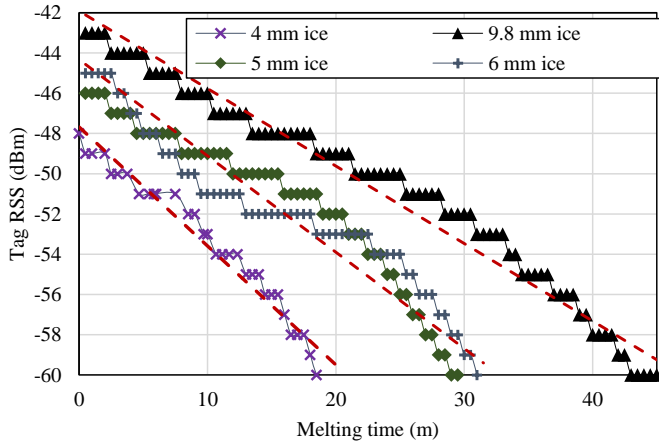


Fig. 11. Measured RSS of the sensor tags during thawing at 24°C for different ice thicknesses (setup-a).

metres from the reader. It can be observed that as the ice-loaded tags thaw, the increase in the water content in the ice superstrate results in a reduction in the RSS and eventually the reader failing to detect the tag. This is attributed to water's properties ($\epsilon_r=78$; $\tan\delta=0.16$) resulting in a significant shift in the antenna's resonance. Moreover, the high $\tan\delta$ will result in a reduced radiation efficiency due to an increase in the power absorbed by the water.

For all ice thicknesses investigated (4-9.8 mm), the melting response is highly linear, evidenced by the close agreement of the best-fit line having an $R^2=0.97$ and 0.95 , for $t=4$ and 9.8 mm, respectively. In addition, the measured RSS before melting (at time=0) validates the direct proportionality of the antenna's gain (observed through the RSS) to the ice thickness introduced in Section II. Therefore, the proposed RFID sensor is not only capable of detecting ice-formation over a long range in various scenarios, but also capable of observing the ice thawing, whose applications extend beyond industrial and smart city sensors to remote and environmental monitoring.

C. Comparison with Other Ice Sensing Approaches

Recently, an optic fibre-based approach was proposed based on the observed distortion of light propagation when ice deposits on a fibre [27]. However, this approach requires the laser source and the photodetector to exist at both ends of the optic, whereas RFID tags, of significantly lower cost, can be deployed in many locations and covered by a single reader with up to 10 m range. Moreover, a sensing fiber will only cover a small surface area due to its physical size, unlike an RF wireless sensor which can cover a spot with several meters radius as shown in the measured results (Fig. 10). NIR sensors and computer vision can detect ice remotely for road surfaces [14]. However, optical methods were found to be generally less sensitive than microwave sensors [17].

Compared to the recently reported RF ice and frost sensors [17], the proposed antenna-based sensor enables wireless detection with a measured range of 10 m. In addition, the sensitivity of the antennas (ΔRSS) is between 8 and 16 dB, comparing favorably with the $S_{21} < -20$ dB which requires

a VNA or highly sensitive circuitry to detect the sensor's response. To explain, should the two-port resonator in [17] be connected to two tag antennas (i.e. chipless RFID), its read-range will not exceed 1 metre due to the low S_{21} of the sensor, significantly reducing the back-scattered signal. As for heater-integrated sensors [18], [28], both the low frequency and microwave sensors are one or two-port devices which require active sampling circuitry, adding to the complexity of the sensing approach and limiting their pervasiveness in a city environment. Another RF alternative is utilizing wireless power transmission to a rectenna-powered sensor node. However, state-of-the-art rectennas, based on off-the-shelf components, operating at a similar range to the proposed tag (up to 10 metres) cannot charge a conventional microcontroller in few seconds [29], or produce sufficient voltage without a boost converter [30], [31], resulting in a long delay before the node can be charged to a sufficient level to perform any sensing. Therefore, the proposed RFID-based sensing mechanism is the most suited method for long-range and wide-scale ice detection.

Finally, it is key to note that while the proposed RFID sensor achieves a state-of-the-art wireless read-range compared to most reported RFID sensors, the read-range is limited by the tag's turn-on threshold (-21 dBm) and the reader's sensitivity (-74 dBm). For example, a higher sensitivity reader such as [32] would enable the proposed RFID ice sensor to be interrogated at ranges in excess of 20 m. Furthermore, recent advances in CMOS rectifiers demonstrating high RF-DC power conversion efficiencies as low as -30 dBm [33] will enable future RFID ICs to operate with a much higher sensitivity, where the tag will require less than -30 dBm of RF power to report its ID to the reader.

V. CONCLUSION

In this paper, a UHF RFID-based approach was proposed for long-range wireless ice detection and monitoring. Despite the low permittivity of ice, the proposed sensor demonstrates that RFID sensing is highly-suited for detecting freezing events, the presence of ice, as well as monitoring the thawing of ice with high linearity. Using sub-100 μm -thick RFID tags, the existence of mm-thick layers of ice as a superstrate translates to a resonance shift which can be detected wirelessly through the tag's RSS, even in a highly echoic multi-path environment. The proposed sensor was demonstrated in a variety of use-cases showing state-of-the-art performance. The ice-loaded sensor tags maintain read-range of 10 m with 10 mm of ice cover and up to 14 dB RSS sensitivity, with the antenna's measured loaded response showing a close agreement to the simulated results. Based on the performance of the proposed sensor, RFID sensing is one of the most promising candidates for detecting and monitoring ice in a range of smart cities and industrial applications.

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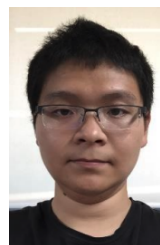
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