Passive UHF RFID Tags in Arctic Environment

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***Abstract*—**Radio frequency identification (RFID) systems are becoming more and more common in several industries. This enhances the requirements of tag antennas. Especially in logistics and supply chain management, which are major applications for RFID, the operating environment is expanding all the time. The identifiable items often travel in very cold, even arctic, environments. This can happen for example in geographically cold areas or in freezers with frozen food. In addition ice or snow can also be accrued on the tag surface. It is important that RFID tags work well in these extreme circumstances and the technology can be trusted. This paper studies the behaviour of passive UHF RFID tags in a cold (-20°C) environment. The effect of snow and ice on the surface of the tag was studied too. Both Gen1 and Gen2 antennas were tested and the results proved that passive UHF RFID tag antennas are usable in extreme conditions.

***Keywords*—**arctic environment, frozen tags, ice and snow, low temperature, passive UHF RFID, radio frequency identification, ultra high frequency

I. Introduction

In recent years, RFID technology has become more and more common in several industries. Especially in logistics, interest in using RFID has grown due to the undeniable benefits it can offer to supply chain management [1]. Additionally, the development of more efficient multi-tag reading algorithms and studies concentrating on security and privacy issues expand the possible application environment [2, 3]. This increasing use of RFID technology also expedites the requirements for tag antennas due to the various environments they confront during their progress along different types of supply chains.

One important environmental challenge is cold. When RFID is used in item identification during the supply chain, the tag antennas may be required to function at low temperatures in various situations. First, when tracking frozen food, the tracked item has to be at temperatures below freezing throughout the supply chain from the manufacturer to the end-user [4]. Secondly, almost any product may need to be transported in a geographically cold environment, especially during winter, even though the product does not need to be frozen. Given these frequently occurring situations, it is important to ensure that tag antennas function without change and with no loss of performance at low temperatures.

This paper studies the functionality of passive UHF RFID tag antennas at low temperatures, which in this case means -20 °C degrees, and when covered with ice and snow. Both Gen1 and Gen2 tags are tested [5]. Also an indicative strain test, in which the tags were exposed to several rapid temperature changes, was performed. Chapter 2 presents the basic theory of low temperature RFID, in chapter 3 the test methodology is described, and the measurement results are given in chapter 4. Chapter 5 concludes the paper.

Manuscript received December 22, 2008.

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II. Low temperatures and RFID

Low temperature has different effects on different aspects of RFID tag functionality. This chapter describes the effect on the electromagnetic radiation and different components of the tag antenna. Also the effect of possible accumulation of snow and ice on the tag surface is discussed.

A. The effect of temperature on the electromagnetic radiation

In the atmosphere, radio wave propagation is affected by not only the distance, but also the different types of gas molecules and particles. The electrical characteristics of the atmosphere depend on the amount of gas molecules, such as oxygen and water. Some gas molecules, like oxygen, are neutral until they are polarized by an electric field. Some other molecules, like water, have permanent electric dipole moment, whose direction is turned by electric fields. Both of these transactions incur a phenomenon called gas polarization, whose level corresponds to certain value of *relative permittivity* ε_r. The gas polarization influences the refraction of the signal, and resonance of the attenuation. The refractive index of the air can be calculated from permittivity:

$$n = \sqrt{\varepsilon_r} \tag{1}$$

When the composition of the air changes, the refractive index also varies. However it is always very near to 1, and therefore a more descriptive magnitude N has been taken into use. N describes the deviation of n from 1, in parts per million and it can be calculated as follows:

$$N = (n-1) * 10^6 \tag{2}$$

The value of N for the air can be calculated from the formula:

$$N = \frac{77{,}6}{T}\left(p + 4810\frac{e}{T}\right) \tag{3}$$

, where T = absolute temperature [K]
p = overall pressure in atmosphere [mb]
e = vapour pressure [mb]

As can be seen from (3), the temperature clearly affects the refraction of the radio signals in the atmosphere. However when operating at the temperatures and transmission distances in this study, the effect is minor. [6, 7]

In addition to this refraction, the radio signal also attenuates in the atmosphere. The level of attenuation is dependent on the molecule composition of the air. In the atmosphere the amount of oxygen is nearly constant, unlike the amount of water molecules, which is highly dependent on the temperature. The attenuation is directly proportional to the quantity of water molecules, which increases along with the temperature. At low temperatures, the amount of water molecules is low, but at 30 °C, the amount is similar to the total of other gas volumes. The relevance of this attenuation increases with the frequency, and although there is an effect in the RFID UHF band in the tested circumstances, it is minor from the RFID point of view. Rain, snow and fog attenuate the signal due to scattering but its effect is not discussed here. [7, 8]

In antenna technology, temperature affects the level of thermal noise which emanates from the antenna, in accordance with the following equation:

$$P_N = kTB \qquad (4)$$

, where k = Boltzmann constant = $1{,}380 \cdot 10^{-23}$ J/K
T = temperature of the surrounding medium [K]
B = frequency bandwidth [Hz]

It can be seen from (4), that the noise power is directly proportional to temperature, as well as bandwidth. In this UHF study, where the temperature alteration is less than 50 degrees, this effect is however very small. [9, 10]

B. The effect of temperature on the tag operation

Temperature affects tag operation through thermal expansion and the thermal dependence of electrical characteristics. The alternating temperature affects different parts of the tag differently due to the different temperature dependences materials have. This means that some materials may be much more sensitive to temperature changes than others, and some may even, for example, have a positive thermal expansion coefficient in a certain temperature range, when others have negative ones.

The thermal expansion might cause problems when two materials with very different thermal expansion coefficients are coupled together. For example polymers, which are used in printed antennas, have a high coefficient ($100 \cdot 10^{-6}$ m/°C) while silicon, which is used in IC chips, has a very low coefficient ($0{,}5\text{-}2 \cdot 10^{-6}$ m/°C). The coefficient of copper is $16{,}6 \cdot 10^{-6}$ m/°C. Thus the method of attachment is very important. Thermal expansion may also change the surface current of the antenna, due to changes in antenna size though in relatively broadband antennas, such as the bow-tie type antennas in this study, the effect is very small. [9, 11]

The IC chips used in RFID tags are usually based on CMOS technology, and they include semiconductors and passive components, such as resistors and capacitors. The decreasing temperature has different effects on these components. The effect on resistors is largely through the amount of free mobile charges. When the temperature decreases, the linear momentum of mobile charges also decreases, which leads to the fall of the resistor's conductivity. Because of this, the resistors actually work better. The resistors typically used in CMOS-technology, have a temperature coefficient of 1500-8000 ppm/°C, and the capacitors 50 ppm/°C. The capacitors are therefore not very much affected by temperature. [12]

The above described effect occurs also in conductors: when the temperature decreases, the momentum of free mobile charges decreases. In this case it only means that the conductor deteriorates. For semiconductors this momentum of mobile charges is exponentially dependent on the temperature. It can be expressed as follows:

$$\sigma(T) = ke^{cT}T^{3/2} \qquad (5)$$

, where T = temperature [K]
k = material dependent constant
c = material dependent constant [12]

C. The effect of snow and ice on the tag surface

When the temperature drops below 0 °C, the effect of snow (i.e. frost) and ice must be taken into consideration. Even though the tags would mainly operate inside, the moisture, which turns into ice and frost, can be condensed on tag surfaces.

The snow consists of ice crystals and air, and possibly also water. If there is no water, the snow is called dry snow. Otherwise it is called wet or moist snow. Snow moisture is usually expressed by relative percentage by volume of water, and it is the main characteristic of snow, when considered from the electromagnetic point of view. The scattering features of the snow are also influenced by density, particle size and form, thickness, and temperature of the snow layer. [13, 14]

The particle size and form of snow vary along with temperature. At lower temperatures particles are sharp and clean-cut. As the temperature rises, they round and turn watery. Wet particles also adhere to each other and form larger structures. If the temperature then again drops, these wet structures freeze and turn to permanent fragments of the snow layer. This type of snow layer is called *deformed,* and these deformation layers affect the scattering characteristics of the snow.

The permittivity of the snow is dependent on the frequency, density (ρ) and the amount of water. For dry snow the only factor is density, but when the snow is wet, the other factors become relevant. The real (ε'_{ws}) and imaginary (ε''_{ws}) parts of the permittivity of wet snow can be calculated as follows:

$$\varepsilon'_{ws} = A + \frac{Bm_v^x}{1+\left(\frac{f}{f_0}\right)^2} \qquad (6)$$

$$\varepsilon''_{ws} = \frac{C\left(\frac{f}{f_0}\right)m_v^x}{1+\left(\frac{f}{f_0}\right)^2} \qquad (7)$$

, where $A = 1,0+1,83\rho_{ds}+0,02A_1m^{1,015}+B_1$
$B = 0,073 * A_1$
$C = 0,073 * A_2$
$x = 1,31$
$f_0 = 9,07$ GHz
$A_1 = A_2 = 1,0$
$B_1 = 0$, when $f < 15$ GHz

In (6) and (7) f is used frequency, f_0 is relaxation frequency and A, B, C and x are experimentally defined parameters. [15, 16]

The real part of the ice permittivity is nearly constant $\varepsilon \approx 3,2$, and the imaginary part can be calculated from the formula:

$$\varepsilon_i'' = \frac{\alpha}{f} + \beta f \qquad (8)$$

, where f = frequency [GHz]
$\alpha = (0,00504 + 0,0062 * \boldsymbol{\theta})\, e^{-22,1*\theta}$
$\beta = \frac{0,502-0,131*\theta}{1+\theta} * 10^{-4} + 0,542 * 10^{-6}\left(\frac{1+\theta}{\theta+0,0073}\right)^2$
$\boldsymbol{\theta} = T_0 / T\text{-}1$, and scaling temperature $T_0 = 300$ K. [17]

Ice, as with snow, scatters the electromagnetic signal. This means, that radio waves disperse from the boundary of two mediums (surface scattering), or from the inner structures of each medium (volume scattering). In the case of a tag antenna covered with ice (or snow), the scattering occurs in three areas: 1) the boundary of the air and the ice, 2) within the ice itself, and 3) the boundary of the ice and antenna. The mutual ratio of these three scattering effects depends on the type and amount of snow, ice and water. [8, 18]

To summarize chapter 2, the effect of low temperature on UHF RFID will mostly be manifested in the form of the functioning of the IC chip and the attenuation of radio waves due to ice and frost on the tag surface.

III. Test Methodology

The tests were performed in a frost warehouse, where the temperature was -20 °C. The warehouse had metal walls and roof, but the distance to them was set to several metres to nullify their effect. Two types of tests were performed: Gen1-tests, and Gen2-tests. In Gen1-tests the tags were EPCglobal UHF Class1 air interface specification –compliant, and in Gen2-tests, the tags satisfied the newer specification, UHF Class1 Gen2.

A. EPCglobal Class1 -tests

In Gen1-tests, the used RFID-reader was Alien ALR-8780, with one Huber+Suhner SPA 860/65/9/0/V -antenna. The test set-up can be seen in figure 1. The tested tags were self-made bow-tie type tags, with Alien IC-strap. One tag can be seen covered with ice in figure 2. The height of the antenna and the tag was 0,66 metres from the concrete floor, and the distance between tag and reader antenna was variable (see table I). As shown in figure 1, with the aforementioned configuration, the maximum reliable read range (MRRR, continuous 1 minute identification with over 75% of maximal reads-per-second rate) [8, 19] was measured, for five different tag types, in three different circumstances – at a temperature of +15,6 °C, at -20°C, and at -20°C with tags covered with ice and frost, as in figure 2.

Fig.1. The test set-up for Gen1 tag measurements

Fig.2. The Gen1 tag covered with ice and frost

These temperatures were chosen, because they were easily available at the measurement site. The chosen five tag types were:

- *Printed (4 tags)*: 4 different kinds of silver paste antennas, paper or cardboard underlay, glued IC-strap.
- *Cu/paper/tape (5)*: copper antenna, paper underlay, IC-strap attached with tape.
- *Cu/paper/glue (5)*: copper antenna, paper underlay, IC-strap attached with conductive glue.
- *Cu/transparency/tape (5)*: copper antenna, transparency underlay, IC-strap attached with tape.
- *Cu/transparency/glue (5)*: copper antenna, transparency underlay, IC-strap attached with conductive glue.

Each tag was measured three times at three different temperatures, and the mean values are presented in the results.

B. EPCglobal Class 1 Gen2 -tests

In Gen2-tests, the used testing equipment was Voyantic Ltd's Tagformance™ Lite –measurement device with two Huber+Suhner SPA 860/65/9/0/V –antennas. The distance between the antennas and the tag was 1m. The set-up is presented in figure 3.

Tagformance™ measured the threshold power in the 860-870 MHz frequency span in cold (-20°C) and in warm (+20°C) conditions. When measured in the cold, the tags (Alien ALN-9540 Squiggle) were covered with 5-6mm ice/frost, as seen in figure 4. The warm measurements were performed after the ice had melted and the tags were entirely dry. In total three different kinds of underlay were tested: paper, transparency and cardboard. Cardboard underlay was added to the list of materials because it is in wide use in different kinds of packages, even though it was not tested in the Gen1-tests

C. Strain test

The indicative strain test was performed by moving seven different tags several times from a cold (-20°C) to a warm environment (approximately +30°C) and back. The warm environment was achieved with a fan heater, and the time elapsing to temperature transformation was about 10 seconds. The MRRR was measured three times for each tag in three circumstances: before the first temperature transform, after 20 transforms and after 40 transforms. Each temperature transform into either cold or warm was counted as one. Mean values of the three measurements were calculated and these results were then compared to each other.

Fig.3. The test set-up for Gen2 tag measurements in cold conditions

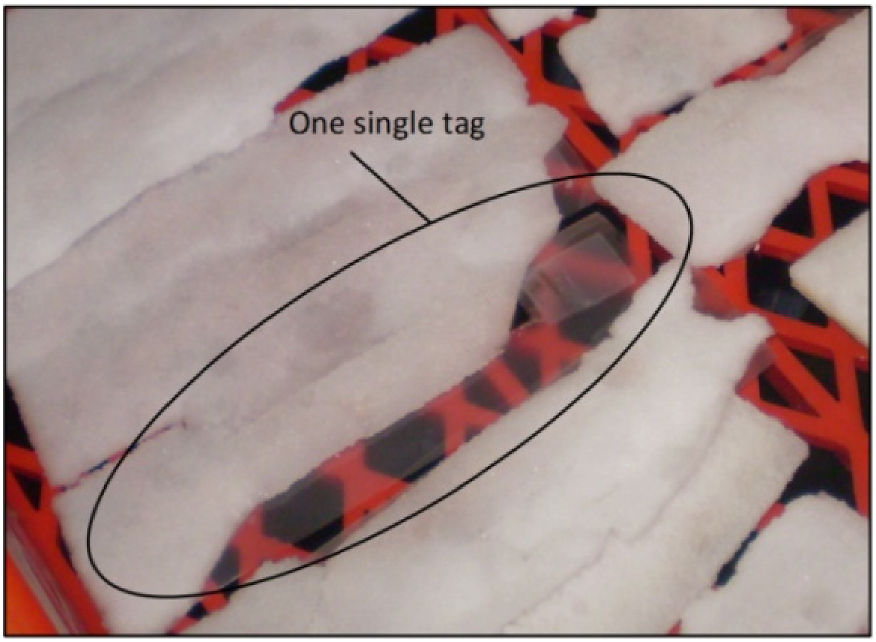


Fig.4. The Gen2 tags covered with ice

IV. Results

The results of the Gen1 and Gen2 measurements are presented in tables I and II, respectively. Table I shows the MRRR values of five different tag types at three different temperatures. Table II shows the threshold power, that is to say the minimum reader transmission power levels, which enabled the reading of the tag, in the 860-870 MHz frequency span. Three different types of underlay were tested (transparency, paper, and cardboard), each with and without the ice coverage.

Table III presents the results of the strain test. The graph shows the MRRR values for each tag in each phase. If the values are not shown, it means that the tag has broken during the test.

Table I. The MRRR for different Gen1 tag types in different circumstances [cm]

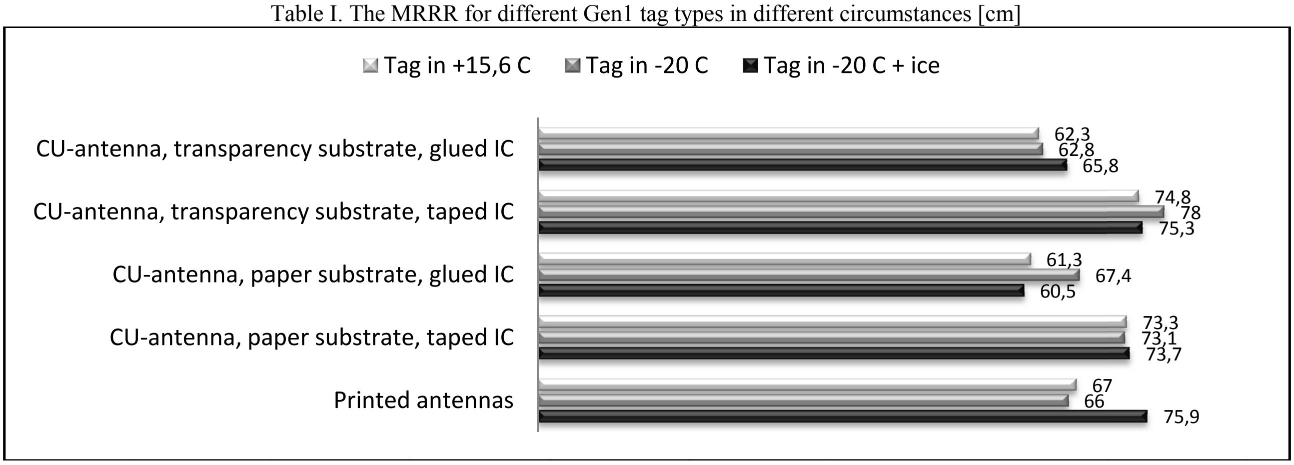
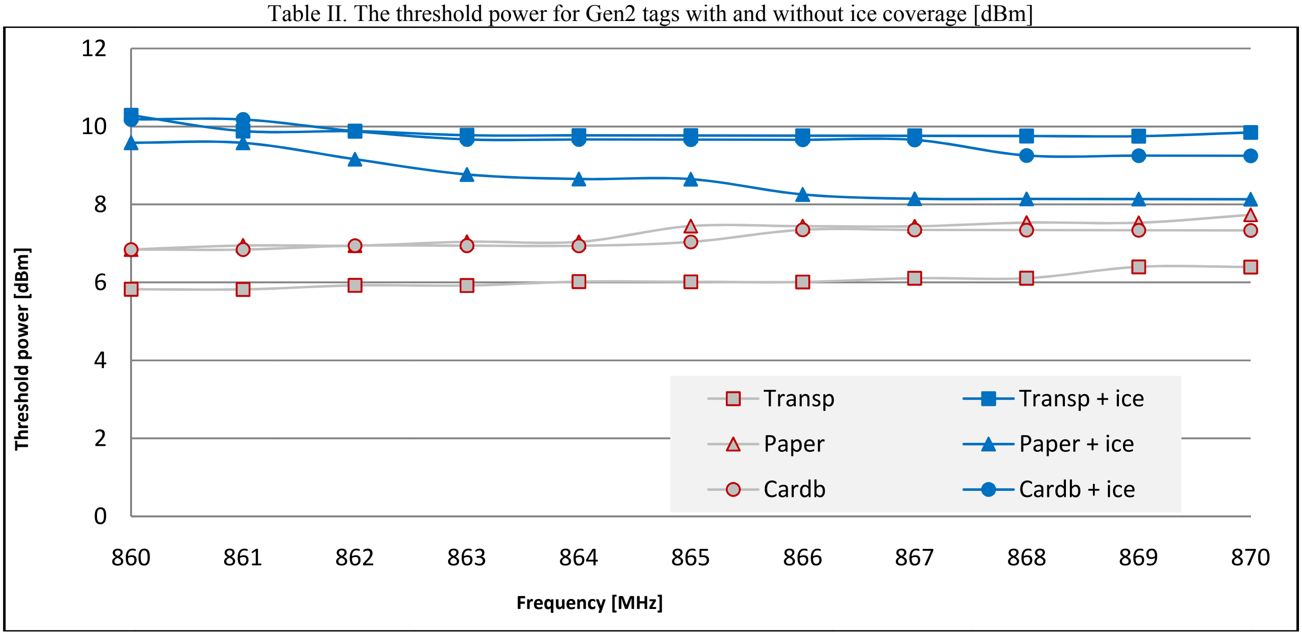


Table II. The threshold power for Gen2 tags with and without ice coverage [dBm]



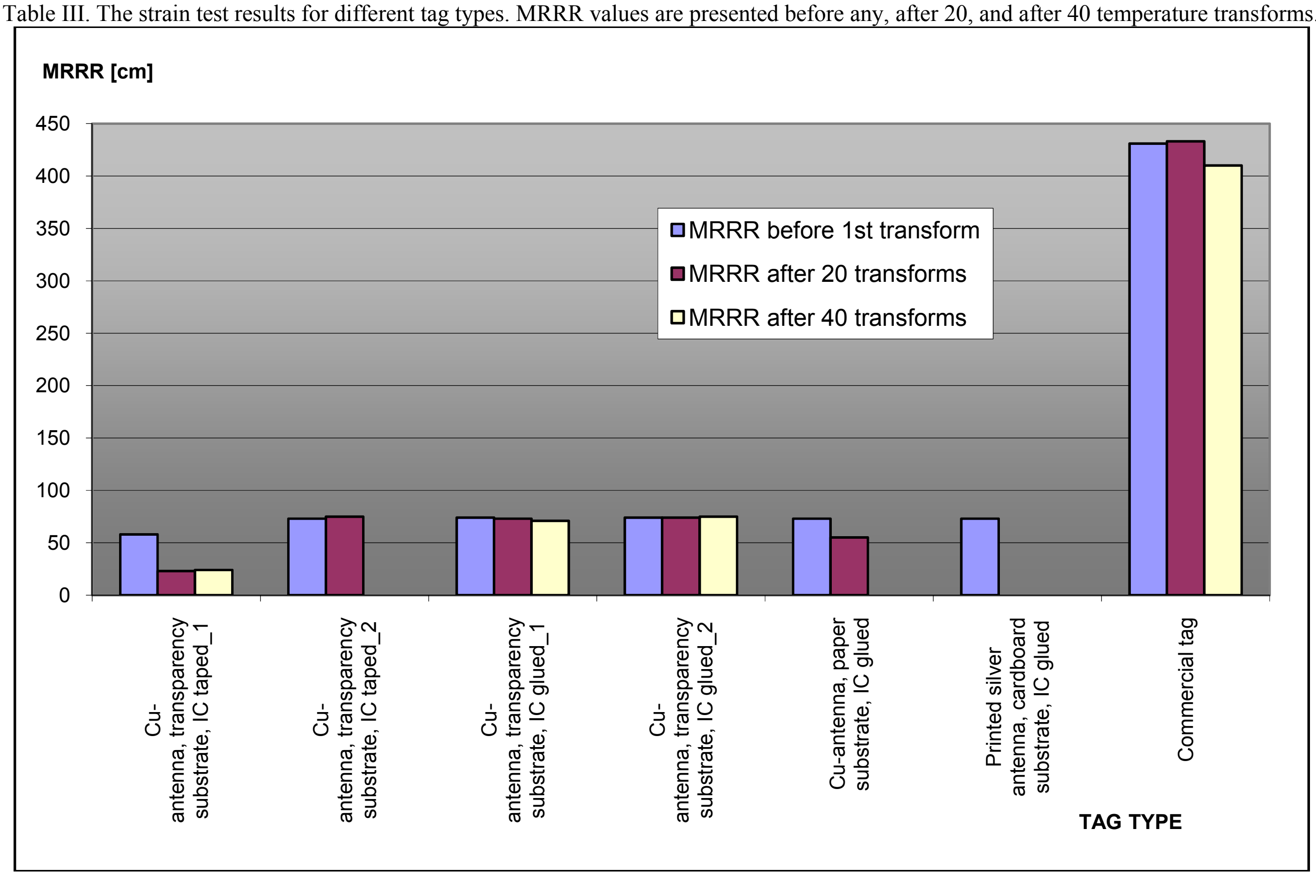
V. Discussion

When analyzing the results, it is not the magnitude of the values, but the changes to them in different circumstances which demand attention. This is due to the fact that Gen1 tags were designed to work under a thick layer of paper, so they were not in their optimal environment to reach maximal MRRR values.

As can be seen in table I, the effect of temperature, and also the ice coverage, on the MRRR is small. The tags worked well in cold environments, as well as with the ice/frost coverage on the surface. In some of the cases, the MRRR was even higher with ice, due to the similar permittivity values of the paper and the snow/ice. When examining the differences between the tag types, it can be seen that tape attachment between the IC strap and the antenna provided slightly better values than conductive glue.

From table II it can be seen that when tags were covered with ice they required a notably higher transmission power level with each of the tested underlay-types. In some cases the power needed to “wake up” the ice covered tag was twice as high as without the ice. It is also notable that the effect of ice and snow declines as the signal frequency is increased. This effect would have been easier to confirm, if the frequency span had been wider. It must also be remembered, that Gen2 tags were not designed to work under paper or ice, and the ice layer was clearly thicker than in the Gen1 measurements.

Table III. The strain test results for different tag types. MRRR values are presented before any, after 20, and after 40 temperature transforms.



The strain test results in table III gives us indicative results about the effect of rapid temperature changes. The performed test with a small number of tags was supposed to indicate whether this would be an interesting and useful research topic in the future, or not. The test was not carried out to achieve comprehensive results. The results indicate that some tags did not survive the test and the MRRR of tags which survived did not decrease markedly. Most significantly, altering the temperature affects tags where antenna and IC strap materials have different thermal expansion coefficients. In these situations the strap attachment will very likely be damaged. This happened in the strain test on a printed tag, whose polymer based silver antenna has a high thermal expansion coefficient. However, this test was only indicative, due to the small number of tags, but in the future more extensive studies could be carried out.

VI. Conclusions and Future Work

From the results which were presented in this paper, it can be concluded, that UHF RFID tags work well at the tested temperatures. They also work well when they are covered with ice/frost, but if the ice layer is very thick, for example over 10 millimetres, more transmission power is needed. The tested underlay materials (transparency, paper, or cardboard) of the tags did not cause any notable changes in tag behaviour.

Future work would involve more comprehensive studies on the effect of rapidly alternating temperatures on different types of UHF RFID tags. An increase in the frequency span in gen2-tests to cover global UHF frequencies would give useful and interesting results. In this paper, the tested span covered European frequencies only. A wider span would clarify the effect of snow and ice coverage in terms of the used frequency.

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