Design of a Low-Power Temperature Sensing Tag Based on RFID

Shihua Cao, Qihui Wang, Lidong Wang and Huixi Zhang

Abstract Designing a low-power RFID enabled sensor for detecting temperature is the main aim of this paper. The functionality of this sensor is hinged on the fact that temperature change leads to the bending of the structural beams which causes displacement of the plate resulting in a change in the capacitance. This means that the RFID tags resonant frequency is influenced by the sensor capacitance variation. The frequency shift can be detected and measured by UHF RFID readers that operate in the range of 900–930 MHZ band, then the temperature change can also be measured. In this paper, a tag is employed and the aim is to make a low-cost, low-power and efficient sensor that is able to function in many environmental conditions. The efficiency of operations in the cold supply chain can be made much better by pervasive sensing of the temperature.

Keywords RFID · Temperature · Tag · Reader

1 Introduction

Monitoring temperature is very crucial in the modern world since the degree of hotness or coldness in an object dictates the functionality of a product and its efficiency. This applies in many products: from electronic devices to livestock's and farm produce. Therefore it is very crucial to monitor these changes and ensure that they are within the expected range so as to minimize losses and failure of systems. There are many ways in which temperature can be monitored. In this report, using Radio Frequency Identification method to detect the changes in temperature will be investigated.

RFID may as well be used as a Real Time Location System (RTLS), which is rapidly becoming popular in industries. RFID uses the principle of electromagnetic

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induction to transmit information or data from the object to the monitoring device. This can be simply explained by the principle of electromagnetic induction which is a principle that plays a major role in today's science [1]. Electromagnetic induction occurs when a current cuts through a magnetic field which in turn induces a charge in a conductor that can be measured.

Radio Frequency Identification (RFID) is defined as any method of identification where an electrical device, that uses radio frequency or magnetic field disparities to transfer data, is attached to an object. A simple RFID device is made up of some basic components that make it possible for the device to achieve it sole duty. The main component is RFID tags or Transponder. The transponder/tag is made up of a miniature chip that carries an integrated circuit (IC). This IC contains a unique identification code that allows the controller to uniquely identify the object being monitored [2]. The IC, also, has the capability of storing required data of the object under investigation; managing its power use, intercepting and broadcasting of radio frequencies from the object. Currently, there are three major categories of transponders.

Operations in the cold supply tend to suffer oftentimes due to lack of visibility. It is estimated that close to 25 % of the perishable goods get damaged or even end up destroyed in the transportation operations. Research has demonstrated that the efficiency of the cold chain can be improved significantly if the temperature sensors can be utilized in the monitoring of the ambient temperatures [3]. Currently, operations in cold chain make use of wireless sensors that are expensive and to minimize the cost, monitoring the temperature is done by equipping places that are dedicated like trucks and storage rooms. The temperature of these places is then extrapolated and assumed to be the temperature of the goods inside. This is not effective and a good solution is to monitor the goods inside. This, however, requires pervasive sensors of temperature that can be deployed cheaply on each item passing through the cold chain.

RFID technology offers a good and practical choice for the temperature sensor design based on RFID tags. This is due to the fact that this technique comes with many features that are attractive such as low-cost tags and communication protocols that are standardized. In addition, the technology has been adopted by many companies as a tracking and tracing solution for most of their assets, thus making it easy to get practical help on the technology. RFID has, therefore, emerged as one of the solutions for sensing temperature in the current market [4]. Solutions that already exist depend on RFID features that comprise of a battery and a dedicated sensor.

The deviations in temperature can be detected as the strength of the signal received from the RFID tag changes. It is crucial to consider that the signal strength is not only influenced by temperature deviations but also by the distance of separation between the tag and the reader, and also the multipath and fading issues. This calls for the use of a second RFID tag that adds the cost of the sensor.

This paper seeks to address the above limitations by using measurements in the frequency domain. In this domain (frequency), measurements have a high tolerance to noise and the tag, and reader separation is irrelevant. This, therefore, means that frequency domain operation eliminates the requirement of a second tag and greatly saves on the cost. The sensor design presented here operates by converting the violations in temperature to changes in the tag antenna characteristics by the use of a metal plate and a shaped memory polymer [5]. It is designed to be single-use implying that the sensor can't be reset once the threshold temperature violation happens. Sensing principle that has been proposed are discussed in Sect. 2. A Discussion of the sensor prototype are discussed in Sect. 3. The analysis of the methodology of the temperature sensor design is shown in Sect. 4. System efficiency and tag read rang and environmental effect are discussed in Sect. 5. We concluded in Sect. 6.

2 Sensing Principle

2.1 Radio Frequency Transmission Concept

The First equation of transmission in free space is the governing principle in radioactive coupling between a receiving antenna and a transmitting antenna. The formula is given as

$$P_r = \frac{P_t G_r A_e \tau}{4\pi d^2} \tag{1}$$

where

P_r received power
G_r reader gain
P_t transmitted power
A_e effective aperture of the tag and antenna
d distance between receiver and transmitter
τ transfer coefficient

In (1), the transfer coefficient τ, is regarded as one of the main components that have profound effect on the tag read range [1]. It can be further expanded to give the equation;

$$\tau = \frac{4R_a R_c}{|Z_E + Z_c|^2} \tag{2}$$

where

R_a antenna resistance
R_c chip resistance
Z_a antenna impedance
Z_c chip impedance

The coefficient of transmittance, τ, determines how much power the chip consumes. The coefficient can only take values between 0 and 1, i.e., $0 < \tau < 1$.

For maximum power in the chip, the transmittance value is unity. At this condition, the impedances are equal in magnitude i.e.

$$\tau = 1, Z_{a=}Z_{c;}P_{r=\text{maximum}} \tag{3}$$

This implies that, for conditions that are well matched the read range for the tag is longer. Therefore, for a specified read range, the reader will require less power for it to be able to read or detect the tag [6]. Also note that both Z_a and Z_c depend on the frequency of operation of the antenna of the reader. Whenever there is temperature violation, Z_a is forced to change. This means that one can manipulate the frequencies where $\tau = 1$ and make sure it is less than unity, thus, minimizing power consumption. For this paper the frequency shift is constrained to 900–930 MHz band.

2.2 Temperature Sensor Material

Polytetrafluoroethylene (PTFE) has been widely used in microwave substrates and packaging applications because it exhibits excellent dielectric properties, such as low permittivity ($e_r = 2.1$), extremely low loss tangent ($\tan\delta = 0.00001$ at 800 MHz). Its large thermal expansion and easy-machinability make it a good candidate of temperature sensing material. Here, the linear thermal expansion in height direction of the copper coated PTFE post with height 6 mm are measured using a thermo-mechanical analyzer in the range 25–120 °C, which is shown in Fig. 1. It is observed that the thermal expansion of the PTFE is linear and has a thermal expansion coefficient of 140 ppm/ °C, which is much larger compared with 25 ppm/°C of Rogers RO3006 [7].

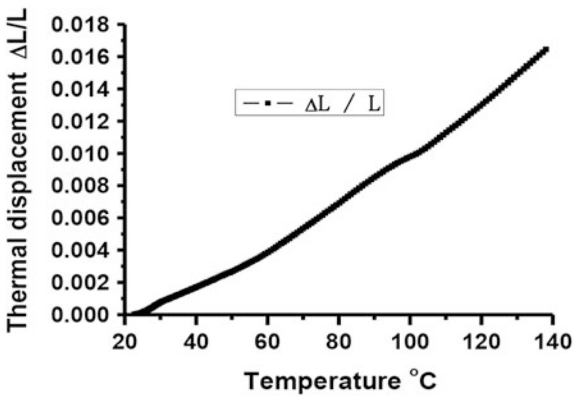

Fig. 1 Thermal expansion of the PTFE post

If a tag antenna exhibiting the above properties can be designed, then the result is a frequency domain detection mechanism that is easily implementable on the RFID readers that are readily available. For a specified reader to tag separation, the threshold transmitted power is determined where the reader just starts to detect the sensor tag and the frequency channels in which the tag responds.

3 Sensor Prototype Design

The tag IC used is a RF24L01 chip which is to be controlled by software. The nRF24L01 stores all the practical information such as the full voltage and the extreme signal strength and the role of each pin of the MCU msp430 microcontroller which needs to be taken into account when coding the software. The tag is made to be moveable and since the tag used is tag it had an electromotive source of its own. The nRF24L01 is then connected to a 3 v power source. The RFID sensor prototype is shown in the Fig. 2.

The reader is fixed in a position that enabled the reception of the signal from the tag within an acceptable range, it is then powered by a 3 v adapter connected to the nRF24L01 power pins [8]. The user interface is connected to the computers USB port which allowed it to pass the received data from the tag to the computer user interface for the controller to analyze the temperature change. In order to get the exact tag readings from a distance a method for the reader to calculate the change in temperature is established.

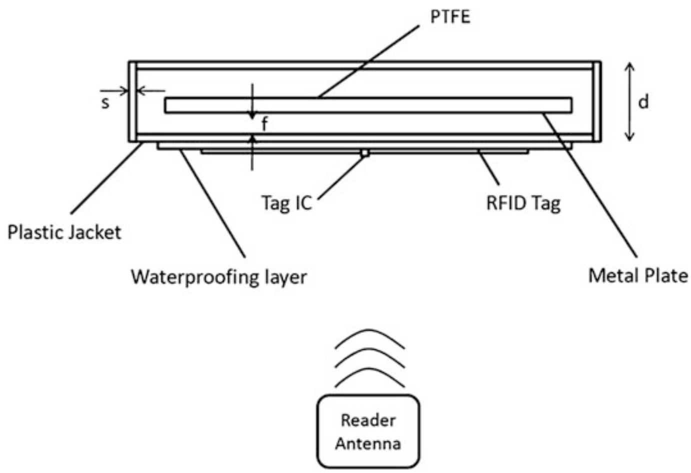

Fig. 2 RFID sensor prototype

3.1 Calculation of the Signal to Temperature and Pixel to Temperature Ratio

To calculate the signal to distance ratio the highest and lowest signal is obtained, then the difference of the two are calculated:

$$\text{max}_{\text{signal}}\,\text{difference}(\text{dB}) = \text{max}_{\text{signal}}(\text{dB}) - \text{min}_{\text{signal}}(\text{dB}) \tag{4}$$

The temperature in degrees Celsius between the two nodes is then divided by the maximum-minimum signal difference to get the ratio of the temperature to the signal.

$$\text{ratio}_{\text{temperature}}(c\ \text{per dB}) = \frac{\text{node}_{\text{temperature}}(c)}{\text{max}_{\text{signal}}\,\text{difference}(\text{dB})} \tag{5}$$

3.2 Calculation of the Nearest and Adjacent Nodes

Note that the nearest node continuously has the least signal and the adjacent nodes can be known by examining the x and y coordinates of the nearest node. The adjacent node upsets the tags x-coordinate and has identical x-coordinate as the nearest node and also has a different y-coordinate as the nearest node. The opposite state identifies the adjacent node that affects the tags y-coordinate as this node having the same y-coordinate as the nearest node and having a different x-coordinate as the nearest node.

3.3 Conversion of the Signal Values to Temperature

The signal values are taken from the nearest and adjacent nodes and transformed into temperature using the signal to temperature ratio.

The software for the components used is designed using Synapse portal software. This software allows coding using python script which is the most recommended language for such devices. The scripts can then be conveyed to the chips by inserting them on the evaluation board. The evaluation needs a power source to function and also to power the RF chip nRF24L01 consequently an EMF source is employed. A serial cable is then connected to the PC with the synapse portal software running and the Transponder is then programmed through the portal.

4 Methodology

This section basically goes through the technique used to design a low power sensor for temperature that experiences a shift in the optimum frequency of operation, whenever the set temperature threshold is violated. To help in the process of design the benchmark for the antenna to be designed are set:

4.1 Narrow Band

The antenna is designed in a manner that the optimum frequency of operation will lie the bandwidth of 900–930 MHz, and is reduced rapidly at all the other frequencies. This in essence makes sure that the states can, clearly, be distinguished so that the power that is transmitted at the threshold can be minimized, thus making the sensor low power.

4.2 The Frequency Shift in the 900–930 MHz Band

The matching frequencies that are optimum for the two sensor states of the tag antenna are required to be within a band of 30 MHz, this is due to the fact that commercial readers will be employed for the tag sensor interrogation and have the ability to detect only this operating range of frequencies.

4.3 τ Close to One at the Optimum Frequency

Note that to minimize the transmission power of the reader the range in which reading of a tag can be done is influenced by τ for the states. To make sure that the sensor states can be detected at a distance that is reliable and long, one should make sure that τ, for the states at the given optimum frequencies, is made close to 1.

5 Discussion

5.1 State Detection Efficiency

This refers to the fraction of the number of times the detection of the tag happened at a given frequency channel for the transmitted power threshold at which detection of the tag occurred. The test is done in open space. The separation distance between

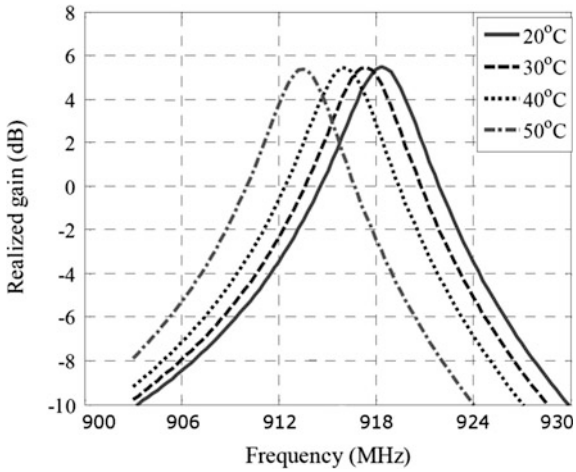

Fig. 3 Realized gain comparison of the PTFE sensing antenna under different temperatures

the tag and the reader is made to be about 3 m and there are no provisions to reduce multipath or reflections. This procedure is then repeated several times with the main aim of determining the antenna sensitivity to the various performance variables. It is observed that the repetitions varied but the optimum frequency of operation somewhat remained consistent.

The simulated realized gain of the RFID PTFE sensing antenna is shown in Fig. 3, which shows maximum 4 MHz/10 °C frequency shift and the realized gain is over 5 dB. These results prove that the PTFE sensing antenna, which uses material thermal properties, does provide a higher sensitivity [7]. Better sensitivity of the sensor minimizes the power wasted in detecting the device by the reader.

5.2 Determination of the Read Range

Determination of the read range in which the tag can be detected in a reliable way for the two states of the sensor is a crucial part. One replica is used to run the test for state detection over various reader sensor separations. It is observed that the sensor can be detected in a manner that is reliable over a range of 7 m. Nonetheless, the variations are seen to be minute in comparison to the shift in frequency caused by the stage change. It is noted that the transmitted power threshold for 3 mm PTFE plate sensor separation is 0 dBm for a reading distance of 3 m that is much less than the maximum reader transmitted power of the reader of 20 dBm [9, 10]. This suggested that the maximum sensor reads distance is greater than 7 m.

5.3 *Environmental Effect*

It is important to note that the low power temperature sensing tag is most likely to be employed in environments that are different from open spaces to storage rooms that are confined. The sensor is examined in clustered room with a lot of furniture and metal surfaces that can reflect close to the RFID tag. The only constant is the reader antenna and tag antenna line of sight. This means that the low power tag performance is independent of the environmental conditions.

6 Conclusion

This paper has illustrated a design technique for a low power temperature sensor based on UHF RFID tag. It is observed that the sensor shifts its frequency of operation between 900 and 930 MHz whenever there is a violation of the temperature threshold. It is realized that there is reduced power consumption, form factor and cost of the temperature sensing device that has been designed using the principle outlined above. It is also realized that choosing lengths of antenna that are short will give room to making sure that the various objectives of the design are met, such objective included making sure the frequency shift falls between 900 and 930 MHz band while meeting the requirement for τ to realize low power sensor.

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