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Non-invasive Frozen Meat Monitoring System Using UHF RFID Tag Antenna-Based Sensing and RSSI

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Abstract*— The conditions of frozen meat products must be closely monitored in cold chain logistics (CCL) to maintain their quality and safety. Sensing and monitoring meat products are currently invasive, costly, and lacking tracing capabilities. Therefore, developing a wireless, passive, and cost-effective sensing system capable of tracking and monitoring remains challenging. This work investigates the UHF RFID system performing antenna-based sensing for monitoring frozen meat using the received signal strength indicator (RSSI) data. A commercial off-the-shelf (COTS) UHF RFID reader is programmed through a single-board computer to acquire the RSSI data throughout the RFID 902-926 MHz band. In the experiments, RSSI data from an RFID inlay tag affixed to a defrosted frozen meat sample is acquired for approximately 20 minutes. Then, the RSSI data is recorded periodically during the changes in the sample condition. The experimental results signify that the RSSI data have monotonic relationships with the temperature and hardness of the meat sample. The three-degree polynomial regression models are constructed to show the non-linear relationships between the RSSI and the frozen meat condition. During defrosting, the RSSI lowers as the meat temperature rises and the hardness reduces. Therefore, antenna-based sensing employing the RFID RSSI data can detect changes in frozen meat temperature and hardness, allowing conditional fluctuations in the CCL to be monitored. This work paves the way for low-cost IoT-based sensing systems for improving food safety in cold chain applications.

***Keywords*— Cold chain logistics; food safety; intelligent packaging; RFID sensors.**

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I. INTRODUCTION

Food safety and quality are critical in the global supply chain management arena. Each year, unsafe food causes more than 200 diseases, 600 million illnesses, and 420,000 fatalities [1]. Various food safety and quality issues exist throughout the supply chain, particularly for perishable foods. Temperature control is required for dairy products, eggs, fruits and vegetables, meats, seafood, and fish across the supply chain (SC), from production to consumer touchpoints [2]. Meat is one of the most popular agricultural products because it provides proteins, minerals, and critical vitamins, all of which are important in human nutrition and health. As a result, there are worries about its quality and safety [3]. Operator habits, inadequate refrigeration equipment design, and climatic variables may all contribute to unexpected temperature abuses in cold chain logistics (CCL). It jeopardises the safety and quality of products, lowering consumer confidence and increasing food waste [4]. Therefore, effective meat tracing and monitoring systems are required to ensure proper handling during distribution and consumer safety [5].

Traditionally, food safety is shown by the printed 'best-before-date.' However, it is not a reliable indicator of product quality because it does not represent real-world conditions, such as temperature differences throughout distribution at various levels of the food supply chain. Food quality and safety can be improved by using sensors to track and monitor food items. Simple barcodes can be used to track items, but they lack the ability to store and update data locally. Time-temperature indicators (TTI) can reflect the thermal history of products but do not have tracking capabilities [6]. Electronic noses can measure the freshness of food; however, they are not suitable during the distribution process [7], [8]. Other technologies include microfluidic sensors [9], [10], hyperspectral imaging [11], [12], infrared sensors [13], and multi-sensor fusion [14]. There is no single solution that fits all. The methods are effective but may include opening the packaging (invasive), manual processes, are costly, slow, and lack tracking capabilities. The future trend of food safety in CCL, particularly for meat, is towards intelligent packaging that provides both tracing and monitoring [15], [16].

The internet of things (IoT) technologies enables a new opportunity to monitor, regulate, and track the myriad aspects influencing good quality over its long trip from farmers to customers via the internet [17]. In line with the trend of IoT, WSNs and RFID are the new technological solutions for cold chain monitoring [18]. RFID is a smart IoT enabler that allows for remote functionality and data collection and distribution. By collecting vital information from production, postharvest, and processing, RFID technology can increase the efficiency and traceability of the cold food chain [19]. Therefore, current and future studies might focus on building IoT-based monitoring using RFID. The main advantage of RFID for improving cold chains is its traceability capabilities, temperature fluctuations management, and shelf-life management [20]. The RFID sensing approach combines contactless, battery-free, and cost-effective advantages. In addition to traceability capabilities, RFID automatically updates the food product data as it moves along a supply chain. Continual measurement of food conditions can help detect improper handling during distribution and provide data for analysis.

RFID technologies have been studied for food safety and quality monitoring towards intelligent packaging and digitalization of the meat supply chain [21]. Fish and milk spoilage, fruit ripening, and cheese maturity are among the famous cases that have been experimented with RFID [22]. Miscioscia et al. use the high-frequency (HF) RFID transponder embedded with a capacitive temperature sensor to monitor perishable foods [23]. Karuppuswami et al. proposed an RFID sensor based on polyaniline thin film for quality monitoring of packaged food [24]. Abdelnour et al. studied the UHF RFID sensor for cheese quality monitoring [25]. Saggin et al. added biopolymer material to the UHF RFID sensor for cheese quality monitoring [26]. Researchers tend to add sensing capabilities to tags using external sensors and additional materials to use RFID as a sensor. However, it will add complexities, increase the power requirements, and burden extra costs for each tag. Integrating RFID tags with sensors, power supplies, and other circuitries makes the sensors less robust and difficult to combineith the package [27]. In contrast, the antenna-based sensing paradigm is simple yet has shown its capability to monitor changes in structures and material properties [28]. The investigations into the UHF RFID tag antenna-based sensing applications for CCL, especially frozen meat monitoring, are still limited in the literature.

In this paper, we investigate using the commercial off-the-shelf (COTS) UHF RFID system along with RSSI data to monitor frozen meat in the food cold chain application. The UHF RFID band is chosen because it is popularly used for supply chain, logistics, and distribution. Moreover, it naturally has a long-read range, faster data transfer, and good anti-collision capability. To show that the off-the-shelf UHF RFID tag can be used as a sensor, the antenna-based sensing indicated by RF communication between reader and tag, i.e., RSSI, is examined in this study. The concept of a UHF RFID sensor system for frozen meat monitoring will be described along with the theoretical bases of the sensing method and the RFID RSSI. Then, the system implementation using a COTS UHF RFID reader and tag is explained. The relationship between the meat condition, including temperature and the meat hardness, and the RSSI variation is observed in the experimental study.

II. Materials and Method

To apply a UHF RFID system for frozen meat monitoring, the materials used in this research include a UHF RFID reader, an RFID tag, a single-board computer, and a frozen meat sample. The monitoring system uses the received signal strength indicator (RSSI) captured by the RFID reader from the tag antenna attached to the meat sample. For clarity, the materials and method are described as the operating principle of frozen meat monitoring using the UHF RFID system, supported by the theoretical basis of the RFID tag antenna-based sensing using the RSSI. The method description is then followed by implementing the UHF RFID system for RSSI data acquisition on a single-board computer.

A. *Principle of Frozen Meat Monitoring Using UHF RFID System*

The operating principle of frozen meat monitoring using the UHF RFID system is illustrated in Fig. 1. The UHF RFID-based monitoring system comprises a reader and an inlay tag. The UHF RFID inlay tag is attached to a frozen food product, e.g., beef. The reader transmits radio waves to the tag, which powers up the tag and causes the tag to emit backscattered radio waves to the reader. The backscattered signals contain information on tag ID and RSSI data. The tag ID is useful for tracing, while the RSSI is used for monitoring the frozen meat condition in this study. In the system, the reader is connected to a computer that allows for capturing ID and the received signal strength indicator (RSSI) data.

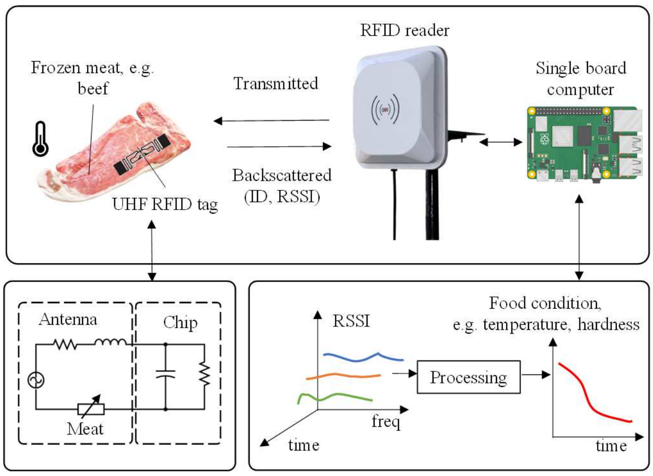


Fig. 1 Operating principle of frozen meat monitoring using the UHF RFID system.

Theoretically, the frozen meat on which the tag is attached affects the RFID tag antenna impedance. The physical condition of meat detunes the impedance matching between the antenna and the chip, making the reader-tag RF communication varies with the meat conditional changes. The computer that controls the RFID reader captures the RSSI for multiple frequencies. The collected RSSI data for different meat conditions can be used to investigate correlations between the meat condition and the RSSI.

B. Physical Condition of Frozen Meat and Its Effects on RFID Tag Antenna

The physical properties that may vary with the environmental conditions must be sensed to monitor frozen meat in the cold chain. The affected parameter is the permittivity or dielectric property, which is influenced by several factors, including frequency, ionic nature, moisture content, temperature, concentration, nature, and constituents of food materials. Among them, temperature variation is a vital parameter in cold chain monitoring. Temperature rising can trigger microbial proliferation and, subsequently, meat deterioration [29]. In the frozen temperature range, the dielectric property of meats rapidly increases with the increasing temperature from –10 to 0°C [30]. Generally, the dielectric constant and loss factor increased with temperature for muscle and marrow, the latter significantly above 25 ºC at 915 MHz. The rate of change of dielectric constant and dielectric loss factor with temperature depends on the food materials' free and bound water content. When the frozen meat's temperature increases, the water content increases, and thus the permittivity increases.

When an RFID tag is attached to frozen meat, its antenna impedance is affected by the meat's permittivity. An RFID tag antenna is designed to be conjugately matched with the chip input impedance to maximize power transfer. A proper matching between the tag chip impedance ($Z_c = R_c + jX_c$) and the tag antenna impedance ($Z_a = R_a + jX_a$) is denoted by a low reflection coefficient (Γ), which can be expressed as [31]

$$\Gamma = \frac{Z_c - Z_a^*}{Z_c + Z_a} \quad (1)$$

The RFID tag antenna is sensitive to the change in the background medium. The meat condition changes contribute to the antenna's electric property changes corresponding to its impedance variation. In the case of a homogeneous space-filling material, the antenna input impedance is frequency dependent, shifted and scaled relative to when the antenna is placed on an air medium.

$$Z_a(\omega, \varepsilon, \mu) = \sqrt{\frac{\mu_r}{\varepsilon_r}} Z_a(\sqrt{\mu_r \varepsilon_r}\omega, \varepsilon_0, \mu_0) \quad (2)$$

where ω is the angular frequency, $\varepsilon = \varepsilon_0 \varepsilon_r$ is permittivity, $\mu = \mu_0 \mu_r$ is permeability. Since the antenna impedance is affected by the properties of surrounding materials, it is possible to monitor the physical properties of frozen meat using RF communication through the tag antenna.

C. RSSI as Sensing Indicator

In the RF communication between an RFID reader and tag antennas, RSSI is the strength of backscattered power that can be acquired at the reader side. RSSI represents the RF communication performance between the reader and the tag, which is affected by the reader and tag antennas and the frequency and communication distance. Ψ denotes the physical variable to be monitored. Thus, the power retrieved at the tag chip can be written as

$$P_{R \to T}[\Psi] = \left(\frac{\lambda_0}{4\pi d}\right)^2 P_{in} G_R(\theta, \phi) G_T[\Psi](\theta, \phi) \tau[\Psi] \eta_p \quad (3)$$

where λ_0 is the free space wavelength at the operating frequency, d is the distance between the reader and the tag, P_{in} is the transmitted power input to the terminal of the reader antenna, G_R is the gain of the reader antenna, G_T is the gain of the tag antenna, θ and ϕ are the angles to account for the reader and the tag orientations and η_p is the polarization mismatch between the reader and the tag. τ is the power transmission coefficient of the tag related to the impedances of the tag chip and the tag antenna as

$$\tau[\Psi] = \frac{4 R_c R_a[\Psi]}{|Z_c + Z_a[\Psi]|^2} \quad (4)$$

The power backscattered by the tag and collected by the reader is

$$\mathrm{RSSI} = P_{R \leftarrow T}[\Psi] = \frac{1}{4\pi}\left(\frac{\lambda_0}{4\pi d^2}\right)^2 P_{in} G_R^2(\theta, \phi) \eta_p^2 \mathrm{RCS}_T[\Psi(\theta, \phi)] \quad (5)$$

where RCS_T is the tag's radar cross-section related to the modulation impedance Z_{mod}, which can be assumed equals to the chip impedance Z_c. $\mathrm{RCS}_{\mathrm{tag}}$ can be written as

$$\mathrm{RCS}_T[\Psi] = \frac{\lambda_0^2}{4\pi} G_T^2[\Psi](\theta, \phi) \left(\frac{2 R_a[\Psi]}{|Z_{\mathrm{mod}} + Z_a[\Psi]|}\right)^2. \quad (6)$$

From (6), the tag antenna impedance affects the tag's RCS and hence the RSSI, which is measurable by the reader. The RSSI, which indicates the tag antenna performance variation, can be considered sensing capability. With the change in frozen meat conditions, its permittivity changes. It varies the tag antenna performance and subsequently alters the RSSI. Therefore, the RSSI can be a sensing indicator of the frozen meat condition based on this theoretical basis.

D. Implementation of UHF RFID System for RSSI Data Acquisition and Monitoring

The monitoring system is implemented using a COTS UHF RFID reader and tag. The RFID reader, Electron HW-VY06K, is chosen because of its compatibility with various hardware platforms, such as Raspberry Pi, Arduino, and PCs. The reader is programmable using different languages, including Python, C, C++, and QT. With its programmability feature, Electron HW-VY06K can be used as a low-cost development platform for research. The reader specification is detailed in Table 1. The reader uses EPC Gen 2 protocol. It supports UHF bands from 860 MHz to 960 MHz, and a specific band based on country or a particular carrier frequency can be selected through the register settings. The transmitted RF power is adjustable up to 26 dBm, while the reading range is limited to 6 m depending on the tag. The reader is connected to a single-board computer (SBC), i.e., Raspberry Pi, through the USB interface. The reader is powered with a 9-36V supply, although USB power is enough to operate the reader.

TABLE I
SPECIFICATION OF THE UHF RFID READER ELECTRON HW-VY06K

Parameter	Specification
Frequency	UHF (860-960 MHz)
Protocol	ISO18000-6C (EPC Gen2)
RF Power	26 dBm (Adjustable)
Read Distance	5-6 m (Depends on Tag)
Interface	RS232, USB, WG26, Relay, TCP/IP
Power Supply	9-36V

The RFID inlay tag EL-U8-9424-W is used on the tag side, with the specifications detailed in Table 2. The tag operates at the entire UHF RFID frequency band, i.e., 860-960 MHz, and is based on ISO18000-6C (EPC Class 1 Gen 2) protocol. The chip used on the tag is the NXP Ucode 8, having an impedance of 14-j252 at 915 MHz. The tag antenna is made from etched aluminum on a PET substrate, so the tag is suitable for food product labels. More importantly, the tag's operating temperature ranges from -40°C to +85°C, ensuring that the tag inlay can be used in cold chain applications.

TABLE II
SPECIFICATION OF RFID INLAY TAG EL-U8-9424-W

Parameter	Specification
Frequency	UHF (860-960 MHz)
Protocol	ISO18000-6C (EPC Class 1 Gen 2)
Chip	NXP Ucode 8
Chip impedance	14-j252 at 915 MHz
Read/write sensitivity	-23 dBm/-18 dBm
EPC/TID memory	128-bit/96-bit
Material	PET, etched aluminum
Dimensions	98 mm x 27 mm +- 0.5mm
Operating temperature	-40°C to +85°C

For RSSI data monitoring purposes, the reader is programmed in C++ to collect RSSI at multiple frequencies. The RSSI data acquisition algorithm is shown in Fig. 2. The reader sets the transmitted RF power by specifying the CFHid_SetPower register with a byte value representing the desired RF power. For example, 0x1A represents 26dBm RF power. Then, it sets the carrier frequency to the lowest frequency, i.e., 902.75 MHz, by specifying the CFHid_SetFreq register with two-byte values representing the highest and the lowest frequencies, FreqH and FreqL. The upper and lower frequencies are calculated as

$$f = 902.75 + 0.5N \text{ (MHz)}; \; N \in [0,49] \tag{7}$$

where N is specified by the FreqH and FreqL registers. The FreqH starts from 0b00000000 or 0x00, while the FreqL starts from 0b10000000 or 0x80. For the US band 902.75-926.25 MHz, the full bandwidth transmission is represented by 0x31 and 0x80. Filling the registers with 0x31 leads the N to be 49 so that according to (7), the upper frequency becomes 926.25 MHz. To transmit a single frequency carrier of 902.75 MHz, the FreqH and FreqL register should be set to 0x00 and 0x80, respectively. After setting the single carrier frequency, the reader reads the tag and records the time stamp, the tag ID, and the RSSI. The frequency is then shifted to the next adjacent frequency by incrementing the FreqH register. The tag reading and the RSSI data recording are repeated for different frequencies until the carrier frequency reaches the highest for a specific band.

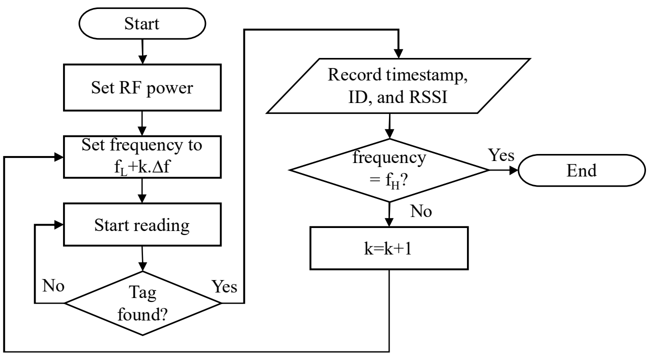


Fig. 2 Flowchart of the RSSI data acquisition swept over the UHF RFID.

III. RESULTS AND DISCUSSION

Experimental studies were conducted to evaluate the use of the UHF RFID system and RSSI data for frozen meat monitoring. The experiments were to study the behavior of RSSI data against the tag distance and the frozen meat condition. The first set of experiments was to test the effect of the tag distance against the RSSI. The second set of experiments was carried out to seek the possible relationships between RSSI data and the frozen meat condition for monitoring. Since frozen meats would thaw in an uncontrolled environment, temperature and hardness are two parameters to investigate in the experiments. In cold chain applications, these two parameters should be kept stable to guarantee frozen meat quality during distribution.

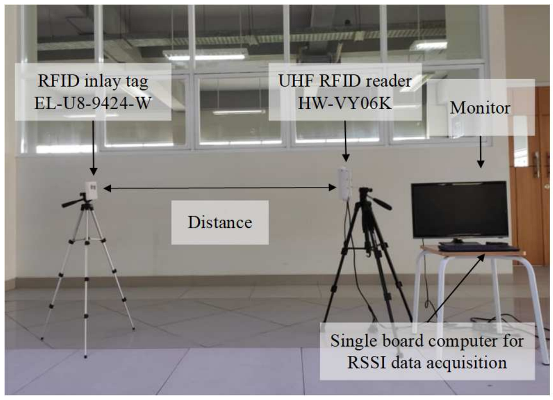


Fig. 3 The experimental setup for measuring the RSSI against the tag distance.

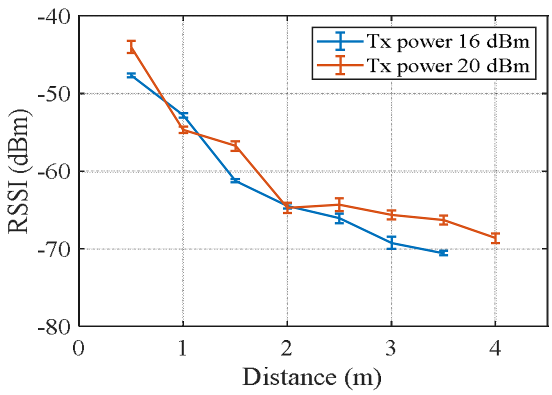


Fig. 4 RSSI tends to decrease as the distance between tag and reader increases.

Fig. 3 shows the experimental setup to test the effect of the tag distance on RSSI. The experiment was done in a hallway with no obstacle between the RFID reader and the tag. The RFID reader and tag were mounted on tripods and separated at a distance from 0.5 m to 4 m. Then, the RSSI data was recorded for each distance for two different transmitted power, i.e., 16 dBm and 20 dBm. It can be seen from Fig. 4 that the RSSI decreased when the tag moved further away from the reader. As in (5), RSSI should be inversely proportional to the distance. In this experiment, the maximum reading distance for the RFID reader and the EL-U8-9424-W tag was around 4 m. The tag was no more detectable when the distance was longer than 4 m with 20 dBm power.

The second set of experiments with a frozen meat sample was conducted with the setup shown in Fig. 5. The frozen meat sample was wrapped in packaging and was chilled in a fridge. For the experiment, it was taken out to room temperature (25°C to 30°C) so that the frozen meat sample thawed, and thus its temperature and hardness changed over time. The frozen meat sample was taken out right before the experiments began with the RFID inlay tag already attached to the sample. Then, the RFID reader on a tripod facing toward the frozen meat sample is laid on a tray 50 cm from the reader. The transmitted power of the UHF RFID reader was set to 16 dBm. The experiment collected RSSI data, temperature, and meat hardness every 2 minutes. The temperature was measured using an industrial non-contact temperature gun, while the meat hardness was measured using a Shore-A Durometer with a measurement range of 0-100 HA.

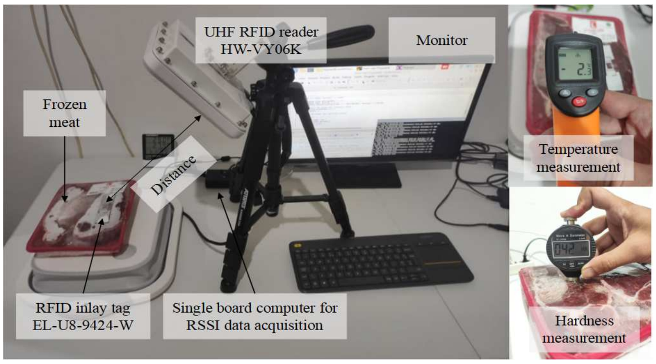
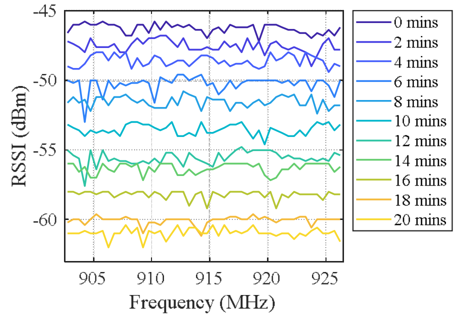


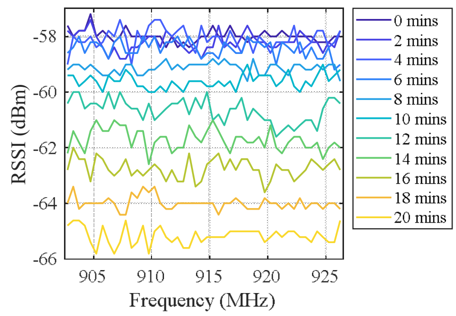
Fig. 5 Experiment setup of frozen meat monitoring using RFID and the photographs of temperature and hardness measurements.

The experiments were conducted with different reading distances: 50-cm, 75-cm, and 100-cm distance. The RFID RSSI data is collected every 2 minutes in the three experiments and is exhibited in Fig. 6. It can be inferred that when the tag is attached to the frozen meat sample, the RSSI data over the 902-926 MHz band tends to decrease with time regardless of the reading distance. With a 50-cm distance, the RSSI decreases from around -46 dBm to -62 dBm. With a 75-cm distance, the RSSI varies from -58 dBm to -65 dBm. Finally, with a 100-cm reading distance, the RSSI data changes from -61 dBm to -65 dBm. Generally, the RSSI data can be acquired for 18 to 20 minutes as the tag is no more detectable afterwards. In addition, it can be seen that the reading distance affects the variation of RSSI over the frequency. When the RSSI is used for frozen meat monitoring, the range of RSSI is consequently limited as the reading distance increases. Also, the RSSI tends to fluctuate more when the reading distance increases. As a result, noisy RSSI data is obtained for the reading distance of 100 cm. Over 100-cm distance, the RSSI becomes very low, and the tag is hardly detectable because communication between the reader and RFID tag now degrades by two factors, i.e., the long reading distance and the frozen meat condition.

Not only the RSSI but also the temperature and hardness of the frozen meat sample change over time. The measured temperature and hardness from three experiments are plotted against time, as depicted in Fig. 7. Since the meat sample was placed at room temperature, the meat's temperature rose over time. When the frozen meat sample was at room temperature for 20 minutes, the meat temperature inclined from around -13°C to 4°C. Conversely, the meat hardness tends to decrease from around 80 HA to 20 HA. It is reasonable that a slice of frozen meat will soften when its temperature increases, which should be avoided in the cold chain. The three experiments' data show consistent temperature and hardness trends against time, representing the mistreatment of frozen meat products in CCL. Hence, Fig. 6 and Fig. 7 confirm that the RSSI is affected by the frozen meat's temperature and hardness.



(a)



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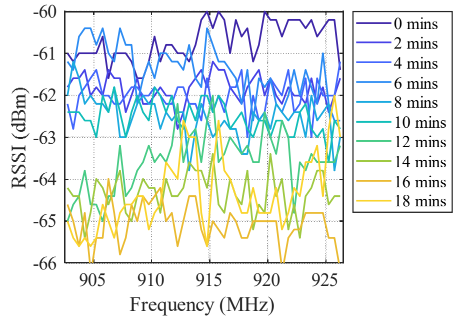


(c)

Fig. 6 The measured RSSI with different reading distances and the tag attached to the frozen meat sample: (a) 50-cm distance, (b) 75-cm distance, (c) 100-cm distance.

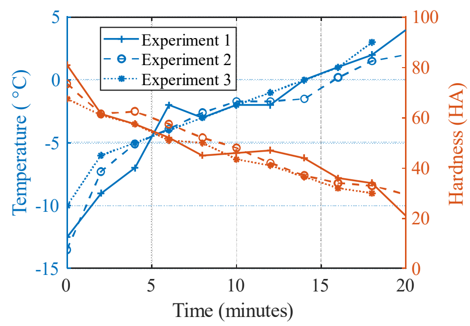
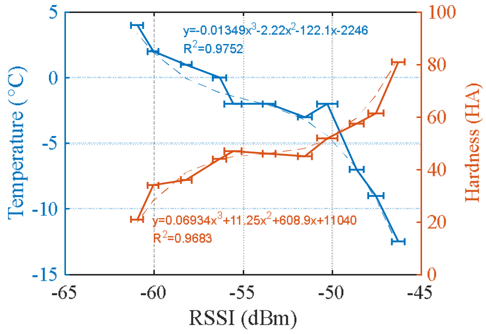


Fig. 7 The meat temperature and hardness change over time.

In Fig. 8, the RSSI is plotted against temperature and meat hardness to understand their relationships. The RSSI generally decreases monotonically with the inclined temperature and the declining meat hardness. There is a monotonic but non-linear relationship between RSSI variation against the frozen meat temperature and hardness. The resulting curves in Fig. 8 are fitted with 3-degree polynomial regression equations to find the relationship models of RSSI against temperature and RSSI against hardness. For the 50-cm reading distance, the polynomial coefficients for RSSI-temperature equation are [-0.01349, -2.22, -122.1, -2246] with the goodness-of-fit R^2=0.9752. The polynomial coefficients for RSSI-hardness equation are [0.06934, 11.25, 608.9, 1.104e4] with R^2=0.9683. For the 75-cm reading distance, the polynomial coefficients for RSSI-temperature and RSSI-hardness are [-0.0517, -9.64, -599.6, -1.244e4] with R^2=0.8468 and [0.103, 19.72, 1261, 2.696e4] with R^2=0.9806, respectively. Lastly, for the 100-cm reading distance, the polynomial coefficients for RSSI-temperature and RSSI-hardness equations are [0.007201, 0.8811, 22.88, -256.3] with R^2=0.8823 and [-0.3081, -57.43, -3558, -7.321e4] with R^2=0.8531. Hence, the temperature and hardness of frozen meat can be approximated using the RSSI data.



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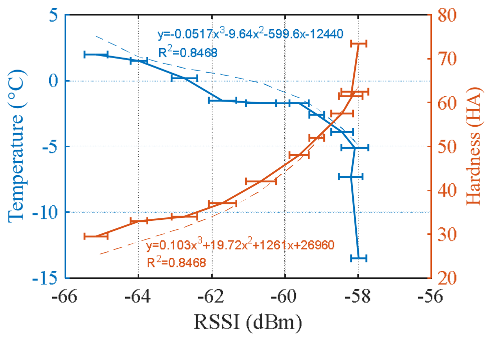

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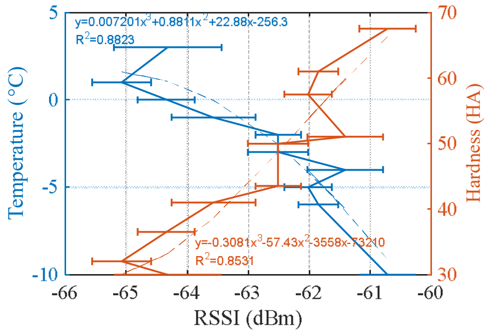

(c)

Fig. 8 The relationships between RSSI and meat condition with different reading distances: (a) 50-cm distance, (b) 75-cm distance, (c) 100-cm distance.

The experiments suggest that the mean of RSSI data over the entire frequency band can be used as a sensing indicator for monitoring the frozen meat condition. This study has proven experimentally that the RSSI data has a monotonic relationship with the temperature and the meat hardness. RSSI is inversely proportional to the meat temperature and directly proportional to the hardness. It is found that the RSSI data along 902 MHz to 926 MHz generally decreases when the meat temperature increases and the hardness decreases. As the frozen meat increases in temperature, its moisture and dielectric constant varies and detunes the impedance matching between the tag chip and the tag antenna. The detuned impedance matching degrades the communication performance between reader and tag represented by the RSSI data.

Since RSSI is also an indicator of communication performance, the UHF RFID antenna-based sensing has a drawback associated with the trade-off between sensing and communication. The longer the distance, the RSSI range decreases since the RSSI also degrades with the distance between reader and tag. It has been demonstrated that the sensing distance is feasible up to 100-cm. The long reading distance limits the sensing performance as the RSSI value is degraded and becomes unstable. Furthermore, the relationships between RSSI and meat condition change with the reading distance. Since the RSSI is distance-dependent, the distance of frozen meat from the RFID reader must be fixed or known priorly. The effects of distance could be resolved by extracting more features from the RSSI data. Since the distance affects the fluctuation of the RSSI data, RSSI data variation or standard deviation could be used to identify and classify the reading distance.

IV. Conclusion

A non-invasive frozen meat monitoring system using the COTS UHF RFID reader and tag along with the RSSI has been demonstrated in this study. The UHF RFID system can be used for product traceability and condition monitoring through antenna-based sensing. The RFID reader was programmed to collect RSSI data when a frozen meat sample was thawed in an uncontrolled temperature environment. Based on the experimental studies, RSSI data can be used as a sensing indicator to detect frozen meat's physical condition, specifically the fluctuations in meat temperature and hardness. Therefore, the UHF RFID system provides a non-invasive means of monitoring cold chain applications, which is wireless, passive, and low-cost. The monitoring using RSSI data was feasible in 50 cm to 100 cm reading distance. Hence, UHF RFID antenna-based sensing can be an alternative method for frozen meat monitoring towards intelligent packaging. The direction for future research could be to resolve the dependency of reading distance on monitoring by additional tags and feature extraction methods.

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