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Battery-less Pork Freshness Monitoring Based on High-Efficiency RF Energy Harvesting

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Abstract

Food safety has emerged as a growing concern for human health in recent times. Consuming contaminated food may lead to serious health problems, and therefore, a system for monitoring food freshness that is both non-detrimental to the quality of food and highly accurate is required to ensure that only high-quality fresh food packages are provided to the customers. This paper proposes a method to monitor and detect food quality using a compact smart sensor tag. The smart tag is composed of three ultra-low-power sensors, which monitor four major indicators of food freshness: temperature, humidity, and the concentrations of ammonia and hydrogen sulfide gases. An RF energy scavenging circuit is integrated into the smart sensor tag to harvest energy from radio waves at a high frequency of 13.56 MHz to supply sufficient power to the tag. Experimental results show that the proposed energy harvester can efficiently obtain energy at a distance of approximately 40 cm from a 4 W reader. In addition, the proposed smart sensor tag can operate without any battery, thereby eliminating the requirement of frequent battery replacement and consequently decreasing the cost. Meanwhile, the freshness of preserved pork is continuously monitored under two conditions—room temperature and refrigerator temperature—both of which are the most common temperatures under which food is generally stored. The food-monitoring experiments are conducted over a period of one week using the proposed battery-less tag. Based on the experimental results, the food assessment is classified into four categories: fresh, normal, low, and spoiled.

Keywords: Chemical sensors, Ammonia Gas, Hydrogen Sulfide Gas, Food Freshness Monitoring, Battery-less, RF Energy Harvesting, RF Energy Scavenging

1. INTRODUCTION

Meat is one of the most common types of food consumed by humans every day. The freshness of meat has an influence on its flavor, taste, and nutritional value. As consuming spoiled meat may cause serious health issues, proper assessment and monitoring of meat freshness is essential to protect human health. All foods have their own shelf life, which varies based on their type and storage conditions. Although different storage conditions, such as temperature, moisture, or light [1-3], do not exactly have any positive influence on the quality of food, they can prevent the deterioration of food quality, and hence, help to extend their shelf life. Until now, several methods have been proposed to determine the freshness of meat. Particularly in [4-5], the authors attempted to clarify the methods and design an accurate system for monitoring meat freshness based on the changes in meat color or compounds during storage. These methods and systems, however, are bulky, expensive, and time-consuming, and therefore, are normally employed in food-safety agencies or laboratories rather than in supermarkets, stores, and customers' homes. The freshness of meat deteriorates due to the growth of microorganisms, which convert the meat proteins into smaller compounds, resulting in the generation of gases such as ammonia (NH_3), hydrogen sulfide (H_2S), and H_2O [6-7]. Thus, there exists a clear relationship between meat freshness and changes in the concentrations of these gases. As a result, these concentrations can be employed as a real-time qualitative indicator of meat freshness during storage.

There are several devices that enable food-quality prediction, such as an electronic nose [8-9]. However, these solutions often require wired power supply or batteries for their operation, which increases the size of the system; moreover, frequent battery replacement leads to increase in system cost, which in turn, contributes to environmental pollution. Additionally, batteries, if subjected to negligent usage, can even cause an explosion. Recent application demands require devices that are small, easy to design, convenient to use, and harmless to users and the environment;

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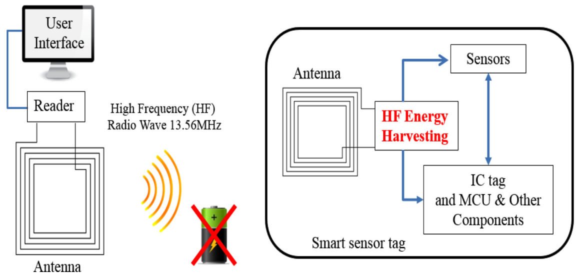

Fig. 1. Block diagram of the proposed battery-less system.

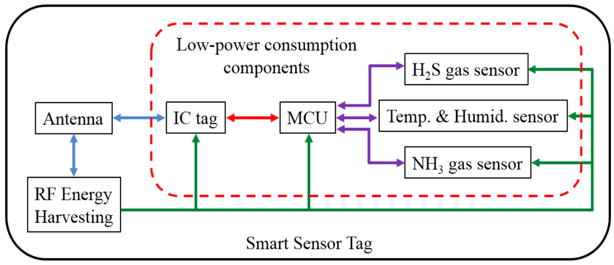

Fig. 2. Block diagram of the proposed battery-less smart sensor tag.

therefore, a solution for overcoming the issue of battery usage is essential. Although several methods such as thermal and solar energy harvesting have been employed [10-13], they still present their own disadvantages, including a decrease in light density, particularly at night, with solar panels, and the large size and low efficiency of thermoelectric systems. Thus, it is difficult to apply these solutions to designing a small, battery-less meat monitoring system that can be easily attached to food packages.

This study aims to employ an RF energy scavenging circuit [14-17] to harvest energy from radio waves and supply power to a smart sensor tag. The concept of RF energy harvesting is not novel and many systems have been designed to operate at different frequencies, such as 13.56 MHz, 433 MHz, 915 MHz, and 2.4 GHz. Although ultra-high-frequency (UHF) systems provide a faster data transfer and longer reading range, liquids and metals in the environment tend to interfere with the radio wave. Designing a UHF system is more complicated than designing a high-frequency (HF) system; in addition, if people are in close proximity of the high-power RF source for a long duration, the UHF radio waves can have a negative effect on their health. Therefore, our system was designed to operate at a frequency of 13.56 MHz (HF).

The final goal of our battery-less pork monitoring system using the RF energy harvesting technique is to design a full-passive system with an improved food-quality monitoring function. Following are the challenges and contributions of our study.

First, to implement a full-passive smart tag in a relatively long range from a reader, the power consumption of the smart tag is a highly critical issue and should be reduced significantly. Low-power gas sensors that do not consume much power but, at the same time, are efficient enough to capture the changes in gas concentrations were carefully chosen. Electrochemical sensors are a great candidate for this purpose, taking into account their lower power consumption as compared to other widely used metal-oxide sensors. Thus, we used two electrochemical gas sensors to measure the concentrations of ammonia and sulfur dioxide gases, along with low-power temperature and humidity sensors, to improve the pork freshness-monitoring function.

Second, a longer reading range between the reader as an RF power source and the smart tag as an RF energy scavenger is another important requirement of the system, considering its practical usage. In previous research, the reading range was relatively short at 13.56 MHz, from 10 cm to 20 cm. To extend this range, we mainly focused on the following methods: (1) efficient RF–DC conversion and DC busting, (2) charging-time reduction for the supercapacitor, (3) efficient management of RF-harvested energy at the smart tag, and (4) utilization of a low-power smart tag with ultra-low-power sensors. Consequently, the reading range was extended up to 40 cm.

2. SYSTEM DESIGN AND IMPLEMENTATION

Fig. 1 shows a block diagram of the proposed system, which includes a reader at the required high frequency of 13.56 MHz, a server to display the monitoring results, and a battery-less smart sensor tag.

2.1 Battery-less smart sensor tag

The concept of a battery-less smart sensor tag has originated from the typical 13.56 MHz full-passive radio-frequency identification (RFID) tag, which does not require any battery or wired power supply for its operation. While typical full-passive RFID tags are applied for simple applications such as item-tracking or access control, our battery-less smart sensor tag is designed for more complex applications. Fig. 2 illustrates a block diagram of the smart sensor tag, which includes an integrated circuit (IC) tag to communicate with the reader, a microcontroller to process data from the sensors and to write the sensed data to the memory of the IC tag, a high-efficiency RF energy harvester, and three ultra-low-power sensors to measure the temperature, humidity, and concentrations of NH_3 (CNH_3) and H_2S (CH_2S) gases.

2.1.1 Component selection

As mentioned earlier, the proposed battery-less sensor tag is designed to be operable without any external power source. In other words, the power supplied to all tag components is obtained only by the RF energy harvesting circuit integrated on the tag. The trade-off between the obtained and consumed power of the sensor tag is a challenge to its design. Therefore, the type and number of tag components must be carefully chosen to ensure that the total power consumption of the components is less than the total harvested energy. Thus, only low-power components, particularly the sensors, are appropriate for the design of the proposed battery-less smart sensor tag.

Similar to a high-frequency RFID tag, the smart sensor tag requires an IC tag operating at a frequency of 13.56 MHz to communicate with the corresponding reader. Recently, various commercial IC tags suitable for this requirement have been developed. However, most of them are used for simple applications, such as access control or item-tracking. Such IC tags cannot be applied in our study because the required data backscattered to the reader are the real-time values of sensors, including temperature, humidity, and concentrations of NH_3 and H_2S gases, instead of the information available in a typical IC tag, such as location, serial number, and manufacturer. These data need to be written automatically to the memory of the IC tag by a microcontroller unit (MCU); therefore, the IC tag must have an SPI or I^2C port to connect with the MCU. Particularly, our battery-less smart sensor tag comprises a low-power IC tag, M24LR04E (STMicroelectronics, USA), complying with the ISO 15693 standard for communication with the reader at 13.56 MHz, and an extremely-low-power microcontroller, PIC16LF1513 (Microchip Technology, USA), to process the data from the sensors as well as to write them to the memory of the IC tag using the I^2C protocol.

The concentrations of both NH_3 and H_2S gases are measured in pork freshness monitoring to predict the pork quality. These gases are released naturally during storage due to the decomposition of small compounds of meat, such as proteins and amino acids, due to the growth of microorganisms. There are several devices for measuring CNH_3 and CH_2S, such as electrochemical gas sensors and semiconductor metal-oxide sensors [18]. However, semiconductor metal-oxide sensors require a temperature of 150 °C-500 °C for heating, thus consuming considerable power and being unsuitable for application in a battery-less sensor tag. To optimize the power consumption of our battery-less sensor tag, two commercial and extremely-low-power electrochemical gas sensors—ME3-NH_3 (Winsen, China) and 3SP-H_2S-50 (Spec Sensors, USA)—were selected to measure CNH_3 and CH_2S, respectively. These low-power electrochemical gas sensors exhibited high sensitivity and accuracies in tracking the concentrations of NH_3 and H_2S. The output signals of these sensors were analog; therefore, they required to be converted to digital signals to write to the memory of the IC tag. In addition, an amplifier was employed to amplify their output current, which was as low as a few microamperes (μA). To filter the noises that were also amplified by the amplifier, a low-pass filter was used before the signals were passed to the microcontroller. The digital values of the output signals were then converted into the corresponding gas concentrations using conversion equations provided by Winsen and Spec Sensors, which are available at the datasheet of these gas sensors.

Table 1. Specifications of sensors

Characteristics	ME3–NH_3	3SP–H_2S–50	SHT21
Sensing Range	0-100 ppm	0-50 ppm	-40 °C-125 °C 0-100% RH
Sensitivity	0.1 ± 0.05 uA/ppm	212 ± 87 nA/ppm	± 0.3 °C ± 2%RH
Resolution	0.5 ppm	<5 ppb	N/A
Response Time	< 30 s	< 15 s	< 8 s
Operating Temperature	-20 °C-50 °C	-30 °C-55 °C	

To ensure that the CNH_3 and the CH_2S are accurately measured, the electrochemical gas sensors need to be periodically calibrated. The manufacturer proposes a time interval for the calibration; however, a monthly calibration is generally suitable to protect the effectiveness, sensitivity, and accuracy of these sensors. This procedure must be simple and straightforward for the users. The calibration procedure involves two stages: zero calibration and span calibration. Following the manufacturer's instructions, initially, a zero value for the sensors is obtained when the CNH_3 and CH_2S of ambient air are measured in a room under the conditions of 23 ± 3 °C temperature and 50 ± 5% RH after these sensors are powered on with the bias voltage for one hour. According to the manufacturer, after six weeks in continuous operation, the sensitivity changes from 5% to 15%; therefore, a short program can be used to compensate for the concentration result, such as span calibration.

Moreover, according to the manufacturers, the outputs of these sensor respond differently within the range of -30 °C to 30 °C of temperature. Therefore, temperature of the experiments conducted in this study was kept stable, which will be described in more detail in Section 3.

Food-storage conditions, particularly temperature and humidity, have a strong influence on food quality. An ultra-low-power digital sensor, SHT21 (Sensirion, Switzerland), with high accuracy was utilized to measure the temperature and humidity inside the food packages. With an internal analog-to-digital converter (ADC), this tiny sensor can directly send digital values to the MCU by using the I^2C protocol. The characteristics of the selected sensors are listed in Table 1.

2.1.2 High-Efficiency RF Energy Harvesting Design

By using the RF energy harvesting technology, the energy of radio waves generated from RF sources can be captured and transformed to DC power, which can then be used to supply power to low-power electronic devices.

However, we cannot convert all energy of RF radio waves to usable power. The amount of obtained energy varies depending on certain factors such as the distance between the RF source and the transceiver and the intensity of the RF source. The efficiency of conversion from radio waves to usable power and the reading range of the system are the most important characteristics in this field. A block diagram of the proposed high-efficiency RF energy harvesting circuit is shown in Fig. 3. The circuit includes an antenna operating at a high frequency of 13.56 MHz, an RF-to-DC circuit, a boost converter, and a charging circuit.

In the design of a battery-less smart sensor tag, the antenna plays an important role in the communication of the transceiver as well as in capturing a certain amount of energy from the electromagnetic field, which is generated by the reader antenna. Thus, the antenna has a substantial impact on the reading range of the system, and hence, requires cautious consideration in its design. Antennas with different sizes, types, gains, and materials are designed for different operating frequencies. At 13.56 MHz, the rectangular antenna is one of the most common and effective

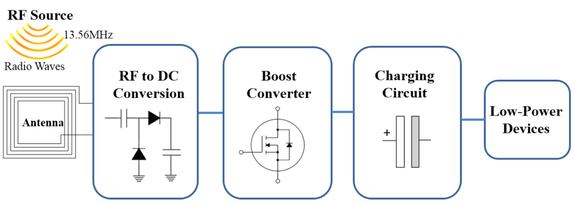

Fig. 3. Block diagram of the proposed high-efficiency RF energy harvesting circuit.

Table 2. Dimensions of the real-tag antenna

Dimension of the tag antenna	Number of turns: 3 Length × Width: 7.893 cm × 5.727 cm Width of turn: 0.76 mm Resonant frequency: 13.59 MHz Material: FR4 substrate

types [19]. The inductance and resonant frequency of the antenna are calculated by (1) and (2) as follows:

$$L = \frac{u_0 N^2}{\pi}\Big[-2(w+h)+2\sqrt{h^2+w^2}-h\ln\left(\frac{h+\sqrt{h^2+w^2}}{w}\right)- w\ln\left(\frac{w+\sqrt{h^2+w^2}}{h}\right)+h\ln\left(\frac{2h}{a}\right)+w\ln\left(\frac{2w}{a}\right)\Big] \tag{1}$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

where $u_0 = 4\pi * 10^{-7}$, N is the number of turns, w and h are the width and length of the antenna, respectively, a is the track width, f_0 is the antenna resonant frequency of 13.56 MHz, L is the inductance of antenna, and C is the internal capacitance value. Compared to other operating frequencies, 13.56 MHz antennas are less complex because they use inductive coupling instead of far-field electromagnetic technology to convert the magnetic field of the power source into electrical signals. In our tag, we designed a spiral rectangular-loop antenna using copper on the FR4 material. The antenna of the sensor tag was first simulated by high-frequency structure simulator software. The return loss and the voltage standing wave ratio (VSWR) of the antenna were then measured and modified by a network analyzer (Keysight

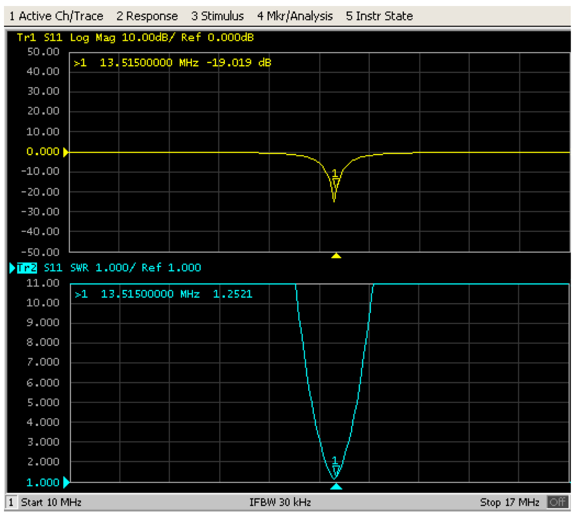

Fig. 4. Measured result of the real-tag antenna using the network analyzer. The upper curve was the return loss of the antenna, and the lower curve was its corresponding VSWR.

Technologies, USA) to ensure that the antenna exhibited suitable performance. The resonant frequencies of the simulated and real antennas were 13.56 and 13.52 MHz, respectively, while the return losses at these frequencies were −26.3 dB and −19.02 dB. Table 2 shows the dimensions of the tag antenna and Fig. 4 shows the measured results of the real-tag antenna.

The energy captured by the antenna is, obviously, AC power, and hence, must be transformed to DC power prior to being supplied to the operation of the sensor tag. There are several methods that can be utilized for this purpose, such as using a half-wave rectifier, full-wave rectifier, and multipliers. In our design of the battery-less smart sensor tag, we employed a three-stage Cockcroft–Walton multiplier to convert the AC signals to usable DC power and to increase the DC output voltage [20–21]. According to [21], the output voltage of an N-stage multiplier can be approximated using (3):

$$V_{out} = 2 \times N \times V_{max} \quad (3)$$

where V_{out} is the output voltage of the multiplier and V_{max} is the peak voltage of the AC input signal. This converter requires three Schottky diodes, HSMS-2855 (Avago Tech., USA), which are designed and optimized to operate at frequencies below 1.5 GHz. They are completely appropriate for applications in which DC power is unavailable. These diodes have a forward voltage drop of as low as 150 mV, which means that they allow the conversion from AC signal to DC signal as fast as possible. Compared to other types of rectifiers, especially at long distances where the energy of radio waves is extremely small, resulting in a small converted DC power, the three-stage multiplier has an advantage that the output DC voltage is sufficient for the tag operation while the charging time is short enough. In particular, increasing the

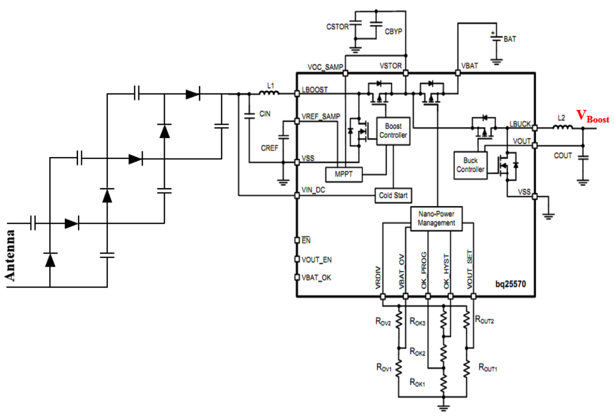

Fig. 5. Schematic of the three-stage multiplier and the boost converter.

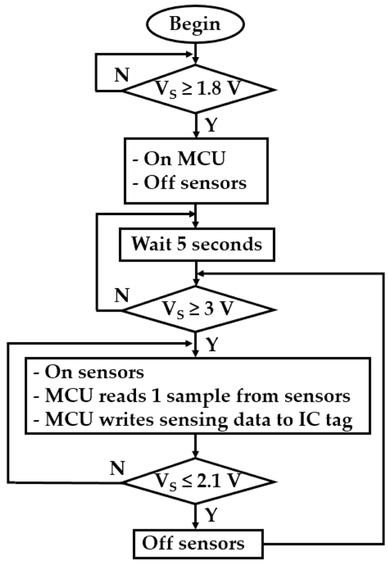

Fig. 6. Flowchart of power management of the smart sensor tag.

number of stages may reduce the current passing through the load, resulting in a longer charging time for the charging circuit, although this will generate a higher output DC voltage. Conversely, we can reduce the time to charge the charging circuit by using fewer stages. Consequently, it has been proved that the output DC voltage is smaller and insufficient for supplying power to the device.

The main aim of the high-efficiency energy harvester is to harvest a sufficient amount of energy to provide for the operation of the sensor tag and to extend the reading range of the system. However, when the distance from the source is longer, the amount of energy generated from the RF source is significantly decreased, and consequently, generating sufficient DC voltage that is to be supplied for the operation of the sensor tag can prove challenging. Although the output DC voltage is enhanced after using the three-stage multiplier, it is still insufficient to be directly supplied to the tag, particularly at a longer distance. Most of the sensor tag components require a DC voltage within the range of 2.1–3 V. In conventional circuits using external power sources, a voltage regulator is usually applied to regulate a higher DC voltage to the voltage of interest, usually 3.3–5 V. This configuration, however, cannot be employed in the proposed system due to the shortage of the harvested energy. Thus, a boost converter [22–23] is utilized to boost the DC signal provided by the rectifier to an output voltage of approximately 3 V. In addition, the buck-boost converter, BQ25570, has an input voltage regulation to prevent collapsing high impedance input sources and an internal buck converter to provide the required output voltage.

We chose an ultra-low-power harvester power management IC, BQ25570 (Texas Instrument, USA), for this purpose. It is specifically designed and optimized to be applied with various extremely-low-power sources, ranging from microwatts to milliwatts, such as thermoelectric generators and solar panels, with a high efficiency of up to 90%. This IC integrates an energy harvesting nanopower management that can effectively operate with an extremely-low input voltage. It can start up at 330 mV of input voltage and then maintain the operation by decreasing this value to as low as 100 mV, as soon as the VSTOR pin is charged to 1.8 V or higher. The boosted efficiency of the boost converter is related to the input voltage; for example, the boosted efficiency is approximately 85% if the input voltage is approximately 0.7 V. Technically, the boosted efficiency can be configured to reach 90% with the maximum power-point tracking technology of the IC. Fig. 5 shows a schematic of the three-stage multiplier and the boost converter.

In a typical energy harvesting circuit, the obtained energy will be stored in a charging circuit, such as a battery, an IC, or a capacitor. In our sensor tag, the energy harvested is stored in a supercapacitor (AVX, USA) with a value of 0.47 F/5.5 V to ensure a smooth power delivery to the load while functioning as an alternative power source when the external power resource is unavailable.

2.1.3 Power Management Policy

In this study, a power management policy was developed to efficiently manage the received power and reduce the charging time of the supercapacitor. Fig. 6 illustrates the detailed process of the power management policy. The first time that it is used, the RF energy harvesting circuit collects energy and charges the supercapacitor. As soon as the voltage of the supercapacitor (V_S) exceeds 1.8 V, the MCU begins to operate and turns off all sensors. The V_S is checked every 5 s using the ADC module of the MCU. When it reaches 3 V, the MCU turns on all sensors by controlling a P-Channel MOSFET switch, IRLML6401 (Infineon Tech., Germany), to collect the sensing data and write them to the memory of the IC tag. However, we cannot collect sufficient energy for the smart sensor tag to operate continuously for a long period; therefore, the energy stored in the supercapacitor will sharply decrease. When V_S is lower than 2.1 V, the sensors cannot operate accurately; hence, the MCU is programmed to turn off all sensors again while waiting for the V_S to charge to 3 V. In other systems that do not utilize this process, all energy stored in the supercapacitor is consumed until V_S = 0 V; therefore, the

Table 3. Total power consumption of the sensor tag

Components	Operating time	Operating voltage	Average power consumption
NH_3 gas sensor	150 ms for sensing operation	~ 3 V	~ 3 mW
H_2S gas sensor	150 ms for sensing operation	2.7 V – 3.3 V	~ 50 μW
Temp.-Humidity sensor	At 8 bit, 1 measurement/ s	2.1 V – 3.6 V	~ 3.2 μW
MCU	Always in active mode at 1 MHz	1.8 V – 3.6 V	~ 0. 17 mW
IC tag & other components	Always in active mode	2.1 V – 3.3 V	~ 1.5 mW
Total			~ 5 mW

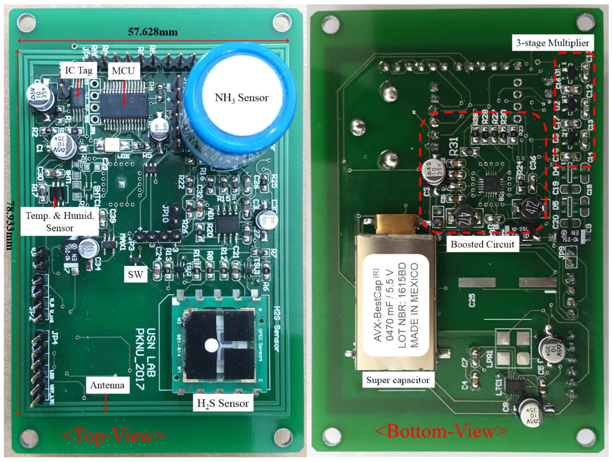

Fig. 7. Photographic top-view and bottom-view of the smart sensor tag.

supercapacitor requires a longer time to charge from 0 V to 3 V for the next duration of the system operation. With the proposed policy, the supercapacitor will require a shorter time to charge from 2.1 V to 3 V. Consequently, this process helps minimize the power consumption and reduce the charging time of the circuit.

Table 3 lists the total power consumption of the battery-less smart sensor tag, and Table 4 presents the experimental results of the proposed energy harvester related to the distance.

The design of the high-efficiency energy harvester in our sensor tag allows the tag to operate at a maximum reading range of up to 40 cm from the reader antenna. At a distance of 45 cm, the voltage stored in the supercapacitor reaches 1.95 V due to the low charging current after 253 s of charging; therefore, it is still not sufficient to ensure that the sensor tag operates perfectly. Fig. 7 shows a picture of the top and bottom views of the smart sensor tag.

The proposed smart sensor tag is expensive because of the sensors used. However, the cost can be substantially reduced by

Table 4. Experimental results of the proposed energy harvester related to the reading range

Distance (cm)	Received current (mA) at 3 V	Charging time (s)	Battery-less device
0	159	16	Yes
5	153.2	20	Yes
10	142.5	28	Yes
20	112.7	50	Yes
30	75.1	92	Yes
40	37.4	147	Yes
45	12.5	253	No

applying the latest system-on-chip technology, where all components are placed onto a single, compact chip; however, this is beyond the scope of this study. Thus, the concept of our proposed battery-less food-monitoring system can be a cost-effective method in the real world if appropriate manufacturing and packaging technologies are applied.

2.2 Reader and User Interface

Because our tag is compliant with the ISO 15693 standard, we employed a commercial reader, CF-RH9402 (ChaFon Co., Hong Kong), which operates at a high frequency of 13.56 MHz and can generate a maximum output power of approximately 4 W. This reader supports ISO 15693 tags manufactured by many companies, such as Philips, Infineon, and STM. To generate radio waves at this frequency, a commercial rectangular antenna with a high power of up to 6 W, CF-RA1002 (ChaFon Co., Hong Kong), was connected to the reader. Besides functioning as a power source to the proposed smart sensor tag, as described earlier, the reader communicates with the tag to read the sensing data from the memory of the IC tag. In addition, it can simultaneously process multiple tags with a high speed of 30–50 tags/s, which extends the feasibility of the battery-less sensor network.

The reader can read and write data from and to the tag and display the measurement results on the server. To monitor the freshness of food, a user interface is designed using C# language to demonstrate the experimental results and predict the food quality on the server. In particular, the interface displays all data of measurements, including temperature, humidity, gas concentrations, and information about pork quality, which is denoted by the following four colors: green for fresh, yellow for normal, orange for low, and red for spoiled.

3. EXPERIMENTAL INITIALIZATION AND RESULTS OF FOOD MONITORING

The proposed system was designed to be applied mainly in supermarkets and food stores, where awareness of the quality of packaged food is required. Pork was selected as the subject of the experiments.

First, the smart sensor tag was placed inside the food package to measure temperature, humidity, and concentrations of both NH_3 and H_2S gases. To avoid the negative effects that the sensor tag material could have on the meat quality, the sensor tag was tightly attached onto the lid of the package. The distance from the sensor tag to the meat was approximately 1.5 cm to ensure that the sensor tag did not touch the food inside. Data collected from the sensor were sent wirelessly to the reader through radio waves at 13.56 MHz. Finally, the reader processed these data and displayed the

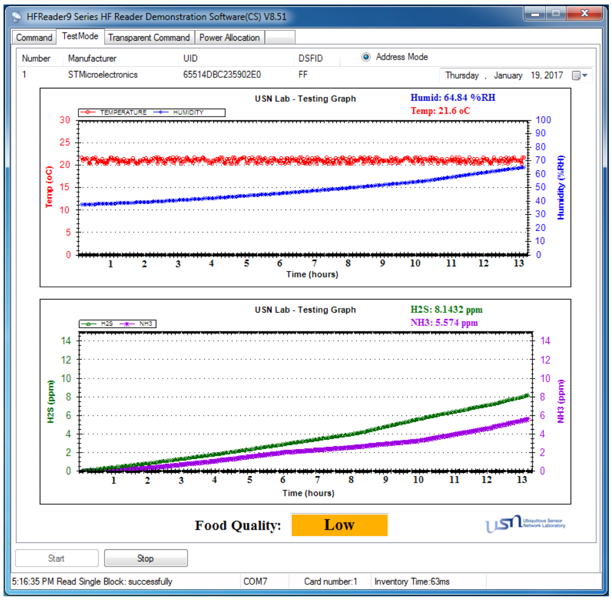

Fig. 8. Screenshot of the designed user interface.

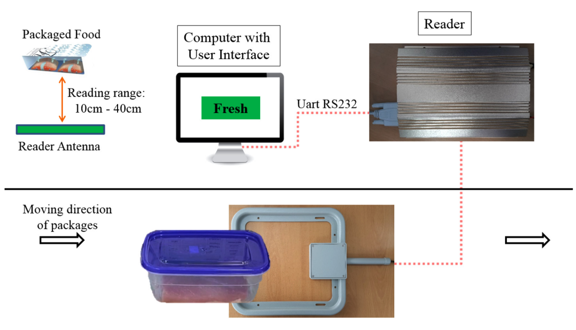

Fig. 9. Configuration of the proposed system.

results on a computer. Fig. 8 shows the developed interface with data displays on the computer. To apply the proposed system for a large number of food packages, a conveyor belt can be used to continuously transfer food packages to the reading field of the reader antenna.

Fig. 9 shows the experimental configuration for the proposed system. To avoid the negative influence that the material used for making the box might have on the quality of meat as well as to increase the accuracy and reading range, a plastic box was chosen instead of a metal box to store the food. Thus, other items that were in close proximity to the system were eliminated to ensure that the communication between the tags and reader was accurate.

The experiments were performed under two conditions, room temperature and refrigerator temperature, which are the usual conditions under which food is generally stored. The temperature of both conditions was kept stable to guarantee the reliability of the output data of the gas sensors. Every package used in the experiments contained 200 g of pork. Two packages were stored under the same condition and monitored until they were spoiled. In each package, the gas concentrations were recorded and filtered using the 3-point moving average filter method. The data of each experiment were the average values of the results from both packages. The experiments were carried out four times under each storage condition. Totally, eight packages were used in the research.

When the packages were stored inside the experimental room, the room temperature was maintained at approximately 21 °C for the above-mentioned reason of data reliability. Each package was monitored continuously until it was spoiled. Fig. 10 shows the experimental results of these packages. The results indicated a substantial increase in humidity as well as NH_3 and H_2S gas concentrations after 14 h of storage. Based on the variation in

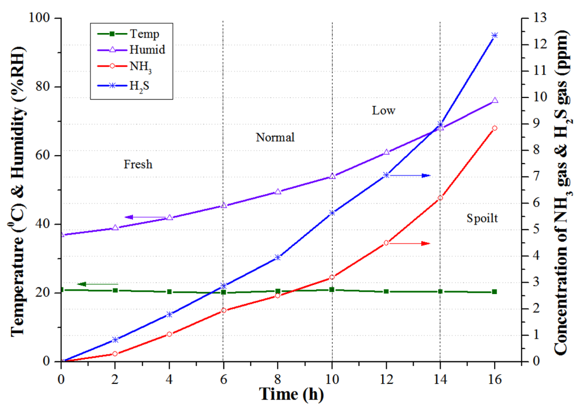

Fig. 10. Experimental result of the packages at room temperature.

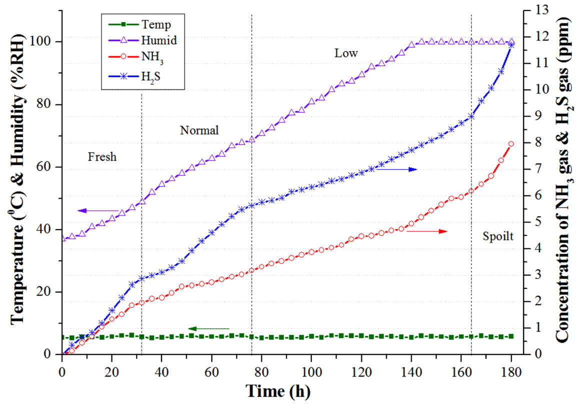

Fig. 11. Experimental results of the packages at refrigerator temperature.

CNH_3 and CH_2S, the freshness of pork was classified into four categories: fresh, normal, low, and spoiled. Additionally, the color and smell of the pork meat clearly changed, from light pink and free-of-smell at the beginning when the meat was fresh to light brown and rotten-smelling when it was spoiled. These changes showed the deterioration process of the pork meat during storage. According to the results, fresh pork meat should be consumed within 10 h of storage under room temperature to ensure that its spoilage does not affect human health.

Refrigerators are an ideal place to store food at stable, low temperatures of 4 °C–6 °C. The packages placed inside a refrigerator shared the same weight as those stored at room temperature and were measured every 2 h until the pork meat was spoiled. Fig. 11 shows the experimental results of the food packages at the refrigerator temperature. The results indicated a slight growth in data compared to that in the data of food packages at room temperature. In case of humidity, 100%RH is the maximum scale of the SHT21 sensor; therefore, once the humidity reached 100%RH, the data did not change. Table 5 lists the CNH_3 and CH_2S released during storage, which were used to classify the quality levels of pork [24]. Table 6 presents a comparison of how long the quality of the pork meat was preserved under both room and refrigerator temperatures. The

Table 5. Pork quality-level classification based on gas concentrations

Level	C_{NH3} (ppm)	C_{H2S} (ppm)
Fresh	< 1.95	< 2.88
Normal	1.95 – 3.2	2.88 – 5.64
Low	3.2 – 6.18	5.64 – 9
Spoiled	> 6.18	> 9

Table 6. Preservation time (h)

Level	Room (21 °C)	Refrigerator (4 – 6 °C)
Fresh	< 6	< 32
Normal	6 – 10	32 – 76
Low	10 – 14	76 – 164
Spoiled	> 14	> 164

table shows that the pork meat could be maintained at good quality until 76 h, after which it got spoiled. These results agree with those obtained by previous studies [24-25].

4. CONCLUSIONS AND DISCUSSION

This paper proposes a harmless and highly accurate device for monitoring and predicting the freshness of pork based on four factors—temperature, humidity, concentration of NH_3, and that of H_2S gas—using a battery-less smart sensor tag. The tag was designed with a highly efficient full-passive RF energy harvesting capability to scavenge energy within a distance of up to 40 cm from the reader antenna.

This system can be used to monitor the spoilage process of many pork packages as well as to identify the packages with the best-quality pork meat. Moreover, this battery-less system can be employed to monitor other types of meat, including beef, chicken, and fish. It not only helps people consume food before its expiration date but also helps save food and reduce wastage. Furthermore, the gas concentrations are varied with different weights of food samples. Therefore, different types of meat with different weights should be examined in the following studies and deep learning can be employed for better analysis of the relationship between food spoilage and the proposed gas concentrations.

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