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# 음식물 신선도 모니터링을 위한 풀 패시브 UHF 스마트 센서 태그

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# A fully UHF-powered smart sensor tag in food freshness monitoring

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**요 약** 본 연구는 915MHz의 UHF (Ultra High Frequency) 대역에서 RF 에너지 하베스팅 기술을 이용하는 풀 패시브 스마트 센서태그 개발을 목표로 한다. 다양한 방사 조건에서 전력수집을 최적화하기 위해, 최대전력점추적(MPPT: maximum power point tracking)을 활용하는 효율적인 에너지 하베스팅 모듈이 사용된다. 특히 제안하는 태그는 에너지 획득과 데이터 전송 능력 향상을 위해 두개의 직교 안테나를 사용한다. 실험 결과 개발된 스마트 센서태그는 4m 거리에서 DC 3.6V 출력을 위해 0.19mW 정도의 낮은 입력 RF 전력을 획득 할 수 있음을 보인다. 더욱이 제안하는 스마트 센서태그는 저전력 센서어레이로 2m 거리에서 무전원 식품 신선도 모니터링을 완벽하게 실현가능하다.

• 주제어 : RF 에너지 하베스팅, RF 동력, 원거리 RF 에너지 하베스팅, 스마트 센서 태그, 식품 신선도 모니터링

**Abstract** This study aims to develop a fully passive smart sensing tag utilizing RF (Radio Frequency) energy harvesting technology at UHF (Ultra High Frequency) band of 915MHz. To optimize the power collected under various radiated conditions, an efficient energy harvesting module exploiting a boost circuit with maximum power point tracking (MPPT) is employed. Specifically, the proposed tag features two orthogonal antennas to enhance its capability of both energy scavenging and data transmissions. The experimental result shows that the developed smart sensor tag can scavenge an RF input power of as low as 0.19mW at a distance of 4 meters for a 3.6Vdc output. Furthermore, the proposed smart sensor tag performs the feasibility of completely autonomous monitoring food freshness at 2 meters with a low-power sensor array.

• Key Words : RF energy harvesting, far-field RF energy harvesting, smart sensor tag, food freshness monitoring

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## Ⅰ. Introduction

The growing interest in wireless sensor network and IoT applications has driven a lot of research into the scope of energy harvesting towards an extendable sector of applications [1], [2]. The combination of smart nodes which are able to interface with standard wireless communications standards and energy harvesting capability has shown vital to the development of both technologies [3]. Among these, RF-powered devices are emerging as promising solutions over the last two decades [4] to overcome the limited internal energy sources for the autonomous operation of wireless sensor nodes.

Typically, an RF energy harvesting network includes the energy harvesting zone in which the RF-powered devices are illuminated by energy transmitters and the information transmission zone where the devices wirelessly communicate with information gateways. A number of radiation sources can be the energy sources, including cellular base stations, wireless routers, radar, satellite transmitters, FM/AM transmitters, and dedicated RF sources. The operating frequencies in the network can vary from 300 GHz to as low as 3 kHz [5].

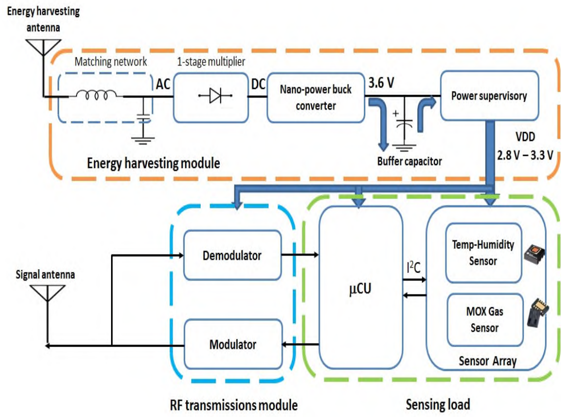
Among various RF energy harvesting technologies, wireless power transfer (WPT) has become a popular trend of wirelessly supplying power to wireless nodes. This technology mostly makes use of LF (low frequency) or HF (high frequency) bands, to magnetically couple the magnetic field of the source for powering the node. Although the power transfer efficiency can reach up to 50% [6], the transmission distance between the source and the node is limited to less than one wavelength of the signal to be transmitted [7].

Far-field RF energy harvesting is an alternative technique to resolve this limitation. The RF energy is extracted from the propagation waves instead of inductive coupling, resulting in an extended distance from the source. One of the major challenges of far-field energy transmission is a very low RF power density at the terminal, since the propagation energy drops off significantly when the distance increases. Theoretically, it drops at the rate of $1/d^2$, where d is the distance from the source [8]. With multi-path fading, the power density falls off at a much faster rate than $1/d^2$. Therefore, the energy harvesting system of the node must be able to capture very low input power in microwatts and convert them to a sufficient voltage level for the node operation. To overcome this issue, a multi-stage multiplier is normally used to output the required dc voltage. However, multi-stage multipliers can be bulky, causing more power loss due to voltage drops on rectifying diodes, degrading their performance [9].

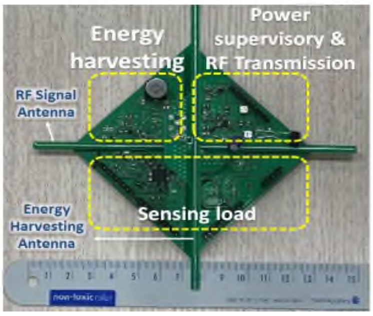
This paper aims to present a fully RF-powered smart sensor tag utilizing far-field RF energy harvesting technology at UHF band of 915 MHz, where all the components are selected and jointly optimized to obtain a good harvesting performance within a distance of 4 meters. This work also proposes a novel antenna system of two orthogonal antennas for improving simultaneous energy scavenging and data transmissions capability of the tag. The combination of a nano-power DC-DC converter and an appropriately configured mode of a complex sensing load allows the full operation of the proposed tag in 2 meters.

## Ⅱ. Materials and Methods

Figure 1 shows the overall structure of the proposed smart sensor tag. It is comprised of four sub-systems: (1) an antenna system, including two orthogonal antennas, (2) an energy harvesting module which extracts energy from the received radio waves to supply to the load, (3) an RF transmission module for wirelessly communicating with a UHF reader, and (4) an ultra-low power sensing load to collect the environmental conditions. The tag is designed to operate in UHF band of 915 MHz. These different modules will be discussed in more details in the following sections.




(a)

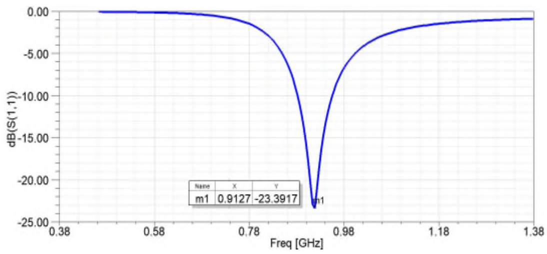



(b)

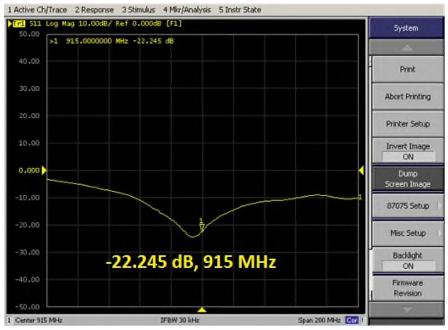
Fig. 1. Structure of the smart sensor tag: (a) block diagram, and (b) tag fabricated prototype

## 2.1 Antennas

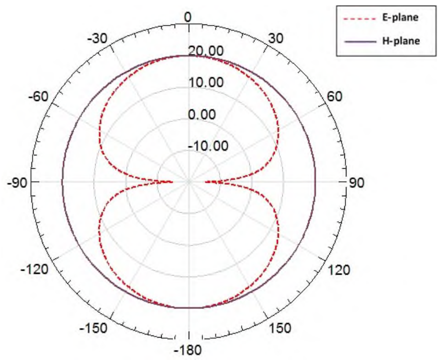
Antenna is an essential part of the sensor tag for harnessing the ubiquitous RF energy and converting it into a useful power. We chose dipole antennas in this paper due to their good performance in radiation efficiency, both in transmitting and receiving radio waves. The width, length, and space between two arms of the antenna are optimized using Optimetrics tool (Ansoft HFSS) for tuning the antenna to the required resonant frequency of 915 MHz and to satisfy the expected return loss of lower than -20 dB. The optimized size of each arm is 0.8 mm x 68.98 mm, while the space between two arms is 0.8 $mm^2$. The substrate chosen is FR-4 with a relative permittivity $\varepsilon_r$ of 4.4 and the effective dielectric loss tangent $\tan\delta$ of 0.02. Fig. 2a shows the simulated and measured return loss of the designed antenna, which are -23.4 dB and -22 dB, respectively. The antenna was trimmed following the methods described in [10], giving a good return loss compatible with the simulated one at the operating frequency. The radiation patterns including E- and H- planes are plotted in Fig. 2b. As expected, the antenna has omnidirectional radiation pattern in the horizontal plane with a considerable peak gain of 1.8 dBi. All simulations are implemented using HFSS simulator.




(a)




(b)




(c)

Fig. 2. Antenna performance test and simulation: (a), (b) simulated and measured return loss in dB, and (c) E- and H-field radiation patterns at 915 MHz

Specifically, in order to improve the tag performance in simultaneously scavenging energy and back scattering sensing data, a novel antenna system consisting of two orthogonal antennas is developed for this research. The layout of the proposed antenna system is reported in Fig. 1b. It consists of a harvesting antenna which captures the RF power for the harvesting module, and a signal antenna for communications. These antennas are perpendicularly oriented to each other right at the middle.

The goal of featuring two different antennas is to allow the harvesting antenna to continuously scavenge RF energy without being interrupted for communications as introduced in [11], [12]. The antenna for RF communications is oriented in orthogonal polarization in order for reducing the mutual coupling [13]. Using Optimetrics tool of the HFSS simulator to calculate the best relative position of two antennas, we found that the return loss of the harvesting antenna is even better, -24.6 dB compared with the previous -23.3 dB with that optimized position. Fig. 3 sketches the simulated return loss in case of one or two antennas.

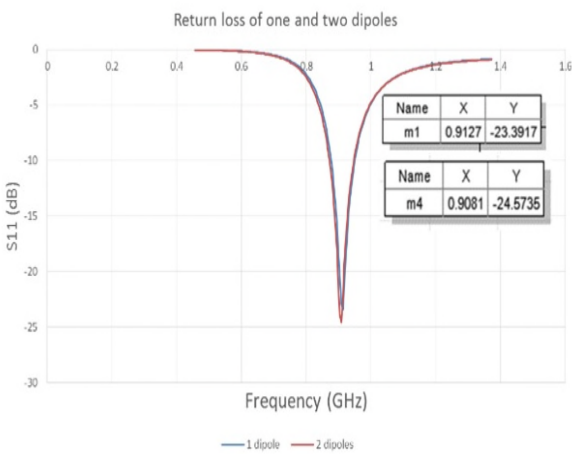



Fig. 3. Simulated return loss in case of one and two orthogonal antennas (m1: one antenna, m4: two antennas)

## 2.2 Energy harvesting module

The module utilizes an impedance matching network, a voltage multiplier, a DC-DC boost converter and a power management circuit (PMC) that control the harvested power delivery to the load. For maximum power transfer of the collected RF energy available at the antenna terminals to the multiplier, an impedance matching network is employed to match the antenna impedance to the multiplying circuit. The network is in L-type topology, including a shunt capacitor and a series inductor.

A Schottky diode-based Dickson voltage multiplier is applied for rectifying and multiplying the peak alternating voltage at the antenna terminals. Schottky diodes are widely used for RF energy harvesting due to its very low forward voltage and low series resistance [14]. This work makes use of Avago's HSMS-285C with 150 mV of forward voltage and 25 of series resistance. Different than our previous studies [15], the number of multiplying stages is minimized to one to make the tag more compact and reduce power loss across diodes. Moreover, single-stage multiplier shows a comparable RF-to-DC conversion efficiency in low power density of available RF environment, according to [16].

An important metric to evaluate the RF harvesting performance is Power Conversion Efficiency (PCE) or RF-to-DC conversion efficiency. It refers to the proportion of the power received at the antenna terminals that is successfully delivered through the rectification circuit to the load [17]. It is defined as the relationship between the absorbed power and the load power as shown in Eq. 1.

$$PCE = \frac{P_{load}}{P_{absorbed}} = \frac{P_{load}}{P_{incident} - P_{reflected}} \quad (1)$$

Figure 4 illustrates the RF-to-DC conversion efficiency and the output dc voltage of the developed multiplication circuit. The load is optimized in ADS software to be 12 kΩ. The circuitry is powered by a 3-W UHF transmitter (Powercast, USA) at varying distances from 0.1 to 4 meters, corresponding to the RF input power ranging from 8 dBm to − 8 dBm. The peak efficiency is 69% by simulated and 52% by measured. The RF input power is the available power measured at the terminals of our fabricated antenna by a Spectrum Analyzer.

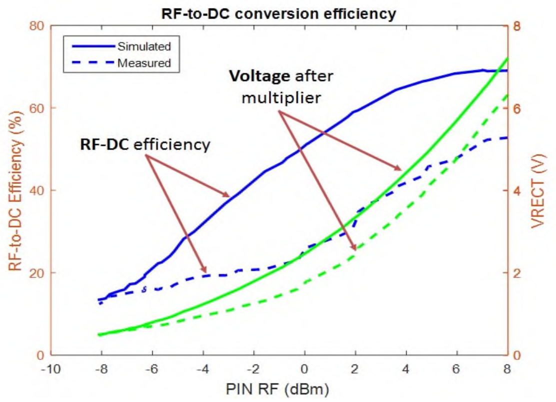



Fig. 4. Simulated and measured RF-to-DC conversion efficiency. Rload is optimized to be 12 kΩ

Both simulated and measured results of the multiplier show that at -8 dBm (0.19 mW) of RF power, equivalent to 4 meters away from the energy source, the proposed tag is able to generate a dc voltage of 480 mV, which represents a practical limit for the chosen DC-DC boost converter (BQ25570, Texas Instruments, USA). This nano-power DC-DC boost converter is configured to output a fixed voltage of 3.6 V with a minimum input of 350 mV. Employing MPPT (maximum power point tracking) technology, the BQ25570 shows its high efficiency of up to 80% when the input voltage is 1.4 V, which can be acquired by the developed harvesting module at -4 dBm (0.4 mW) of RF input power, as reported in Fig. 4.

Consequently, the results in Fig. 4 have shown that the proposed harvesting module is capable of harvesting 0.19 mW RF power in 4 meters to generate 3.6 Vdc for use of applications, enhancing the harvesting performance compared to our last study [18].

## 2.3 RF transmission module

This module is developed to wirelessly communicate with a UHF reader. The demodulator employs an AM (amplitude modulation) envelope detector, which is comprised of a single-stage Dickson multiplier, a RC equalizer, a RC low pass filter and a low voltage comparator (NCS2200, ON Semiconductor, USA). The detector detects the modulated inquiry data sent by the reader. The sensing data from the sensing load, modulated by the modulator, is then back scattered to the reader. All these comply with the RFID air interface protocol for communications at UHF band, known as EPC Radio-Frequency Identity Protocols Generation-2 UHF RFID or EPC C1G2 in short.

## 2.4 Sensing load

The sensing load is comprised of an ultra-low power microcontroller and a sensor array. For the purpose of monitoring food freshness, a temperature-humidity sensor (HDC1080, Texas Instruments, USA) and a metal-oxide-semiconductor based gas sensor (CCS811, ams, Austria) were chosen to sense the environmental changes caused by the degradation of food. The ultra-low power Texas Instruments MSP430FR5969 microcontroller interfaces with the sensor array for data acquisition through I2C interfaces and manages communications with the RF transmission module.

The operating voltage of the load ranges from 2.7 V to 3.6 V. Hence, the PMC in the energy harvesting module, exploiting the ultra-low leakage load switch Texas Instruments TPS22860, is configured to supply a voltage ranging from 2.8 V to 3.3 V.

In addition to lowering its power consumption, the sensing load is programmed to operate in duty-cycle mode with D = 19%, with the total operational time of one single cycle is 291 ms. The average current consumption is measured to be 3.2 mA correspondingly. Hence the buffer capacitor $C_{buff}$ in the PMC which stores and releases the harvested energy should be at least

$$C_{buff} = \frac{Q}{\Delta U} = \frac{I_{average} \times \Delta t}{3.3\,V - 2.8\,V} = \frac{3.2mA \times 291ms}{500mV} = 1.86\,(mF)$$

where Q (Coulombs) is the average charge consumption of $C_{buff}$, $\Delta U$ (Volts) is the voltage drop across $C_{buff}$ during the load operational phase, $\Delta t$ (seconds) is the operational time of one cycle. To ensure a longer term operation for the proposed sensor tag, we chose $C_{buff}$ = 6.8 mF.

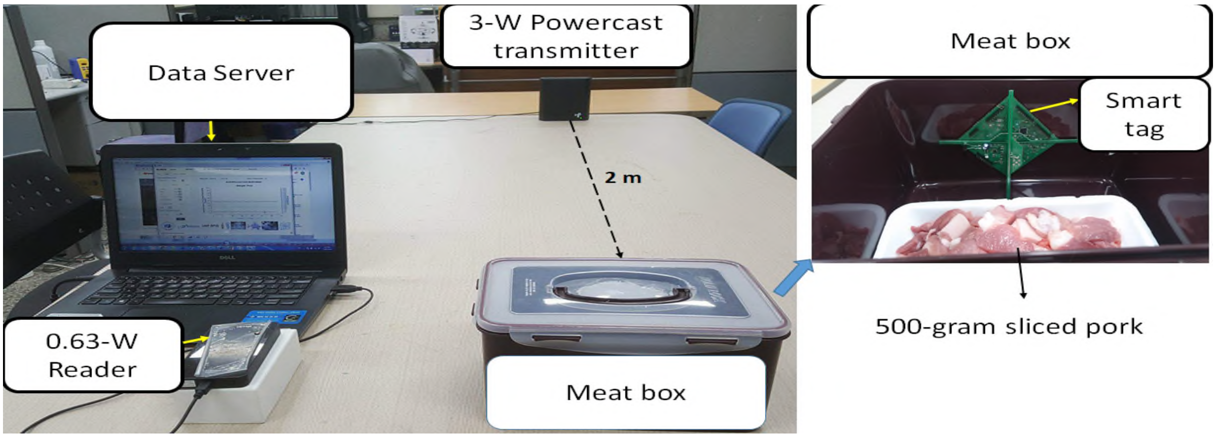



Fig. 5. Experimental set up

## III. Experiments and Results

To evaluate its actual performance, the proposed RF-powered smart sensor tag is experimentally performed for monitoring the decaying process of a food product, represented by the changes in temperature, humidity and equivalent $CO_2$ ($eCO_2$) gas concentration. The food sample is 500-gram fresh pork, packaged in a sealed box and attached inside with a tag prototype. Figure 5 illustrates the experimental set up in laboratory environment to evaluate the food degradation. The smart sensor tag is illuminated by the Powercast Transmitter which emits 3 W power at 915 MHz at a distance of 2 meters. The ams Newton Reader AS3993 is used for wirelessly polling the sensing data from the tag. The reader is completely compliant with the EPC C1G2 RFID standard. A monitor screen is developed to display the captured sensing values on the server, which is shown in Fig. 6.

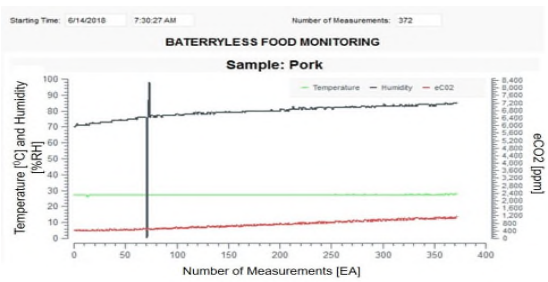



Fig. 6. Monitor screen of sensing data, captured in 12 hours in ambient environment

Two separate food boxes were stored in different conditions, one in ambient environment at 28°C and the other in a refrigerator at 6°C. Each was taken for measurement in 45 minutes x 3 times per day to monitor the changing in humidity and CO2 gas concentration inside the boxes, caused by the natural decay of food quality. Fig. 7 presents these values over 7 days in ambient and refrigerated storage conditions. In case of the food box stored in ambient environment, the humidity reached 90% RH right on the first day, while the equivalent $CO_2$ gas concentration increased rapidly up to 3,000 ppm at the end of Day 1. Correspondingly, the color of the food sample started to change from light pink to darker pink. Since Day 4, it turned to dark pink and the calculated $CO_2$ gas reached its highest value of 8,000 ppm in the sensing range, indicating a total damage on the sample. By the same method, we found that the refrigerated food sample showed much slower decay process. The calculated CO2 concentration reached 3,000 ppm on Day 4, corresponding to a slightly change in the sample color, showing an early indication of food spoilage. It continued to increase up to 7,000 ppm after 7 days. The humidity reached its highest value of 76% RH since the second day and gradually decreased over the remaining days. According to these trends, we propose two timing thresholds in both ambient and refrigeration environments as depicted in Fig. 7, indicating that the food starts spoiling and is not safe to be served.

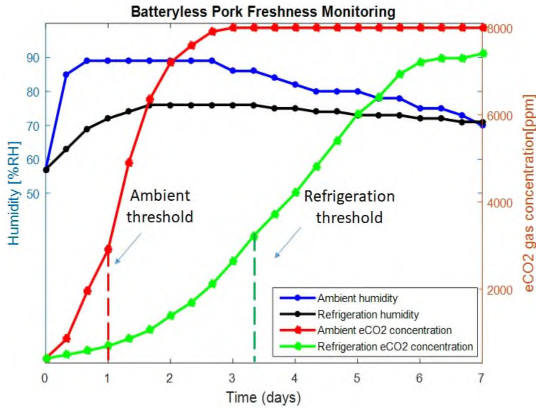



Fig. 7. Humidity and $CO_2$ gas concentration in food boxes stored in ambient and refrigeration environment over 7 days

## Ⅳ. Conclusions

In this work we proposed a fully RF-powered smart sensor tag with autonomous operation capability in 915 MHz UHF band. Temperature, humidity and $CO_2$ gas concentration are acquired and back scattered to the reader using EPC C1G2 RFID standard protocol. A novel antenna system including two orthogonal antennas is introduced to enhance the harvesting performance of the tag. An efficient energy harvesting module, consisting of a dedicated rectifying circuit and a nano-power DC-DC converter with MPPT capability is used to capture a low density RF power at a considerable distance. As a result, the developed smart sensor tag is able to scavenge 0.19 mW RF power at 4 meters to output 3.6 Vdc, and performs fully self-powered operation for sensing ambient environment at 2 meters. In addition, this work presents a non-invasive method of battery-free monitoring the freshness of pork meat, stored in different conditions. The experimental results show an early indication of food spoilage can be detected with this configuration. Finally, the study denoted the feasibility of employing the proposed design to a sensor node in wirelessly monitoring food freshness without the need of batteries.

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