Evaluation of antenna design and energy harvesting system of passive tag in UHF RFID applications

Chengrui Yang

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Evaluation of antenna design and energy harvesting system of passive tag in UHF RFID applications

by

Chengrui Yang

A creative component submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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Program of Study Committee:
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Ames, Iowa
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ABSTRACT

Backscattering communication-based Radio Frequency Identification (RFID) has been essential to the rapid advancement of IoT devices. However, most RFID applications only utilize relatively simple antenna designs. This work contributes in two ways: we investigate the impact of different antenna configurations on a passive network using backscattering technology. In addition, we evaluate the designs of power harvesting technologies valid for Ultra-High-Frequency (UHF) RFID applications. Our evaluations demonstrate that tailored antenna designs can more efficiently achieve application requirements when compared to a simple universal antenna. In addition, we give recommendations on energy harvesters for applications operating in different scenarios.
CHAPTER 1. OVERVIEW

Radio Frequency Identification (RFID) is a wireless technology that uses radio frequency waves to communicate. RFID technology is widely used in multiple application domains due to its high feasibility and low cost. An RFID system usually consists of an interrogator (reader) to send and receive radio signals, and a tag to achieve the task of identification. Tags can be active, semi-passive, or fully passive regarding the utilization of batteries. In this work, we focus on battery-free tag designs of ultra-high-frequency (UHF) RFID applications. Specifically, we evaluate tag antennas, power harvesting systems, and give recommendations regarding the antenna design and selection of power harvesting system when developing battery-free RFID tags in different working scenarios.

1.1 Introduction

Due to the rapid advancement of Internet of Things (IoT) devices, satisfying the need of low energy consumption and low maintenance has become critical. Battery utilization is the primary limiting factor of the active life of applications, as battery maintenance introduces extra human interference and cost. Thus, battery-less RFID tags are becoming mainstream for modern smart applications. Beyond detecting the object which the tag is attached to, making the tag talk to the reader and provide useful information is an advantage that backscattering technology brings to users. Two important considerations, power transmission and tag antenna design, that are closely related to the performance of backscattering RFID are presented in this work.

In a passive RFID system, the RF signal generated by the reader transmits to activate the RF tag, after which information stored in the tag is transmitted back to the reader. This process of communicating through modulation of power reflected by a single antenna is called backscattering. The first use of backscatter communication is Harry Stockman’s work [12]. Today, backscatter communication is commonly used in RFID. To achieve backscatter communication, including sens-
ing and modulating tasks, tags are expected to capture adequate power from incoming signals sent by readers.

The allowable transmission power from a reader is governed by the local regulation: e.g., the European Telecommunications Standards Institute (ETSI) in Europe and the Federal Communications Commission (FCC) in the US. The maximum power that can be irradiated is limited: 2W effective radiated power (ERP) in Europe and 4W effective isotropic radiated power (EIRP) in the US [13]. Thus, the design of the RF front-end (the circuitry between the tag antenna input up to and including the mixer stage) requires careful design in order to fully harvest the limited power. In this work, through an examination of the antenna designs and energy harvesting systems commonly used in the RF front-end of passive UHF RFID tags, we found that a tailored antenna design can more efficiently achieve application requirements when compared to a simple universal antenna. Secondly, we evaluated how three types of power harvesting systems can be utilized to improve performance.

As a significant component in a passive tag, the antenna dominates the dimensions of the whole tag and is closely related to the robustness of communication. However, our research has found that many [14, 15, 16] RFID applications only utilize relatively simple antenna designs. In this report, we investigate applications in the UHF (860 MHz to 960 MHz) band and distinguish tag antenna designs based on an analysis of six featured tag designs with respect to fundamental characteristics. To efficiently achieve RFID application requirements, further optimized combined-structure types of antenna configuration can improve tags with respect to size and operating performance. As previously mentioned, taking full advantage of the energy coming from limited radio waves, power harvesting systems have been introduced in [3, 16] which tend to achieve relatively long working range or rich data transformation based on backscattering technology. Based on a survey of works, we evaluate three energy harvesting technologies and analyze their performance for different working scenarios.

The reminder of this report is organized as follows. Chapter 2 presents three power harvesting technologies available for RFID application and a wide spectrum of tag antenna designs in the light
of current literature. Chapter 3 presents the analysis of six related works of typical antenna designs used in UHF RFID passive tags. From the related works, we show a summary and comparison of these antennas. In Chapter 4, we derive and explain a tailored antenna design that fits tag requirements better. Chapter 5 shows evaluation of three types (RF, body heat, and solar energy) of harvesting systems which can be utilized in the development of passive tags to better meet working requirements.
CHAPTER 2. Related Work

RFID uses an electromagnetic field to identify tags attached to objects. A passive RFID system usually consists of three main parts: an interrogator (reader), a passive tag, and a host computer [17]. Tags serve the function of identification, while readers send a signal and collect a response from tags. In this chapter, we discuss work regarding fully passive tags. As they do not require batteries. In theory, fully passive tags do not require any maintenance and have an infinite operating life, however, the operating range and uplink information is quite limited. Also, in this chapter, we examine three energy harvesting technologies and tag antenna configuration designs available for passive RFID in the light of current literature.

2.1 Energy Harvesting

A passive tag harvests energy from the environment and converts the available energy into electrical energy. Different energy harvesting technologies are used to achieve power capturing and transferring.

2.1.1 Radio Frequency

The basic structure of an RF power harvester, as shown in Figure 2.1, consists of an antenna that captures the incoming radio frequency wave, a rectification circuit that converts RF power to DC voltage, and a power conditioning circuit that delivers voltage to enable load equipment to function properly. For a passive tag, all the energy used to activate the chip is from electromagnetic waves propagated from the reader.

EPCglobal and the International Standards Organization (ISO) are two organizations that approve standards and protocols to provide universal specifications for RFID equipment. The EPC “Gen2” air interface protocol approved as (ISO 18000-6C) defines the physical and logical
Figure 2.1: Description diagram of basic RF power harvester

requirement for RFID systems operating in the 860 MHz – 960 MHz UHF range. According to Mayordomo et al. [13], the power an RF energy harvester can obtain from a certain distance can be theoretically estimated as follows:

\[ P_{rx} = P_{tx} + G_{tx} - FSL - P + G_{rx}, \]  

(2.1)

where \( P_{tx} \) is the RFID reader output power that reaches the antenna; \( G_{tx} \) is the reader antenna gain and \( G_{rx} \) is the tag antenna gain; \( FSL \) are the free space losses for the distance; \( P \) is the polarization mismatch between the reader and tag antennas. Thus, the optimal antenna design and minimum energy loss are important for the RF power harvesting system.

2.1.2 Energy of Light

Besides RF microwave energy, energy of light is an eco-friendly resource that can be converted by photovoltaic (PV) cells to power up RFID applications. The photovoltaic cells are composed of different semiconductor materials that convert light into electricity. The power available for the load converted from the PV cells highly depends on the electrical efficiency. The expression for efficiency of a PV cell [18] can be described as follows:

\[ \eta = \frac{P_{max}}{E \times A_{cell}}, \]  

(2.2)

where \( P_{max} \) is the maximum output power produced by the cell; \( E \) is the incident power of light and \( A_{cell} \) is the effective area of PV cell.

The most efficient type of solar cell to date is a multi-junction concentrator solar cell with an efficiency of 46.0% produced by Soitec and CEA-Leti, France, together with the Fraunhofer Institute for Solar Energy Systems ISE, Germany [19] in December 2014. This cell is extremely
expensive due to the use of exotic materials and is usually utilized to power satellites. In today’s market, the typical conversion of PV cells is within the range of 15% to 20%.

2.1.3 Thermal Energy

Many healthcare-related applications require that tags can be mounted on the human body to sense activities of interest such as temperature and heart rate. Previous work [20] indicates that a typical adult produces approximately 2.4–4.8 W of power in the form of body heat. Harvesting even 1-2% of that power can generate up to 96 mW. A thermoelectric generator (TEG) can be used to harvest electrical energy from human body heat for powering wearable electronics. TEG’s feasibility comes from a phenomenon called the Seebeck effect [21] which can be described by creation of electromotive field.

\[ E_{emf} = -S \nabla T, \]  

(2.3)

where \( S \) is Seebeck coefficient which is a measure of the magnitude of an induced thermoelectric voltage in response to a temperature difference across the material and \( \nabla T \) is the temperature gradient. Thermoelectric materials generate power directly from heat to electric voltage, and consequently they must have high electrical conductivity and low thermal conductivity to obtain good performance. The three major semiconductors used as thermoelectric materials are Bismuth Telluride (Bi\(_2\)Te\(_3\)), Lead Telluride (PbTe), and Silicon Germanium (SiGe). Mayordomo et al. [13] claim bismuth telluride has a Seebeck coefficient around 40 mV/K to 100 mV/K that is utilized in most of the thermoelectric generators.

2.2 Tag Antenna Design

Battery-free RFID tag designs usually pay most attention to the RF front end and digital cores. However, the tag antenna is the largest part of a tag and also requires critical consideration to further improve the durability and cost considerations. In practice, the volume and structure of an antenna can significantly affect the convenience of installment and durability of an RFID tag. For example, the thin dipole antenna in Wireless Identification and Sensing Platform (WISP) [2] is
fragile after fabrication, which, in turn, increases the risk of malfunction. The temperature sensing work done by Bhattacharyya et al. [14] utilizes a T-match antenna, which is effectively a piece of unbendable rectangular copper that would be large and fairly expensive in practice. Reviewing state-of-the-art tag antenna design for UHF RFID applications, we found that the diversity of commonly used antennas is quite large, as well be further shown in Chapter 3.

A Dipole antenna is one of the most popular design option for tags of UHF RFID applications [16, 15]. With only a few exceptions, almost all of WISP based applications do not modify the original design of dipole tag antenna. In the tag design for agricultural applications, Kim et al. [6] utilized an optimized dipole antenna that will be discussed in Chapter 3. Further modified and optimized dipole antennas are dominants among applications requiring reduced size and good versatility [22, 23].

Hoang et al. [24] implement a big circular patch antenna for hazardous material monitoring. In this application, the dimensions of the antenna are less critical because the whole tag is concealed inside a large storage tank. Van et al. [25] have a rectangular, thin copper strap with slots for impedance matching served in a highway toll application. In the “SmartHat” application [5], the tag has a meandered line-based antenna combined with a large metal plate installed inside a construction hat for audio warning functionality. Amendola et al. designed a portable tag [7] with a meandering square loop antenna for human body temperature monitoring. The work done by Mandal et al. [26] has an optimized loop antenna for healthcare applications, with the presented prototype fabricated on a fairly large and rigid substrate. Planar Inverted F Antennas (PIFA) are usually chosen in tags which need to install onto metallic objects [27, 28, 29]. For embedded sensor applications which use standard CMOS processes [30, 31], tag antennas are bonded onto the tag integrated circuit (IC) and printed as small pads located on the corners of the IC.

Both energy harvesting systems and tag antennas play important roles in the design of RFID applications. Multiple energy harvesting technologies such as RF harvester, PV cells, and TEGs, combing with diverse tag antenna configurations provide designers with a high degree of freedom.
of developing desirable tags. In the following chapters, we present in-depth analyses of energy harvester and tag antenna designs.
CHAPTER 3. Evaluation of Six Tag Antenna Designs

In this Chapter, we present an evaluation of tag antenna design based on the analysis of six tag examples in UHF RFID applications including a thin dipole, meander dipole, patch, and three compound optimized types of antenna.

An important metric in this evaluation is antenna gain. For a receiving antenna, antenna gain describes how well the antenna converts radio waves arriving from a specified direction into electrical power. The unit of antenna gain is decibels-isotropic (dBi), which is defined as the ratio of power produced by the antenna from a source on its beam axis to the power produced by a hypothetical isotropic antenna. Due to the fact that antenna gain is highly related to its directivity, a single gain value is calculated as the peak value over all directions. Thus, the standard to determine a tag’s performance with respect to antenna gain deeply depends on the particular application. For example, if the tag is mounted on a fixed object and the reader always sends signal from a specific direction, the value of antenna gain is expected to be large to represent a high electrical efficiency in the fixed transmitting path. However, if the location of reader and tag cannot be fixed or specified (i.e. human body temperature sensing or an objects tracking system), then the incoming signal to the tag is variable in all directions, and consequently highly directional antennas would not be preferable.

3.1 The Wireless Identification and Sensing Platform (WISP)

The Wireless Identification and Sensing Platform (WISP) [2] is a programmable, battery-free, sensing and computational platform designed to explore sensor-enhanced radio frequency identification (RFID) applications. This tag uses a thin microstrip dipole antenna as shown in Figure 3.1.
The detailed parameters for the dipole antenna of the initial WISP developed by the Sensor System Laboratory at the University of Washington is not publicly available. However, according to the principle of dipole antenna as a half wavelength antenna, WISP is designed for a long range RFID communication. Given that its operating frequency is within the UHF band at 915 MHz, the total length of this dipole antenna is around 15 cm. The tag integrated circuit (IC), which contains RF power harvester and digital logic, is located at the middle of the dipole antenna. The height of the tag can be observed from Figure 3.1 as approximately half the diameter of a US quarter 24.3 mm. The total dimensions of the tag are about 150 mm * 13 mm. The simple and compact microstrip dipole antenna makes tag achieve received antenna gain as 2dBi and the maximum operational range is about 4.3 m. The average operating power is -9.5 dBm.

3.2 RAMSES: RFID Augmented Module for Smart Environment Sensing

Donno et al. [3] present a fully passive device with sensing and computation capabilities conceived to explore novel and unconventional RFID applications. This work achieves a long operating range (up to 10 m) using a very large tag. The design requires two antennas: one whip antenna, as shown in the Figure 3.2, is used for power harvesting, and a meander dipole antenna printed on the PCB, which is used for communication between the tag and the reader. However, the design of the RFID antenna has been carefully designed and shows up in other similar passive tag designs [32, 33]. The analysis of this certain type of antenna is presented in Chapter 4.

In Figure 3.2, a fabricated prototype of RAMSES with dimensions: 80 mm * 80 mm * 50 mm is shown. The antenna on the left (used for power harvesting) is a 50 Ω whip antenna. The antenna used for communication is of size 75 mm * 17 mm and achieves 1.8 dBi realized gain and -18 dB reflection coefficient at 866.5 MHz. The operating threshold is -17 dBm.
3.3 Operability of Folded Microstrip Patch Tag Antenna

Conductive materials create challenges for applying RFID technology, since they affect radiation properties, including changing radiation pattern and shifting resonance frequency [34]. Ukkonen et al. [4] present a novel folded microstrip patch-type tag antenna which is verified to be operable when it is affixed to a package containing metallic foil. The paper indicates implementing a conventional dipole-type antenna on a metallic foil wrapped object (i.e. cigarette case) results in 0 meter operating range. Also, some existing metallic application-specific tag antenna designs are not practical for identification of retail packages. Therefore, the authors designed a folded patch antenna as seen in Figure 3.3. The dimensions are $a = 63 \text{ mm}$, $b = 61 \text{ mm}$, $c = 32 \text{ mm}$, $d = 178 \text{ mm}$, and $e = 87 \text{ mm}$. In this photo, the left object is the radiating patch and the object on the right is the ground plane. The overall area of this tag antenna is $271 \text{ mm} \times 87 \text{ mm}$ but in the experiment, the ground patch is folded and the two patches are wrapped around and attached to the opposite side of the object of interest. At 915 MHz, the tag antenna achieved 3.9 dBi of antenna gain and maximum 1.15 m of operating range. The tag’s operating power is not disclosed in [4].
3.4 SmartHat: A Battery-free Worker Safety Device Employing Passive UHF RFID Technology

“SmartHat” [5] is a battery-free safety-critical application which is designed to be integrated into plastic, hard hats-commonly used in the construction industry. This device produces an audible warning alert when the worker is close to a specific piece of equipment. With the RF energy harvester, the antenna achieved 16.46 $m$ of operating range. This tag antenna operates over the 902-928 MHz band. The antenna design contains two parts, as seen in Figure 3.4. The right side V-shaped meandered line segment serves as an optimized dipole antenna. The left side is a large copper plate used as the ground plane for RF components that can help minimize interaction between the RF components and the antenna itself. The overall dimensions of this antenna are 76 $mm$ * 105 $mm$. It achieves 0 dBi of antenna gain. To achieve 16.46 $m$ of reading range, the tag requires -8.48 dBm minimum operating power.
3.5 An RFID-enabled Inkjet-Printed Soil Moisture Sensor on Paper for “Smart” Agricultural Applications

A cost-effective, battery-free work [6] presents an RFID-enabled, passive soil moisture sensor fabricated on paper substrate for agricultural application. As shown in Figure 3.5, the whole tag is integrated with a dipole-like antenna and a printed interdigitated capacitor (IDC), and is printed on a low cost paper substrate. The IDC is used to modify the backscattered signal sending to the reader, depending on the moisture level of detected soil. The multi-fingered rectangle, located at the bottom, is the IDC and the fingers are used to optimize the sensor’s sensitivity. Due to the tag’s low cost and simple structure, it is eco-friendly and easy to manufacture. The antenna was designed based on the half-wavelength (λ/2) dipole antenna. The rectangular termination patches, which introduce additional inductance, were placed to miniaturize the antenna. The length of the proposed antenna was 88 mm which was only 0.27λ (54% of the length of half-wavelength dipole antenna) while the length of the half-wavelength dipole antenna is supposed to be 164 mm. The dimensions of the fabricated tag are 100 mm * 80 mm. According to the experimental results, the reading distance is 0.6 m. The calculated total gain of the antenna in free space, the dry and wet soil are 1.11 dBi, 1.26 dBi, and 0.56 dBi. The measured minimum required transmitting power at 915 MHz varies according to soil moisture. As the soil moisture increases from 0% to 20%, the required operating power increases from 16.5 dBm to 30 dBm.

![Figure 3.5: Geometry of RFID-enabled sensor (reprinted from [6]).](image-url)
3.6 Design, Calibration and Experimentation of an Epidermal RFID Sensor for Remote Temperature Monitoring

Amendola et al. [7] present a RFID sensor that contains a flexible, loop-type antenna and a microchip embedded on a biocompatible membrane which can be directly mounted onto human’s skin for temperature sensing. This application shows a good example of healthcare applications that need to closely interact with humans. For healthcare related RFID applications, the antenna needs to be carefully designed to take into account safety, comfort and energy loss caused by human tissue. The tag antenna designed in this work is based on a flexible, adhesive-backed, copper foil. Figure 3.6 shows the structure of the tag. The meandering loop with other RF components are mounted onto a 600 \( \mu m \) thick biosilicon membrane. A square hole shown in the middle of the membrane is pre-carved to ensure the direct contact between the temperature sensor and human body skin. The top layer of medical tape is used to protect the tag. The tag has relatively compact dimensions of 50 \( mm \) * 25 \( mm \) with a measured antenna gain 7 dBi. In fully passive mode, the tag achieves 0.7 \( m \) operating range. The power threshold to enable temperature sensing is -4.5 dBm.

![Figure 3.6: Descriptive diagram of temperature sensing tag on the left and fabricated prototype on the right (reprinted from [7]).](image)

3.7 Characterization of Studied Tags

In Table 3.1, we summarize fundamental characterizations of the tag antennas for the 6 cases we discussed, including volume, antenna received gain, and return loss. Also, the operating range
and power are shown as descriptions of the entire tag’s performance. In addition, the column of operating power in the table means the minimum power received to activate the tag.

One observation is that introducing the property of meandering helps to reduce the surface area of an antenna. Also the meandering line makes the tag have a rectangular configuration allowing for easier installation on the object of interest. Considering the antenna gain, we found the optimized loop antenna in the human temperature monitoring application achieved received gain as 7 dBi which is the biggest among the six cases. The relatively large antenna gain indicated that the tag antenna’s performance is deeply related to the direction of incoming signal from the reader. Since the tag is designed to monitor temperature as a human-involved healthcare production and supposed to attach directly to the individual person, the unpredictable position of tag will affect the ability of receiving RF energy. Furthermore, the extremely small operating power (-75 dBm) required by the temperature sensor would increase dramatically with changing position of reader and tag. The compact volume of this meandered loop antenna plus its flexible property represents a good example in healthcare-related applications. However the operating range of the temperature sensor is quite limited.

The two applications which reach the operating range beyond 10 m both have meander structure and dipole configuration in their antenna design. RAMSES is designed based on a commercial
ALN-9660 RFID tag which is a meander dipole with rectangular patches at the tips. The one in “SmartHat” has a V-shaped meander line. We believe that the combination of dipole and meandering line can bring satisfactory performance for passive RFID tags. A further optimized meandering dipole will help the tag meet more stringent operating requirements easier.
CHAPTER 4. Tag Antenna Comparison and Recommendation

After reviewing common tag antenna designs in the current literature, we identified four points that should be considered when developing a passive RFID tag:

1. Planar layout, without slender lines - to reduce fragility
2. Compact size - for low cost
3. Omnidirectional radiation pattern - for better communication performance
4. Relatively long range communication

In this chapter, we first investigate the fundamental characteristics of simple dipole and meander line antenna. Then, we present an antenna design that takes cues from a commercial design and demonstrates the advantages of using this type of antenna for potential portable RFID tags.

4.1 Methodology of Antenna Analysis

For this analysis of antenna designs, we used Keysight ADS Momentum which is the leading 3D planar electromagnetic (EM) simulator used for passive circuit modeling and analysis [35]. Based on a design note from Texas Instruments [36], we modeled two antennas through ADS and demonstrate the advantages of applying meandering line technology to tag antennas. In addition, detailed analysis of tag antenna configuration refers to the application note from NXP Semiconductors [8].

4.2 Dipole Antenna

The dipole antenna is one of the simplest antennas commonly used in the domain of UHF RFID applications. Figure 4.1 demonstrates a basic dipole antenna. The size of the antenna from end-to-end will approximately be half the wavelength of the desired operating frequency; consequently
each arm will be a quarter of the wavelength. For example, at 900 MHz within the UHF band, the resulting wavelength is approximately 33 cm and thus the entire length of a dipole antenna is about 16 cm (8 cm for a single arm of antenna). Since the center frequency of UHF band in North America is 915 MHz and 866 MHz in Europe, the resulting length of dipole antenna does not exceed 20 cm.

![Figure 4.1: Concept of a simple dipole antenna](image)

The typical radiation pattern for a dipole antenna in three dimensions is a donut-shaped radiation pattern, which indicates that dipole antennas are very close to an ideal isotropic antenna. The property of omnidirectional radiation is desired for most RFID applications. Due to the two advantages (simplicity and omnidirectional radiation) mentioned above, dipole antennas are widely used for RFID applications that tend to achieve low cost and straightforward implementation.

### 4.3 Meander Line Antenna

Meander line antennas have been widely studied in order to reduce the size of the radiating elements in wire antennas: monopole, dipole and folded dipole type antennas. Misman et al. [37] indicated increasing the total wire length in antenna while keeping the axial length fixed lowers its resonant frequency. Thus, the meandering line antenna can be relatively optimized through modifying the design parameters related to each turn.

Figure 4.3 shows geometry and simulation results including reflection coefficient and radiation pattern of a Meandering Inverted-F antenna. Figure 4.5 shows geometry and simulation results including reflection coefficient and radiation pattern of an Inverted-F antenna without meandering property.
Comparing these two inverted-f antenna designs, it can be observed that meandering line helps reduce the volume of the antenna but doesn’t affect the potential reflection coefficient and radiation pattern.

In the previous chapter, we found the tag antennas designed in “RAMSES” [3] and “Soil moisture sensor” [6] both have loops in the middle of the antenna. To figure out how the loop affects the performance of the entire tag antenna, we found an application note produced by NXP Semiconductors that provides a practical consideration of UHF label antenna design [8]. As seen in
Figure 4.6, it is a typical commercial label antenna for UHF RFID applications. The label antenna consists of a loop in the middle and meandering dipole arms.

Figure 4.6: Label antenna FF95-8 G2X by NXP Semiconductors (reprinted from [8]).

The application note shows a simulation of parametric read range regarding different loop size as shown in Figure 4.8(a). Notice that the legends represent “delta loop” which is compared with the original design of FF95-8 Dipole antenna in Figure 4.6. It can be easily observed that the resonance frequency is decreasing as the loop size is increasing. Therefore, at the desired frequency, the operating range can be optimized through tuning the dimension of the loop. Specifically, in UHF RFID applications with loop-dipole tag antenna, improved reading range can be achieved by decreasing the loop size.

Figure 4.8: (a) Read range vs. loop area. (b) Read range vs. change of dipole arms. (reprinted from [8]).

Due to the fact that a dipole antenna is a half-wavelength antenna, the total length of the meandering aspect is supposed to equal $\lambda/2$. However, the meandering line design can be variable (i.e. the number of turns). The application note also indicates that the change in the length of the meandering dipole arms affects the antenna’s performance. A simulated read range as a function
of the length of the dipole arms is shown in Figure 4.8(b). Note that the legends represent “delta length” which compare to the original design of FF95-8 Dipole antenna. This figure clearly presents that using a fixed frequency, operating range can be improved through increasing the axial length at the meandering dipole arms. To do so, one can decrease the length of each turn of the meandering parts while keeping the wire length.

Because a dipole antenna has a simple structure and expected radiation pattern, meander line helps reduce size, combining both types theoretically produces a better result for tag’s performance with respect to the four design considerations mentioned in the beginning of this chapter. Figure 4.9 gave a possible pattern for a tag antenna design that takes design cues from a commercial ALN-9662 Short Inlay by Alien Technology [38] due to the following reasons:

Figure 4.9: Recommended candidate of tag antenna

- The center loop primarily impacts the tuning of the real part of the input impedance and prevents potential high voltage discharge.
- The meandered line reduces the size.
- The rectangular termination patches which introduce additional inductance that facilitate the impedance matching and were placed to miniaturize the antenna.
- The entire tag antenna has a symmetrical pattern in rectangular shape so that it can be easily integrated with other components on the object of interest.

All in all, this antenna pattern combined all four aspects as mentioned above to provide a tactic of volume reduction and an easier way to do impedance matching. Depending on the actual
tag design, the designer is recommended to combine any of those aspects to optimize the antenna design.
CHAPTER 5. Evaluation on Energy Harvesting System in RFID Technology Based Applications

In this chapter, three methods of energy harvesting systems available in RFID applications are presented: RF power harvesters which harvest electromagnetic waves; thermoelectric generators which harvest heat energy; and photovoltaic cells which capture photon energy.

5.1 RF Harvester

Usually, due to path loss in signal transmission, the power that can be utilized by the tag is quite limited (µW to mW). To improve operating range and communication robustness, an efficient system for converting incoming RF energy to DC power is significant in the development of tags. In the following subsection, we introduced the construction of RF power harvester through two examples.

5.1.1 Wireless Identification and Sensing Platform

Figure 5.1: Schematic of WISP power harvesting circuit. (adopted from [2])
In the WISP [2], the power harvester, as seen in Figure 5.1, consists of a dipole tag antenna, a matching network helps maximum power transfer from the antenna to the rectifier, and a five stage voltage-doubling circuit that converts the incoming RF power to DC voltage. Then, the DC voltage is stored in a large storage capacitor following the rectifier and supplies an 1.8 V regulator to power the platform.

The dashed block in the figure shows the structure of a DC voltage doubler circuit. The working mechanism is as follows: during the negative half cycle of the sinusoidal input waveform, diode D1 is forward biased and conducts charging up the capacitor, C1, to the negative peak of the AC input. Because there is no return path for capacitor C1 to discharge into, it remains fully charged acting as a storage device. During the positive half cycle, diode D1 is reverse biased, blocking the discharging of C1 while diode D2 is forward biased, charging up capacitor C2. But because there is a voltage across capacitor C1 already equal to the peak input voltage, capacitor C2 charges to twice the peak voltage value of the input signal (half from the C1 and half from the input voltage).

5.1.2 RAMSES: RFID Augmented Module for Smart Environmental Sensing

![Figure 5.2: Block diagram of RF power harvester in RAMSES. (adopted from [3])](image)

RAMSES [3] provides both a battery assisted mode and a fully passive operating mode. Here, only fully passive mode is considered. As shown in Figure 5.2, the energy harvester contains a 50 Ω whip antenna used to capture the incoming microwaves. Before the rectifying circuit, there is an LC matching network made of a high-Q RF inductor and a high-Q ceramic trimmer capacitor to make the input impedance of the antenna be a complex conjugate of the input impedance of
the rectifier in order to achieve the maximum power transfer to the rectifier. Then, a single-stage full wave rectifier, made of two Skyworks SMS7630 zero-bias Schottky diodes is applied to convert UHF RFID energy transmitted by the reader into DC power. Note that the capacitor connected to the rectifier is used to convert the full-wave ripple output from the diodes into a smoother DC output voltage.

A Seiko Instruments S-882Z24 charge pump IC is used to store and efficiently release the rectified voltage to power the digital (MCU and sensors) and RFID sections. The output voltage from the rectifying circuit is generally too low to directly power up the application. Also, the output voltage is not stable and will change with changing input power. A DC-to-DC converter can adapt the rectified voltage to desired voltage. The electric power is accumulated in the big storage capacitor. When the capacitor reaches 2.4 V, the DC-to-DC charge pump automatically releases the energy to the 1.8 V voltage regulator that is connected to a microcontroller. The linear voltage regulator is used to convert a variable input voltage to a continuously steady and low-noise DC output voltage. Generally, linear voltage regulators need a large voltage drop between the input and output voltage but since the power budget is this application is low, a low dropout (LDO) voltage regulator is used because it can work well even when the output voltage is very close to the input voltage. The RF harvesting system helps the tag in fully passive mode achieve 10 m of operating range—one of the longest operating ranges of passive tags. With external battery assistance, RAMSES achieves 26 m reading range.

In contrast to WISP, where the rectifier mainly consists of a five-stage voltage doubler circuit that is made of Schottky diodes and capacitors, RAMSES uses a rectifying circuit consisting of a single-stage rectifier and a DC-to-DC charge pump. Reducing the number of diodes in the rectifier stage, reduces the power dissipated in each diode due to the parasitic resistance of practical packaged diode. The reading range of RAMSES is approximately 10 m comparing to 4 m that WISP achieved. While, the WISP maintains a compact size 150 mm * 20 mm and RAMSES has dimensions of 80 mm * 80 mm including one extra antenna for RF energy harvesting leading to higher cost and 3-dimensional structure with 50 mm height.
5.2 Photovoltaic Cell Energy Harvesting

Solar energy is a type of eco-friendly and sustainable resource that can be harvested and converted to satisfy power consumption for daily life. It is a popular topic and continuing to grow. In [1], M. Mackay theoretically summarized a table, as seen in Table 5.1, which describes several sustainable power generation technologies with respect to their power density in the area of continental USA. The technology density is measured in the following method: for example considering bioethanol, energy is derived from each acre of crop that can be fermented into bioethanol. It can be observed that solar energy has remarkably higher power density $25 \text{ W/m}^2$ comparing to the others.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Power Density $\text{W/m}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>25.0</td>
</tr>
<tr>
<td>Bioethanol</td>
<td>0.25</td>
</tr>
<tr>
<td>Petroleum</td>
<td>0.15</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Table 5.1: Estimated power density of several energy technologies. (adopted from [1])

To get realistic measurement on the density of solar energy within a specific area, we found information from the NASA Surface Meteorology and Solar Energy website [39]. For example, the average energy density obtained in the area of Ames, Iowa during 22 years (1983-2005) is 160 $\text{W/m}^2$. Note the $25 \text{ W/m}^2$ takes 10% typical power conversion efficiency of PV cell into account. Thus, the average solar energy density in Ames, Iowa is $16 \text{ W/m}^2$ taking 10% power conversion efficiency into account.

The significantly higher power density of solar energy is a great sign. However, the efficiency of converting solar energy to usable power is critical. Photovoltaic Cells (PVC) are generally used to capture and convert the solar energy. In previous research work [40], widely used PV cells based on crystalline silicon with single p-n junction have a theoretical limiting power efficiency of 33.7% and state-of-art multijunction samples with concentrators can yield up to 44.4% taking into
account the packing ratio, the realistic PV device conversion efficiency is between 17% and 20% for commercially available Si-based solar cells.

Interior lighting is a source of energy inside the buildings. In a typical US office environment with fluorescent lighting, approximately 0.25 W/m² can be available for PV energy harvesting after taking into account 10% conversion efficiency. For interior lighting, specific PV cells should be used because the interior lighting spectrum is significantly different than the outdoor spectrum. Semiconductors such as Cadmium telluride (CdTe), Cadmium sulfide (CdS), and Gallium antimonide (GaSb) are better materials for PV cells due to lower semiconductor band gaps.

Figure 5.3: Configuration of the energy harvesting system using PV cell. (reprinted from [9])

Nasiri et al. [9] present a harvesting system using PV cells as seen in Figure 5.3. Due to the variation of environmental temperature and incidental light radiation, the power harvested from the PV cells is not constant. The target system should not be directly powered by the PV cells. Thus, there has to be an efficient way to store the harvested energy and deliver the energy to the load. There is always an optimal operating point with specific current and voltage values, at which the power extracted from the cell is maximized. To maintain the optimal operating point, a DC-to-DC converter providing a stable and constant voltage to the load needs to be installed between the PV cell and the storage elements. The choice of the DC-to-DC converter depends on the operating voltage of the chosen storage elements and the load.
5.3 Thermoelectric Generator Energy Harvesting

A thermoelectric generator (TEG) can be used to harvest electrical energy from human body heat for powering wearable electronics. As previously mentioned, previous work [13] indicates that Bismuth Telluride is a material that has a suitable Seebeck coefficient—a measure of the magnitude of an induced thermoelectric voltage in response to temperature differences across the material around 40 mV/K to 100 mV/K that is utilized in most thermoelectric generators. Since the difference in temperature is the key making a TEG work, ensuring a relatively big temperature difference is significant to obtaining enough power. Figure 5.4 shows reported human skin temperatures for different points on the body at varying ambient temperatures according to previous work [10]. It can be easily observed that the temperature difference between environment and most parts of human body is larger than 10K in a normal day.

<table>
<thead>
<tr>
<th>Skin Location</th>
<th>Cold (11°C)</th>
<th>Room (27°C)</th>
<th>Hot (47°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forehead (A)</td>
<td>31.2</td>
<td>35.1</td>
<td>36.1</td>
</tr>
<tr>
<td>Back of Neck (B)</td>
<td>30.1</td>
<td>34.4</td>
<td>35.8</td>
</tr>
<tr>
<td>Chest (C)</td>
<td>30.7</td>
<td>34.6</td>
<td>36.3</td>
</tr>
<tr>
<td>Upper Back (D)</td>
<td>29.2</td>
<td>33.7</td>
<td>36.6</td>
</tr>
<tr>
<td>Lower Back (E)</td>
<td>29.0</td>
<td>33.8</td>
<td>35.7</td>
</tr>
<tr>
<td>Upper Abdomen (F)</td>
<td>29.2</td>
<td>34.8</td>
<td>36.2</td>
</tr>
<tr>
<td>Lower Abdomen (G)</td>
<td>28.0</td>
<td>33.2</td>
<td>36.6</td>
</tr>
<tr>
<td>Thigh (H)</td>
<td>26.9</td>
<td>34.0</td>
<td>37.0</td>
</tr>
<tr>
<td>Forearm (I)</td>
<td>23.7</td>
<td>33.8</td>
<td>36.7</td>
</tr>
<tr>
<td>Hand (J)</td>
<td>26.5</td>
<td>32.2</td>
<td>36.8</td>
</tr>
<tr>
<td>Hip (M)</td>
<td>27.3</td>
<td>33.0</td>
<td>36.5</td>
</tr>
<tr>
<td>Side Thigh (N)</td>
<td>26.4</td>
<td>33.7</td>
<td>36.7</td>
</tr>
<tr>
<td>Front Thigh (O)</td>
<td>25.5</td>
<td>32.2</td>
<td>36.0</td>
</tr>
<tr>
<td>Back Thigh (P)</td>
<td>25.1</td>
<td>31.6</td>
<td>35.9</td>
</tr>
<tr>
<td>Calf (Q)</td>
<td>23.2</td>
<td>30.4</td>
<td>36.2</td>
</tr>
</tbody>
</table>

Figure 5.4: Reported human skin temperatures for different points on the body. (reprinted from [10])

TEGs-based technology is a good option for healthcare-related applications or for the working scenario where large temperature differences can be sustained. Kim et al. [41] present a wearable TEG in fabric for use in clothing. The device has a size of 0.6*2.5 cm$^2$ and generates 224 nW (power density is about 1.5 nW/cm$^2$) for temperature difference of 15 K. To enhance the comfort of the wearable device, the TEG material is planted into the fabric leading to a low power density. The typical power density of TEGs is 0.2 W/m$^2$ ($2\times10^{-5}$W/cm$^2$). In previous work, Hyland et al. [42] present a wearable TEG device with optimized heat spreaders made of copper sheets bonded
with a thin layer of polydimethylsiloxane (PDMS) which achieves output power density 6 $\mu W/cm^2$ at no motion and 20 $\mu W/cm^2$ at normal walking speed.

Figure 5.5: Block diagram of thermoelectric energy harvesting powered wireless sensor network. (adopted from [11])

Wang et al. [11] give an example of implementing TEG modules to achieve power harvesting for a wireless sensor network. Figure 5.5 shows the block diagram of thermoelectric energy harvesting powered wireless sensor network. According to Figure 5.5, the wireless sensor network system consists of five parts. TEG modules are used to harvest thermal energy and convert it to electric power. Since the output voltage of most of TEGs is less than 500 mV, an Ultra-low voltage step-up DC-to-DC converter with low minimal start-up voltage is used to adapt the harvested power. Electrical double layer capacitors (known as SuperCaps) are used to store the harvested energy. An Output power regulator (Here they used a buck–boost converter which is a type of DC-to-DC converter with an output voltage magnitude either greater than or less than the input voltage magnitude.) is used to deliver constant voltage to the load. The wireless sensor network module is connected at the end.

5.4 Comparison of Three Type of Energy Harvesting

In this section, we summarize power density of RF, photovoltaic cells and thermoelectric generators energy harvesting systems. Next, we compare the three technologies based on their potential performance when implemented into RFID applications.

Table 5.2 below contains the typical value of power density of the three harvesting technology. It can be seen that PV cells have the highest power density, even when the energy source is interior lighting (rather than solar energy). An RF harvester is the least efficient way to convert power when only taking the power density into account.
<table>
<thead>
<tr>
<th>Technology</th>
<th>Power Density $W/m^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF</td>
<td>$1.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>PV cells</td>
<td>16 (Outdoor) 0.5 (Indoor)</td>
</tr>
<tr>
<td>TEGs</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 5.2: Typical power density in three technologies

The RF power density in Table 5.2 is calculated by assuming a 2 W transmitted power distributing to a tag located at 10 m away from the RF transmitter.

Rather than tags, designed based on a thick substrate, the wearable fabric TEG is a great example of a highly flexible fabricated device that satisfies the need of comfort as a contact application. Considering the human body temperature monitor application [7] presented in Chapter 3, we found the operating power requirement is $3.16 \times 10^{-11}$ W. The size of the tag is 5*2.5 cm$^2$. If we implemented a 5*2.5 cm$^2$ TEG module, we could obtain $2.5 \times 10^{-4}$ W which is about eight million times of the operating power needed. Furthermore, $1.9 \times 10^{-8}$ W, which is still about 600 times of the operating power, can be gained if we used the tag sized TEG fabric developed by Kim et al. [41]. Although, the power density of typical TEGs is relatively good and does not require any effort to obtain (waste body heat), the environmental temperature cannot be fixed or expected so the difference in temperature between human skin and environment is not guaranteed. If the environmental temperature is close to human body’s temperature, the TEG would not be functional. Also, for TEG, the heat from the body must be directed into TEG to minimize the transferring loss. It is also hard to make sure the TEG is always in direct contact with a human body. Additionally, the direct contact to human body may cause a possible allergic problem.

Reliability and feasibility are the biggest advantages an RF power harvesting system can bring. Even though the effective obtainable power density is extremely low, especially when comparing to solar energy, RF power harvesters can provide stable energy to applications as long as the reader is able to radiate RF signal. Under some severe conditions, such as dark environment or isolated containers, RF power harvesters can operate reliably despite changes in relative atmosphere.
Due to the remarkable power density, PV cell-based power harvesting systems are most preferred for tag design in RFID applications. Many RFID applications operate outdoors where solar energy is easily captured. For indoor applications, ambient light is usually available and adequate for PV cells to convert to usable power. Also, Schottky diode-based RF harvesters are usually relatively expensive and complicated. PV cells are simple devices that could be integrated into compact passive RFID tags. Considering the applications in Chapter 3, we found the operating power of WISP and RAMSES is approximately $1.1 \times 10^{-4}$ W and $2 \times 10^{-5}$ W respectively. If the PV cells are implemented into WISP, only about $0.07 \, cm^2$ of PV cell is needed to meet the power requirement when the tag works outdoors under sunlight and $2.2 \, cm^2$ of PV cell is needed for tag working indoor with ambient light. If the PV cells is implemented into RAMSES, only about $0.01 \, cm^2$ of PV cell is needed to meet the power requirement when the tag works outdoors under sunlight and $0.4 \, cm^2$ of PV cell is needed for tags working indoors with ambient light.
CHAPTER 6. Conclusion

In this work, we focused on tag designs for battery-free UHF RFID applications. Specifically, we performed an analysis of related works in the research literature that describes energy harvesting systems and tag antennas commonly designed and discussed in recent works. Second, we chose six featured applications to analyze and compare the tag antenna designs. Then, we demonstrated the advantage of utilizing dipole and meandering line combined antenna based on simulation and an application note. Furthermore, we gave recommendations on tag antenna design in UHF RFID applications. We indicated that carefully designed tag antenna can benefit the entire tag to improve the performance. Besides tag antenna, we talked about three energy-harvesting technologies: RF harvesters, thermoelectric generators, and photovoltaic cells. Finally, we analyzed the pros and cons of the three technologies and present our recommendations about the selection of power harvesting systems when developing battery-free RFID tags in different working scenarios.
Bibliography


