Vibration Powered Battery-Assisted Passive RFID Tag

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Abstract. Real-time supply chain management, theft prevention, and environmental monitoring motivate the need for RFID systems. Battery-assisted RFID tags increase read range and reliability; however, batteries offer only a finite lifetime solution. Hence, an experiment in powering a battery-assisted passive RFID tag using ambient vibration energy was conducted. A piezoelectric power generator was designed at a resonant frequency of 52 Hertz, with potential power output of 500 μ W. Manipulation of the electric signal from the generator through a power circuit produced 8mW pulses to the tag, resulting in successful communication with the reader. Power needs were compared to an earlier experiment in powering a Mica2Dot “Mote” showing a 88% decrease in necessary power supply and 90% decrease in charge time.

1 Introduction

The benefits of RFID technology are plentiful. Real-time inventory management results in instantaneous communication across the supply chain from manufacturing to retail thus improving on-shelf availability and reducing excess inventory. Automatic and instantaneous visibility of inventory movement helps manage theft prevention. And finally environmental monitoring of perishable goods in transit are essential for customer safety and satisfaction [1].

Passive RFID tags are a reasonable solution in close range applications. However in situations such as environmental monitoring of pallets passing in transit, close range is not always possible. Read range and reliability are improved with battery-assisted passive tags or active tags. However batteries only provide a temporary solution due to their finite life. An alternative solution is to power these tags using ambient vibration energy. Ambient vibrations provide an infinite life and maintenance free solution in powering battery-assisted passive RFID tags.

The following paper details an experiment in using vibrations to power a battery-assisted passive RFID tag. Results of the experiment are compared to earlier experiments in powering a Crossbow Mica2Dot Mote.

2 A Battery-Assisted Passive RFID System

The system chosen for implementation is the Alien 2.45 GHz battery-assisted passive tag RFID System. The reasons for choosing this system are: the battery assisted tags

enable longer range, the tags include onboard temperature sensor capabilities which provides a solution for environmental monitoring application, and the tags make use of RF energy from the reader.

The tag battery powers the onboard sensor and electronics including microprocessor and assisting the radio. When a tag is interrogated by the reader, the tag will harness RF energy from the interrogation and use some of that energy in responding to the reader. The RF energy from the reader is harnessed and assists in transmission while the battery helps to increase read range. Information is relayed from tag back to reader through backscatter technology. The signal used to interrogate the tag is modulated and used as a carrier wave for data transmission back to the reader.

Fig. 1. Alien's 2.45 GHz Battery Assisted Passive Tag RFID Solution

The results of the Alien system (Alien Technology ALB-2484) have been compared with the results from an earlier experiment for the Crossbow Motes (Crossbow MPR500CA) [2]. The basic functionality of both technologies are the same; they are wireless sensor transceivers. The major differences are that the mote has more memory and greater processing capabilities and does not rely on interrogation from a “reader” to transmit information. Major characteristics are outlined below.

Physical. The size of the two wireless sensors are comparable. Both nodes operate with a 3V Coin Cell although a 3V input is not necessarily required.

Processor. The RFID tag holds much less memory, 4Kbytes compared to 128Kbytes on the mote. The RFID microprocessor is much more simple and has limited programmability, however current draw is only 1.4mA compared to 8mA for the mote during active mode. During sleep mode, current draw is minimal for both nodes.

Radio. The RFID tag is less effective in range at only 30m, one-fifth the range for motes. The benefit of the RFID is that transmission of information takes the form of modulated backscatter. This means that the tag modulates the RF signal from the reader, and when the signal is bounced back, the reader interprets that modulation. Therefore current draw for transmission is greatly decreased, on the tag side. The mote consumes 27mA during transmit and 10mA during receive.

The choice between mote or RFID based system depends on the application. If the user needs the nodes to perform complex tasks, change functionality of the nodes while they are deployed or long range communication, then motes are probably more applicable for the needs of the system. However, if the task at hand is to monitor temperature, pressure, or any other environmental factor, with short range communication then RFID is a sufficient solution. The mote is specified to require 105mW to

sense and transmit, while the RFID is specified to require 4.2mW. Even with the major differences of these two systems they can perform the same basic functionality. An example of a simple system in which either of the two systems may be used is a one hop network, where each of the nodes/tags needs to periodically sample and store the data and then, when interrogated, the data will be transmitted to the base station for processing. The low power usage of RFID, coupled with an energy scavenging power source, is expected to offer a much more reliable long life solution, to low duty-cycle environmental monitoring systems. Hence these experiments shown in Table 1, that compare RFIS with mote performance.

Table 1. Comparison of Crossbow Mica2Dot Mote and Alien Technology Battery-Assisted Passive RFID Tag

	Features	Xbow Mica2Dot Mote (MPR500CA)	Alien RFID Tag (ALB-2484)
Physical	Size	2.5Ø x 0.64 cm	8x2.5x0.64 cm
	Cost in bulk	\$25	\$28
	Battery	3V Coin Cell	3V Coin Cell
	Parts	CPU, A/D converter, memory, radio, antenna, sensor, battery	memory, radio, onboard antenna, digital thermometer, battery
Processor	Memory	128K bytes	4K bytes
	Programming	TinyOS	limited
	Current Draw (active)	8 mA	1.4 mA
	Current Draw (sleep)	15 uA	1 uA
Radio	Range	150 m	30 m
	Current Draw (transmit)	27 mA	--
	Current Draw (receive)	10 mA	--
Power	Sense and Transmit	105 mW	4.2 mW
	Sleep	45 uW	3 uW

3 “Teeny Temp” System Design

The system design (coined “Teeny Temp”) comprises the following major components: a piezoelectric bimorph generator which converts vibrations to electricity, producing an AC signal, power conditioning circuitry which converts the AC signal from the generator to usable DC signal, and RFID Battery-Assisted Passive Tag with on-board temperature sensor.

The goal of the design is to provide enough power to the RFID system to operate the tag: including powering the onboard sensor, powering the microprocessor, and transmitting useful information to the reader. In order to realize this goal the piezoelectric

power generator must first generate enough power, then the power conditioning circuit must be designed to output a usable supply voltage to the RFID tag while most efficiently making use of the power being generated by the piezoelectric generator.

Fig. 2. “Teeny Temp” System Design

3.1 Power Requirements of the Load

The power requirements of the Alien RFID tag must first be characterized in order to design an optimized power circuit. Three important values need to be determined: critical input voltage, critical pulse length, and current draw. Since we are harvesting minimal amounts of energy, the lowest input voltage and current draw necessary is of value. The critical pulse length must be long enough to reliably wake up the tag, sense temperature, process information, wait for an interrogation from the reader, and transmit tag information.

Fig. 3. Alien's Battery-Assisted Passive Tag

Fig. 4. Schematic of Input Pulses to Load from Vibration Power Generator

Experiments were conducted using a function generator to input an offset square wave into the RFID tag. Voltage input and pulse length were varied to find critical values. Results are tabulated below. At a read-range of half a meter, the critical operating voltage is 2V and critical length of pulse is 2.5 seconds. Current draw of the tag varies with a maximum of 0.25 mA. As this current value is much lower than the specified value, further design uses the specified value to be cautious.

Table 2. Specified Versus Experimental Critical Input Values to RFID Tag

		Specifications	Experimental Values
V_C	Critical operating voltage	3V	2V
t_C	Critical length of pulse	--	2.5 sec
I	Current Draw	1.4 mA	0.25 mA

The critical pulse length of 2.5 seconds is a fairly large number compared to the 0.8 seconds needed by the Crossbow Mica2 Dot Mote. The reason for the longer pulse length with the RFID tag is that the tag waits for an interrogation by the reader before it transmits information while the mote automatically transmits to the base station. Furthermore, the operation of the RFID tag relies partially on harnessed RF energy from the reader. The energy is stored by capacitors onboard the tag and the length of time necessary to charge these capacitors contribute to the critical pulse length.

3.2 Power Conditioning Circuit

Once the power characteristics of the RFID tag are known, the power conditioning circuit can be built to optimally output the critical values. A schematic of the power conditioning circuit is shown below. The AC signal produced by the piezoelectric power generator is first rectified, then stored in a capacitor. A comparator monitors the voltage level of the capacitor and when it has reached a value, V_{HIGH} , current is allowed to flow through the regulator. The switch is turned off again when the voltage level of the capacitor has reached a value, V_{LOW} , to allow the capacitor to charge again.

Fig. 5. Schematic of Power Conditioning Circuit with Regulator

The functional requirements of the RFID tag include an input voltage of 2V for a critical pulse length of 2.5 seconds at a current draw of 1.4 mA. The design parameters to be modified on the power conditioning circuit in order to achieve those requirements are storage capacitance, C_{ST} , trigger levels of the comparator, V_{HIGH} and V_{LOW} , and the output voltage of the regulator, V_{OUT} . The latter three values are programmable via resistors as shown in the figure below. Equipment used include the Maxim MAX6433 comparator and a Texas Instruments TPS72501 voltage regulator.

Fig. 6. Power Conditioning Circuit with Regulator

Of the four design parameters, V_{OUT} is simple to determine and is equal to the critical input voltage of the RFID tag.

$$V_{OUT} = 2V. \quad (1)$$

The next design parameter simple to determine is the low trigger level of the comparator, V_{LOW} . This trigger level must meet the minimum required input voltage level specified for the regulator in order to achieve a voltage output of 2V. Otherwise, a voltage level not high enough to output 2V on the other side of the regulator becomes wasted energy. V_{LOW} can be determined from the specification sheets of the regulator.

$$V_{LOW} = 2.5V. \quad (2)$$

The maximum current draw of the RFID tag is specified to be 1.4 mA. Therefore at a critical input voltage of 2V, critical operating power of the RFID tag is 2.8 mW. At a critical pulse length of 2.5 seconds, the energy demanded by the tag is 7 mJ.

$$\text{Power} = VI = 2.8\text{mW}. \quad (3)$$

$$\text{EnergyDemand} = Pt = 7\text{mJ}. \quad (4)$$

The power conditioning circuit, through the combined efforts of the storage capacitor and trigger levels of the comparator, therefore must supply at least 7 mJ of energy to the RFID tag within a pulse of 2.5 seconds. The energy transferred from the storage capacitor can be found using the following equation.

$$\text{EnergySupply} = \frac{1}{2} C \cdot V_{HIGH}^2 - \frac{1}{2} C \cdot V_{LOW}^2 \geq 7\text{mJ}. \quad (5)$$

In order to achieve such a long discharge time, super capacitors were thought to be the best option. The smallest capacitance, well-suited capacitor found was a 22,000 μF gold capacitor, a Panasonic Electric Double Layer Gold Capacitor (SD Series).

$$C_{ST} = 22,000\mu\text{F}. \quad (6)$$

With a capacitance chosen, V_{HIGH} can be determined.

$$V_{HIGH} = 2.63V. \quad (7)$$

The upper trigger level of the comparator must be at least 2.63V if the super capacitor is able to discharge over 2.5 seconds.

The design parameters for the power conditioning circuit have therefore been determined and will be modified upon experimentation as needed.

3.3 Piezoelectric Power Generator

The last component of the system to be designed is the piezoelectric power generator. In a real-life application-specific deployment, the power generator would be designed to resonate at the peak frequency of the chosen vibration source. However, experimentation for powering the RFID tag will only be conducted in a lab setting, therefore resonant frequency of the generator was not significant. Although experiments were conducted in lab, a setup was created to mimic characteristics of a known vibration source, namely a wooden staircase, a source used earlier in the earlier Mica2Dot Mote experiment [2]. A LabWorks ET-126 vibrating actuator driven by an Agilent 33120A signal generator and a LabWorks pa-138 power amplifier was used to emulate a vibration source which resonated at a frequency of 52 Hz at an acceleration magnitude of 0.5 m/s^2 .

Fig. 7. “Teeny Temp” Piezoelectric Power Generator Mounted on a Small Vibration Table

A piezoelectric bimorph generator was designed to resonate at the same frequency. A piezoelectric bimorph from Piezo Systems with the dimensions $31.5 \times 12.7 \times 0.51 \text{ mm}$ ($1.25 \times 0.50 \times 0.02$ ”) was used in constructing the generator. This bimorph uses a brass center shim and PZT-5A4E. A 20g tungsten mass was affixed to one end using cyanoacrylate glue, and the device was mounted in a rigid plastic clamp. At the given acceleration magnitude, a 40V peak to peak AC signal resulted.

4 Regulator Circuit Results

Upon linking the various components of the “Teeny Temp” system, and experimenting, the design parameters of the power conditioning circuit were fine tuned. The super capacitor of $22,000 \mu\text{F}$ was used with modified comparator trigger levels of 2.465V and 2.92V. These values resulted in a 2.1V output pulse for 3.32 seconds. Under automode interrogation, the reader was able to capture 15 reads from the tag per pulse. Time to charge the super capacitor from VLOW to VHIG was 60 seconds.

An image of the notification message from the reader is shown in the figure below. The message shows tag ID, initial discovery time of the tag, and total number of reads. This particular notification message occurred after two pulses of power were supplied to tag. During those two pulses, 28 total reads occurred and the difference in time between the two pulses was 60 seconds.

Results for the Crossbow Mica2Dot Mote and the Alien RFID tag are compared in the table below. A fair comparison can be found in output power to load and time per cycle. In order to function properly, it was necessary to supply 68mW to the mote and 8mW to the RFID. Charge time for the power conditioning circuit for the mote application was 10 minutes and charge time for the power conditioning circuit for the RFID application was 1 minute.

```

#Alien RFID Reader Auto Notification Message
#ReaderName: Alien RFID Reader
#ReaderType: Alien RFID Tag Reader (Class BPT/2450Mhz)
#IPAddress: 0.0.0.0
#CommandPort: 23
#Time: 2005/04/29 13:45:28
#Reason: TIMED MESSAGE
Tag:1208 2004 1855 2000 0000 0000, CRC:1AEA, Disc:2005/04/29
13:44:29, Count:28, Ant:0
#End of Notification Message
SensorValue = 24

```

Fig. 8. Automated Notification from Alien RFID Reader under Automode

These results show a 88% decrease in output power and 90% decrease in charge time. There are two reasons for the decrease in charge time. First, the difference in trigger levels for the mote is around 1.5 V and the difference for the RFID is around 0.5 V. Therefore, a longer charge time is necessary to collect enough energy for the mote. Second, the trigger levels for the RFID are significantly lower than the trigger levels for the mote. Therefore, the storage capacitor on the RFID power circuit can more efficiently draw power from the piezoelectric power generator.

Table 3. RFID versus Mote Results

Characteristics	Mote	RFID
Capacitor Size	6,600 uF	22,000 uF
Trigger Levels	3.5 V → 5.4 V	2.47 V → 2.92 V
Energy Transferred	56 mJ	27 mJ
Bender Frequency and Accel	2.5 m/s ² at 27 Hz	0.5 m/s ² at 52 Hz
Bender Voltage Signal PP/RMS	40 VPP/ 14 VRMS	40 VPP/ 14 VRMS
Output Pulse to Load	3.3 V for 0.816 s	2.1 V for 3.32 s
Output Power to Load	68 mW	8 mW
Time per Cycle	10 min	1 min

5 A Better Power Conditioning Circuit

Upon analysis of the results in an effort to further optimize the “Teeny Temp” System, it became apparent that a regulator was not necessary and was only wasting usable energy. The range of voltage levels from the storage capacitor were all usable voltage levels of the RFID tag. There was no need to regulate that signal and burn off energy. Therefore, a transistor was substituted in place of the regulator. A schematic of the power conditioning is shown below.

Results from the modified circuit are shown in the graphs below. The top signal on each graph shows the voltage level of the capacitor while the bottom signal shows output voltage to the RFID tag. The new transistor circuit was analyzed under three different modes: no interrogation, manual interrogation, and automode interrogation. Under manual interrogation, the tags are called using a command prompt.

Fig. 9. Schematic of Power Conditioning Circuit with Transistor

Fig. 10. Power Conditioning Circuit with Transistor

There are several interesting things to observe from the graphs. First, there is a voltage drop between the capacitor and voltage output to the tag and this voltage drop occurs though the transistor. Therefore, a “no voltage drop transistor” would be more optimal in future designs. Second, the shape of the voltage output signal shows the benefits of a transistor versus regulator. Output from a regulator would be a flat line whereas the transistor allows the raw voltage to feed through. Therefore the energy saved can be represented by the area of the triangle which would otherwise have been burned to ground by the regulator.

Fig. 11. Capacitor Voltage (*top*) and Voltage Output to Load (*bottom*): a) No Interrogation b) Manual Interrogation c) Automode Interrogation

Third, the current draw during transmission can be found by comparing the pulse lengths between the different modes of interrogation. Under no interrogation, a pulse of 12.8 seconds is observed. The only current draw occurs from onboard sensor and electronics and is calculated to be 1.1mA. Under manual interrogation, where the tag was called twice, the length of pulse dropped to 7.12 seconds, suggesting an average current draw of 1.9mA under two manual interrogations. During automode interrogation, the pulse length drops to 4.2 seconds, suggesting an average current draw of 3.2mA.

Table 4. Regulator Circuit versus Transistor Circuit Results

Characteristics		Regulator Circuit	Transistor Circuit
Automode	Length of Pulse	2.9 sec	4.2 sec
	# of Reads	20	95
	Current Draw	4.4 mA	3.2 mA
Manual Interrogation	Length of Pulse	4.9 sec	7.12 sec
	# of Reads	19	8
	Current Draw	2.6 mA	1.9 mA
No Interrogation	Length of Pulse	9 sec	12.8 sec
	# of Reads	--	--
	Current Draw	1.4 mA	1.1 mA
Time to Charge		41 sec	40 sec
Output Voltage		2.1V flat	2.12 V to 1.88 V

The transistor circuit resulted in an average 44% increase in pulse length. A longer pulse length leads to more reliable transmissions to the reader. Or if shorter time to charge is desired, lower capacitance or lower trigger levels could be utilized since excess energy is no longer burned away via the regulator.

6 Conclusions

An experiment was conducted to evaluate the potential integration of energy scavenging from vibrations with battery-assisted passive RFID tags. The system chosen for analysis was the Alien 2.45 GHz battery-assisted passive tag system. The tags are equipped with onboard temperature sensor. Through experimentation, the tag was found to require at least 2.8mW over a pulse length of at least 2.5 seconds to reliably transmit information to the reader. A piezoelectric power generator was designed with a resonant frequency of 52 Hertz, with potential power output of 500 μ W [3,4]. A power conditioning circuit was designed to most efficiently convert AC power from the piezoelectric power generator to DC power to the RFID tag.

A 0.5m/s² acceleration magnitude vibration at 52 Hertz was emulated by a vibrating actuator. These vibrations in combination with the piezoelectric power generator and power conditioning circuit resulted in a 2.1 V signal for a pulse length of 3.32 seconds to the RFID tag. These values are equivalent to an 8mW power transfer to the tag. This value is in contrast to the 68mW required to power a Crossbow Mica2Dot Mote. Charge time for the power conditioning circuit for the mote applica-

tion was 10 minutes and charge time for the power conditioning circuit for the RFID application was 1 minute. Comparison of results between a battery-assisted passive RFID tag and Crossbow Mica2Dot Mote show a 88% decrease in necessary power supply and 90% decrease in charge time.

Upon further analysis, the power conditioning circuit was modified to optimize power transfer to the RFID tag. By replacing the regulator with a transistor, raw voltage coming from the capacitor was transmitted to the RFID tag since all voltage levels VLOW through VHIGH were acceptable by the RFID tag. Using the transistor resulted in a 44% increase in pulse length.

In summary, battery-assisted passive RFID tags with onboard sensor, are a feasible wireless sensor node solution for integration with energy scavenging from vibrations. Future work should focus on power needs of the tag with respect to distance from the reader. Since these tags rely on backscatter technology, it is assumed more power will be needed, the further away the tag is from the reader. Further optimization of the power conditioning circuit is also necessary. Transistors with no voltage drop should be utilized. In addition, capacitance of storage capacitor and trigger levels of comparator can be further optimized for specific applications. The system design engineer should acquire the necessary duty cycle for an application, then program circuit characteristics to operate at that duty cycle.

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