RF-based Power Transmission for Wireless Sensors Nodes

Guocheng Liu\textsuperscript{1,3}, Nezih Mrad\textsuperscript{2}, George Xiao\textsuperscript{3}, Zhenzhong Li\textsuperscript{1,3}, and Dayan Ban\textsuperscript{1}

\textsuperscript{1}Department of Electric and Computer Engineering, University of Waterloo, g37liu@uwaterloo.ca; zz2li@uwaterloo.ca; dban@ccmail.uwaterloo.ca;

\textsuperscript{2}Air Vehicles Research Section (AVRS), Defence R&D Canada – Atlantic (DRDC)
Department of National Defence (DND), National Defence Headquarters
nezih.mrad@drdc-rddc.gc.ca

\textsuperscript{3}Institute for Microstructural Science
National Research Council Canada
george.xiao@nrc-cnrc.gc.ca

ABSTRACT

A major technical challenge affecting deployment of wireless sensor networks for structural health monitoring (SHM) applications is to develop a way of supplying power to sensor nodes in an efficient and reliable manner. In this paper, we explored a potential solution to this challenge by extracting energy from microwave signals, mainly from a dedicated radio frequency (RF) energy supply, to power strain gauge sensors for sensing and data communication. The wirelessly transmitted microwave energy can be captured by two kinds of receiving antennas (dipole and patch), transformed into DC power by a rectifying circuit, and stored in a supercapacitor to provide the required energy to the sensor node that is interrogated at a distance of 50 meters from the base station. Such a system has the advantage of eliminating permanent physical connection between the sensor nodes and the data acquisition system. The transmitted power was limited to 3 W effective isotropic radiated power (EIRP) in experimental tests and the captured and stored power level was sufficient to power two strain gauge sensors nodes and transmit data back to a base station. Two kinds of receiving antennas are evaluated by impedance matching, and peak received power. Experimental results demonstrate the effectiveness of the evaluated approach in powering selected wireless sensor nodes.

\textit{Keywords:} energy harvesting, wireless energy transmission, wireless data transmission, strain gauge.
INTRODUCTION

Wireless sensor networks (WSNs) have become a ubiquitous technology with various applications [1, 2] including the field of structural health monitoring (SHM) [3]. Wireless sensors present a better option compared to traditional sensors and have some important features such as wireless communication, on-board microcontroller unit, and small size. Besides no connectors or “hard” paths, wireless sensors also have advantages including simply final assembly, minimal documentation, reduced trouble shooting, increased retrofit potential, and system upgrade flexibility [1, 2]. However, wireless sensors for SHM applications are currently at their infant stage, there are many challenges needed to be addressed. Power supply has been a key limiting factor in the WSNs as their sensors are typically powered by on-board batteries. Although life of batteries has been greatly extended due to new materials and technologies, there remain the problems of limited capacity retention, high labour costs associated with their replacement, and ecological issues surrounding their disposal. A promising alternative to batteries is to use energy harvesting technologies which can gather ambient energy and convert it into electrical energy to power wireless sensors [4, 5].

While designing efficient energy harvesting circuits for a specific application, tradeoffs are often made because of various factors needed to be considered, such as operating environment, the characteristics of the energy source, energy conversion efficiencies, power management, power storage, and power requirements of the wireless sensors. The main application envisaged for this work is wireless strain gauge sensors deployed for potential aircraft SHM. These wireless sensor nodes can be located in the structures such as wing skin, aircraft engine, stiffener, or empennage [6-8]. In an aircraft operation environment, two obvious energy harvesting approaches exist: piezoelectric vibration harvester and thermoelectric power generator. Arms et al. [6] developed an integrated SHM and reporting system and tested it on a Bell Model 412 helicopter. The system employs piezoelectric energy harvesting combined with wireless sensors including strain gauges, accelerometers, and thermocouples. The miniature vibration energy harvester can supply 37 mW of continuous DC power under conditions replicating the helicopter’s gearbox. These high speed wireless sensor nodes were demonstrated to be capable of logging data at sample rates of up to 50 KHz, while consuming ~ 9 mA at 3 VDC (27 mW). Zhu et al. [7] also presented a credit card sized vibration energy harvesting smart tag, which can be easily added into various applications including aircraft applications. This device consists of a microcontroller with RF components, an accelerometer, a temperature sensor, and a pressure sensor. The generator is fabricated using thick film printing technology and can generate a maximum RMS output power of 240 µW when excited at frequency of 67 Hz and peak amplitude of 0.4 g (3.9 m·s⁻²). By combining a thermoelectric generator and a heat storage unit, Samson et al. [8] presented an energy autonomous wireless sensor system which consists of a microprocessor controlled power management and a sensor node with the energy harvester. The thermoelectric generator can generate a output power of 189 µW at 3.3 V when making use of a temperature varying between 271.2 K and 293.4 K.

There are given scenarios such as the lack of enough vibration and temperature gradient, in which the amount of harvested energy falls below the level required to power device’s microcontroller, sensor board, and transceiver. To overcome this difficulty, the use of wireless power transmission [9], in which power is generated elsewhere and transmitted to a sensor node through some form of electromagnetic wave or radio frequency (RF) radiation, is proposed.
Fig. 1: Photograph of the microwave power and data transmission system. (a) Wireless power transmission using one transmitting antenna and receiving antenna. (b) Two wireless sensor nodes with strain gauges; (c) Base station with a distance of 50 meters away from the sensor nodes. (d) Schematic of a RF-powered wireless sensor node.

Current research efforts in RF-based wireless power transmission focus on passively powered sensor networks by improving the conversion efficiency [10], and attempting to maximize the output power by designing efficient antennas for exploring various applications including civil SHM and soil sensor network [11-17]. At present, there is no investigation on active-sensing powered with RF energy for potential aircraft SHM applications. This paper presents a RF powering and active-sensing system that can be deployed in the scenarios lacking enough vibration and temperature gradient. This system uses RF electromagnetic waves as medium for power and data transmission. Two types of commercial-off-the-shelf (COTS) receiving antennas (dipole and patch) are evaluated based on impedance matching, and peak received power. Due to the intended applications, the dipole antenna is chosen as the receiving antenna for its smaller size and 360-degree reception. Section II provides the system architecture and characterization of RF power and data transmission system. The importance of each of the major blocks and the design issues in the system are described as well. Section III covers the simulation behind wireless energy transmission. Section IV presents experimental results and discussions.

SYSTEM ARCHITECTURE AND CHARACTERIZATION

Fig. 1 shows the wireless power and data transmission concept which is demonstrated by a commercially available development kit from Powercast Corporation including 915 MHz Powercaster transmitter (TX91501-3W-ID), receiving antennas (dipole and patch), P2110 evaluation board, wireless sensor board, XLP 16-bit development board, PICkit daughter card (2.4 GHz/802.15.4), and PICkit 3 programmer. The transmitter (Tx antenna) would generate a power-providing RF signal, and the receiving antennas (Rx dipole antenna) are connected to wireless
sensor nodes accommodating two linear-pattern resistive strain gauges (062AP from Vishay Precision Group, Inc.) that are mounted on the surface of a cantilevered beam structure. The sensors measure the desired response (Strain) from the strain gauges on the metallic structure and transmit the signal back to a base station via wireless communication. The corresponding schematic block diagram of the wireless sensor node is shown in Fig. 1(d). There are two antennas in the sensor node. One is the Rx dipole antenna for receiving RF signal at central frequency of 915 MHz, the other is used for data transmission operating at frequency of 2.4 GHz, independently. It is seen from the block diagram that the system mainly consists of two function sectors, i.e. wireless power transmission and wireless data transmission. The function of wireless power transmission is quite like that of a battery, which provides the power for wireless data transmission. The microcontroller in wireless data transmission sector controls the power management circuit, wireless transceiver and the sensor (the strain gauge), simultaneously. The wireless power transmission is realized by impedance matching, rectifier, power management and energy storage devices.

The antenna performs best when its impedance matches that of the rectifier circuit at the operating frequency, to reduce transmission loss. Fig. 2(a) gives the return loss of dipole and patch antennas measured with Anritsu VNA Master MS2026C. It is shown that both antennas have the same resonance frequency of 915 MHz. This indicates that good impedance matching between the antenna and the rectifier occurs in the region around 915 MHz. At this resonant frequency, the measured input return loss of the dipole and patch antenna are -25 dB and -17 dB, and the corresponding impedance bandwidth (S11 < -10 dB) are 22.7% (893 MHz to 1029 MHz) and 6% (939 MHz to 975 MHz), respectively. It is clear that the dipole antenna has broader impedance bandwidth than the patch antenna, showing that dipole antenna have a better impedance matching with the conversion circuit than that of patch antenna. In general, voltage standing wave ratio (VSWR) of antenna is one of the most important parameters in the antenna design and application. This value is usually required to be less than 1.5 such that the signal energy loss is relatively low. As shown in Fig. 2(b), the VSWR of two antennas at 915 MHz are 1.22 (dipole) and 1.34 (patch), respectively. This indicates that both antennas can function reasonably well in this frequency range and it also verifies that the dipole antenna is better than patch antenna.

A vital portion of the RF energy transmission process is converting the received RF energy to DC energy which can then be stored in a supercapacitor. It is important that the RF to DC
converter can output an adequate DC voltage to charge the capacitor to an acceptable level. Furthermore, it is desirable that the RF to DC converter has relatively low cost, small size, and high efficiency. The power management circuit consists of a micro-controlled DC-DC converter which charges a storage device. The goal of the power management circuit is to harvest maximum power over a wide range of operating conditions independent of the load behaviour. If the wireless sensor node is not actively sensing or transmitting data, the processor is allowed to go into a sleep mode, waking only upon the request of sensing or data transmission.

Choosing an energy storage device depends on a variety of factors including peak power requirements, cycle life, energy storage capacity, cost, and form factor. Two practical choices available are batteries and electrochemical double layer capacitors (supercapacitors). Batteries are a relatively mature technology and have a higher energy density than supercapacitors (e.g., battery: 8.0 to 600 Wh/kg, supacap: one to 5.0 Wh/kg). However, there remain the problems of limited capacity retention, high labor costs associated with batteries replacement, and ecological issues surrounding their disposal [2]. Supercapacitors have a higher power density than batteries (e.g., supercap: 10.0 to 100.0 kW/kg, battery: 0.005 to 0.4 kW/kg) and have traditionally been used to handle short duration power surges. Though suffer from severe leakage, supercapacitors are more robust than batteries in terms of depth of discharge which tend to lose capacity when exposed to outdoor temperatures.

As shown in Fig. 1(a), the two strain gauge sensor nodes utilize the power from the transmitter at the central frequency of 915 MHz for sensing, and then independently communicate data with the base station at a frequency of 2.4 GHz. Existing strain sensing technologies offer outstanding performance in terms of resolution and time response. However, these technologies require either physical connection of signal communication, battery power supply or expensive equipment for acquiring strain information. Thus, development of a novel strain sensor to overcome those limitations is highly desired.

**SIMULATION OF WIRELESS POWER TRANSMISSION**

The transmission (Tx) antenna is a 8 dBi, 3 Watts of effective isotropic radiated power (EIRP) antenna at central frequency 915 MHz. Two kinds of receiver (Rx) antennas are evaluated, i.e. 1.0 dBi single layer dipole antenna with size of 16.5 cm × 1.9 cm × 0.1 cm and double layers 6.1 dBi patch antenna with size of 17.8 cm × 4.0 cm × 0.1 cm with distance from the ground layer of 1.0 cm. The power ($P_R$) received by the receiver antenna placed at a distance $R$ from the transmitter antenna can be calculated, in free space, from the Friis transmission equation [18]

$$P_R = P_T \left( \frac{\lambda}{4\pi R} \right)^2 G_T G_R$$

where $P_T$ is the power transmitted, $G_T$ and $G_R$ are the gains of transmitting and receiving antennas, $\lambda = c / f$ is the wavelength of radiation with $c$ the speed of light and $f$ is the frequency.

Using equation (1), the received power of the dipole and patch antenna in free space is shown in Fig. 3(a). Due to the fact that the gain of the patch antenna is larger than the dipole antenna, the received power for the patch antenna is higher than the dipole antenna. For the RF transmission, the RF signals will be partially reflected and the remaining portion will be captured, converted to useful DC electrical energy, and stored in a capacitor. The RF-DC conversion efficiency $\eta$ is defined as the ratio of output DC power to incident RF power, which
depends upon the antenna design and conversion circuit. The values of conversion efficiency are obtained from the Powercast datasheet graph and are given in Table 1. The received DC power (after conversion) can be calculated as $P_{DC} = P_R \times \eta$ and is plotted in Fig. 3(a) as well. Using the DC power, a 0.05 F supercapacitor is charged to desired energy level with output voltage of 3.0 V. The charge time as shown in Fig. 3(b) is determined by $T = E / P_{DC}$, where $E = CV^2 / 2$, $C$ is the capacitance and $V$ is the output DC voltage. As the dipole antenna generates a lower DC power, it takes longer times to charge the supercapacitor.

![Graph of received power comparison of dipole and patch antennas](image1)

![Graph of charge time with different distance](image2)

**TABLE 1.** Received power using theoretical analysis method and corresponding RF-DC conversion efficiency at different distance

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>1.00</th>
<th>1.25</th>
<th>1.50</th>
<th>1.75</th>
<th>2.00</th>
<th>2.25</th>
<th>2.50</th>
<th>2.75</th>
<th>3.00</th>
<th>3.25</th>
<th>3.50</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power (mW, Dipole)</strong></td>
<td>2.60</td>
<td>1.66</td>
<td>1.15</td>
<td>0.85</td>
<td>0.65</td>
<td>0.51</td>
<td>0.42</td>
<td>0.34</td>
<td>0.29</td>
<td>0.25</td>
<td>0.21</td>
</tr>
<tr>
<td><strong>Conversion Efficiency</strong></td>
<td>54.9%</td>
<td>54.4%</td>
<td>49.7%</td>
<td>45.1%</td>
<td>45.4%</td>
<td>46.9%</td>
<td>48.1%</td>
<td>49.1%</td>
<td>49.3%</td>
<td>48.8%</td>
<td>47.6%</td>
</tr>
<tr>
<td><strong>Power (mW, Patch)</strong></td>
<td>8.39</td>
<td>5.37</td>
<td>3.73</td>
<td>2.74</td>
<td>2.10</td>
<td>1.66</td>
<td>1.34</td>
<td>1.11</td>
<td>0.93</td>
<td>0.79</td>
<td>0.69</td>
</tr>
<tr>
<td><strong>Conversion Efficiency</strong></td>
<td>51.5%</td>
<td>54.7%</td>
<td>55.4%</td>
<td>55.2%</td>
<td>54.7%</td>
<td>53.5%</td>
<td>51.7%</td>
<td>49.3%</td>
<td>46.3%</td>
<td>44.6%</td>
<td>44.6%</td>
</tr>
</tbody>
</table>

**EXPERIMENTAL MEASUREMENTS AND DISCUSSIONS**

In order to investigate the feasibility of the wireless power and data transmission scheme for strain measurement using the RF based approach, peak received power of two antennas sensor nodes were measured.

**A. Near and Far-field**

It is known that the surrounding space of a RF source antenna is divided to three regions: near-field, transition zone and far-field, based on the distance from the radiating source. The region that is farther than $2D^2/\lambda$, where $D$ is the largest antenna dimension, and $\lambda$ is the free-space wavelength away from the source is assumed to be far-field (e.g. about one meter, in this case). The peak received power from transition zone and far-field are shown in Fig. 4(a) and Fig. 4(b). For both dipole and patch receiver antennas, the received power decreases with the increase of the distance. Furthermore, due to the fact that the size and gain of the patch antenna are larger than those of the dipole antenna, the peak received power of the patch is more than that of the
dipole antenna. In the transition zone, the received power of the patch receiver antenna changes from over 1.7 mW at 0.36 m to less than 0.6 mW at 0.71 m. The received power of the dipole receiver antenna is roughly one half of that of the patch antenna in this region. In the far-field region (1.0-3.5 m), the received power of the antennas is further reduced to mW range. It is noted that these experimental results are smaller than those obtained using Friis transmission equation (1). The reason is eq. (1) represents a simplified model of the generally complex environment.

![Graph](image1)

**Fig. 4:** (a) Measured peak received power of dipole and patch antenna in transition zone (0.36-0.71 m). (b) Measured peak received power of dipole and patch antenna in far-field (1.0-3.5m).

### B. Strain Measurements

Voltages representative of induced strain at the strain gauge (sensor nodes) level are transmitted back to a base station via wireless communication. The strain gauge sensor node is powered by a supercapacitor charged by the DC output voltage converted from RF energy. Though the received power of patch antenna is higher than that of the dipole antenna, its volume is much larger and has 120-degree energy reception pattern (the dipole antenna has 360-degree reception pattern), so it is not practical for the intended applications. Therefore, the dipole antenna was chosen as the receive antenna (2.0 meters away from the transmitter) to power the strain gauge sensor nodes. The peak received power of the dipole antenna was 0.04 mW, which is high enough to charge 0.05 F supercapacitor within 4 minutes (Fig. 3(b)). The two sensor nodes then transmitted the data to the base station 50 m away, and data were successfully acquired and received by the base station approximately at sample rates of 0.3 Hz. Fig. 5 gives one example of strain signals acquired by two sensor nodes at different locations (shown in Fig. 1(a)), and then sent data to the base station.

**CONCLUSIONS**

In this paper, we studied a power and data transmission system for strain gauge sensors used for SHM and other applications. Two kinds of receiver antennas (dipole and patch) are evaluated in terms of return loss and peak received power. Results show that dipole antenna have a better impedance matching with the conversion circuit than that of the patch antenna. Considering the fact that the intended applications need a small volume and omni-direction, the dipole antenna was chosen for powering wireless strain gauge sensor nodes through rectifier, power management and store energy device. It is demonstrated that this captured and stored power level was sufficient for two strain gauge sensors to measure and transmit data back to a base station.

2011 CANSMART CINDE IZFP
The method of wireless energy transmission builds upon a wide field of existing research, and has been proven effective in powering sensor nodes in these applications.

![Graph showing strain signals received from the base station by using stain gauge sensor node 1 and sensor node 2, separately.]

**Fig. 5:** Strain signals received from the base station by using stain gauge sensor node 1 and sensor node 2, separately.

**ACKNOWLEDGMENT**

The work was partially supported by the National Research Council Canada, Defence Research and Development of Canada, the University of Waterloo and Natural Science and Engineering Research Council of Canada, and Ontario Graduate Scholarship of Canada.

**REFERENCES**


