Design and development of an RF energy harvesting wireless sensor node (EH-WSN) for aerospace applications

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Abstract
Numerous applications of wireless sensor networks are constrained by the limited battery power of the sensors. The power consumption of processors and microcontrollers could be scaled down dramatically with the new advances in microelectronics. This reduction gives rise to the possibility of energy harvesting sources to power wireless sensor nodes. In this paper a summary is given of our ongoing research work on RF Energy Harvesting Wireless Sensor Node (EH-WSN) which can plug-in to the already developed Wireless Instrumentation System (WIS) for aerospace applications. Present WSN’s which are powered from battery have limited operational lifetime. While energy harvesting has the potential to enable near-perpetual system operation, design of which is a complex trade-off due to the interaction of numerous factors such as the characteristics of the energy source, power supply requirements, power management futures, WSN application behaviour, chemistry and capacity of batteries used etc. In this work, we have identified a suitable power harvesting cum battery management scheme which harvests power consistently and deterministically from a secondary RF source which can be used even in harsh real-time applications. Using a RF power harvesting receiver IC and a compact power management cum storage circuit, we establish the test bed and conduct a series of experiments to verify the effectiveness of the proposed scheme. We have demonstrated continuous operation of the sensor node at an operating distance of 2 meters from the RF power source for a data rate of 240 sps. This is achieved by using special synchronized MAC protocol, low power techniques, usage of low leakage components and systematic coding of the micro controller firmware. This paper provides an insight into how various power reduction techniques can be used and orchestrated such that satisfactory performance can be achieved for a given energy budget.

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1. Introduction
The past few years have seen an increasing interest in the development of wireless sensor networks for different applications like health care monitoring1, environmental sensing2, industrial monitoring3 etc. Wireless networks
consists of a large number of smaller sensor nodes having the ability of sensing, data processing and communicating to a data sink called a coordinator or a base station. Harvesting energy from the environment is a desirable and increasingly important capability in most of these applications when compared to powering from a battery. Energy harvesting is not new, but what is new is how to build efficient energy harvesting capabilities while satisfying all other constraints. In this paper a summary of the ongoing research work on Radio Frequency (RF) Energy Harvesting Wireless Sensor Node (EH-WSN) which is part of Wireless Instrumentation System (WIS) for satellite launch vehicle applications is presented. Introducing a wireless sensor system for the sensor data results in greater flexibility both for the launch vehicle system designer and the vehicle integration team apart from significant reduction in harness, complexity, weight, volume and power. Being powered from harvested energy, the sensor nodes can be almost agile and doesn’t require routine operations like replacement or recharging of batteries which is slow and expensive.

Network lifetime of WSN’s is of at most importance in launch vehicle applications where the launch preparation time may take up to six months, even though the actual operation period is very short. It has been shown that environmental energy harvesting can potentially prolong the network lifetime of WSN’s, where energy is harvested from external sources (e.g., solar power, thermal energy, wind energy, vibration energy etc.). However, energy harvesting from those external sources are highly depend on the environment, and the continuity of their operation can be hindered by the fluctuating availability of such sources. For real-time aerospace applications, the harvested power need to be consistent and deterministic so that the placement of power source and sensor node can be planned for a fixed amount of harvested power and thus the duty cycle of operation of the sensor node can be determined.

Recently, there is a strong research interest in wireless energy harvesting especially through inductive coupling, magnetic resonance coupling, and RF signals, since wireless energy harvesting techniques are not subject to weather or seasons constraints. RF energy harvesting technique, which is the process of converting RF signals to electricity, has proven to be a reliable method in this regard for powering several devices through low power and long distance transfer. The amount of harvested energy depends on the transmit power, frequency of the signal, and the distance between the energy source and the harvesting node. It can be calculated from the Friis free space equation:

\[
P_r = G_t G_r P_t \left( \frac{\lambda}{4\pi d} \right)^2
\]

where \(P_r\) is the received RF power, \(d\) the distance between the receiver and the RF source with power \(P_t\), \(G_t\) is the source antenna gain, \(G_r\) is the receive antenna gain, and \(\lambda\) is the wavelength. Since the harvested power is very small (of the order of \(\mu\)W to mW), optimum utilization of the available power for maximum throughput in terms of data communication is very important. This calls for an efficient power management, power efficient Medium Access Control (MAC) protocol and low power hardware components. In this paper, we propose an integrated design of an Energy Harvesting Wireless Sensor Node (EH-WSN) which is having an ultra low power radio powered from a RF energy harvesting cum storage system. Low power operation is ensured by running a power efficient MAC and exploiting the low power modes of the devices used.

The first contribution consists of designing an ultra low power WSN radio with a power efficient synchronous MAC. Certain modifications are done in the existing WIS-beaconing MAC to reduce the power consumption further for EH-WSN. The operation of EH-WSN is restricted to a single micro slot to reduce the power consumption during transmit periods. WSN is put in sleep mode for the rest of the time. Second contribution is towards the design and development of an efficient RF power harvester cum storage system which receives and converts ambient RF signals into energy and store in a storage which consist of a compact rechargeable battery plus super capacitor. Battery will provide the power during the sleep periods whereas the super capacitor will provide the power during active transmit/receive periods. Entire system is optimized in a holistic way from the design of the architecture to power management at the application and networking levels. The results that we have obtained, say, continuous operation from harvested power at a data rate of 240 sps and a sleep mode current consumption of <1 uA are the best reported so far. The rest of the paper is organized as follows: Section 2 introduces the existing WIS and
modifications required in the beaconing MAC protocol. Section 3 describes the RF energy harvesting scheme. Section 4 describes the custom modifications of micro controller firmware to exploit the low power modes of the devices used. Section 5 shows the experimental setup and results obtained. Finally, the concluding remarks are presented in Section 6.

2. Wireless Instrumentation System

Wireless Instrumentation System (WIS)\textsuperscript{5} as shown in fig-1(a) consists of a wireless base station (WBS) or a network coordinator and hundreds of wireless sensor nodes (WSN) connected in a single hop star network operating in the 2.4GHz ISM band and having a physical layer(PHY) conforming to IEEE802.15.4.b standard for low power wireless sensor nodes. MAC layer of WIS layer follows a custom low latency micro-slot structured synchronous beaconing MAC protocol\textsuperscript{5} where the WSNs are time synchronized to WBS beacons at the starting of every TDMA frame. WBS collects data from the nodes in the allotted TDMA slots and passes the data to the upstream telemetry by wire line means.

One TDMA frame as shown in fig-1(b), is divided into a programmable number, say N of equally sized mini slots of 4.3ms(including a minimum gap of 44us) duration as shown in fig-1. The largest IEEE 802.15.4 frame size of 133 bytes(Synchronization header: 4Bytes + Frame Length: 1 Byte + Payload data: 127 Bytes) which is having a duration of 4.256ms at 250kbps is present in one mini slot. Each mini slot is further divided in to five equally sized micro slots of duration 860us to enable transmission of smaller packets efficiently. Following modifications are done in the existing MAC to reduce the power consumption of EH-WSN: (a) WSN is allowed to synchronize from any valid packet other than beacon, (b) allows long TDMA frames so that the harvester can get enough power before a transmission, (c) secondary or tertiary beacons are introduced to support the regular WSN’s to send data frequently, (d) 1 byte addressing instead of 6 bytes for EH-WSN to reduce the packet overhead. Hardware frame filtering is dispensed at WBS for this. Further, EH-WSN’s are programmed to transmit the data with a power settings just enough to have a satisfactory communication with the WBS. Assuming the external 32 kHz clock which gives timing for the WSN MCU, drift less than 50ppm, number of re-synchronizations can be reduced to one's in every two seconds to reduce the power consumption while waiting for a beacon. The drift within two seconds will be well within the WIS slot drift tolerance of +−22us\textsuperscript{5}.

3. Proposed Energy Harvesting WSN(EH-WSN)

Our experiments to balance the energy consumption of WSN with limited amount of harvested energy were conducted with the RF power harvest module (P2110) from Powercast Corporation\textsuperscript{13}. Fig-2 shows the hardware
block diagram of the proposed EH-WSN. Right part depicts the WSN-Radio and the left part depicts the WSN-Harvester. Radio part is based on MSP430F2618\textsuperscript{15} an ultra low power micro controller (MCU) operating at 8MHz. It is having an active mode current consumption of 4.7mA at 3.3V and will consume only 900nA during (LPM3) sleep mode\textsuperscript{15}. IEEE802.15.4 radio interface at 2.4GHz is provided by CC2520 transceiver IC\textsuperscript{12}. Maximum output power of the CC2520 is set at 0dBm for low power operation of the radio. MCU is having an internal 12bit SAR ADC which can digitize 8 numbers of high level analog channels (0-2.5V) using the internal multiplexer and channel sequencer.

RF power harvester part is based on P2110 RF harvester receiver IC\textsuperscript{13} which converts 915MHz RF received using a patch antenna (Gain=6dBi) to DC and stores it in a super capacitor (33mF). When a charge threshold (1.25V) on the capacitor is achieved, the P2110 boosts the voltage to the set output voltage level (3.3V or 4.2V) and enables the voltage output. When the capacitor voltage goes below 1.02V, P2110 shut off its output. Capacitor will recharge again and the cycle will repeat. Received RF signal strength (RSSI) is monitored by the MCU through the DOUT pin, allowing for adaptive adjustment of the data transmission duty cycle. Output of the harvester is managed and stored by the power management block. For better power management we have tried two circuits- an integrated solution using Enerchip IC (CBC3150)\textsuperscript{14} shown in fig-3(a) and a discrete solution which consist of a thin film battery(EFL700A39)\textsuperscript{19} and a low leakage power management IC(MAX17710)\textsuperscript{18} shown in fig-3(b).

3.1 Power Management Circuit

Enerchip\textsuperscript{14} provides solid state storage (50µAh) with integrated battery management and low leakage in an IC form with high charge/discharge cycle life and low self-discharge which makes these batteries ideal for our application as backup source for the micro controller. The output voltage from P2110 (set as 3.3V) in fig-3(a) is applied to the Enerchip charge pump, the control logic, and is compared to the user-set threshold (=3.3V) as determined by the VMODE bias settings. The EN pin is a digital input that turns off the charge pump when low. VOUT is either supplied from VDD or the integrated Enerchip energy storage device. RST# is a digital output that, when low, notifies the MCU that VOUT is being sourced by the integrated Enerchip. A low leakage capacitor of sufficient capacity(C=1000uF) is provided at the output of the Enerchip as a buffer to store enough energy to provide the power bursts needed during the active MCU periods (Tx/Rx).

In fig-3(b), we have used a discrete solution consisting of an ultra low quiescent current MAX17710 power management IC\textsuperscript{18} along with a higher capacity (0.7mAh) thin film battery\textsuperscript{19}. MAX17710 is a complete system for charging and protecting micro power-storage cells from poorly regulated sources (output levels ranging from 1mW to 100mW) and can give selectable output voltages with an internal low-dropout (LDO) linear regulator. The output voltage from P2110 (set as 4.2V) is applied to the CHG pin of MAX17710. Here we are using rechargeable solid state lithium thin film battery EFL700A39. The Enfilm battery is connected to the BAT pin of the MAX17710. Whenever the CHG pin voltage is more than the battery voltage, MAX17710 will charge the battery. The regulated output is turned on when PCKP capacitor voltage is greater than 3.7V and the AE is pulsed high. The regulated output (REG=3.3V) is used to power the MCU.

4. MCU firmware customization

In order for the EH-WSN to operate continuously, the harvesting rate should exceed the consumption rate (energy consumption) of the MCU.
neutrality). As the harvested power is very less, it is essential that the duty cycle of operation of the node needs to be kept low. In addition to low duty cycle operation, the power consumed by each of the devices need to be the minimum for the required operation. The energy consumption spent on the RF transceiver usually dominates the energy consumption of the rest of the devices in the node and is mainly determining the life time of the node. In order to reduce the power consumption, we have used CC2520 RF transceiver \(^\text{16}\) which is having a transmit current consumption of 25.8mA and Rx current consumption of 18.8mA at 0dBm RF power output. During low power mode (LPM2) \(^\text{16}\) where the digital voltage regulator is off, no clocks are running, and the data are not retained, it consumes less than 1uA. As the configuration data are not retained in LPM2, CC2520 has to be fully reprogrammed when waking up from LPM2. CC2520 features an extremely fast start up, so the time consumed here is mainly due to the need to reinitialize the configuration data. The MSP430F2618 \(^\text{15}\) used in the EH-WSN has a very short wake-up time (<1us) and both the operating and sleep currents are low. Using the low power features of the MSP430, it is possible to develop systems that consume just a fraction of the current rather than other MCUs would consume. There is a 32 kHz crystal connected to the MSP430 that can be used for an accurate ultra low power sleep timer for waking up in the required time slot.

4.1 Firmware Operation Flow

MCU firmware of EH-WSN is designed based on the modified beaconing MAC as discussed in section 2. At power on, when the MCU is released from reset by the super wiser circuit IC, following initializations are performed:(a) MCU Clock(MCLK) set at 8MHz using internal DCO(digitally controlled oscillator), (b) Auxiliary clock(ACLK) is selected as the external 32KHz clock, (c) Peripheral clock SMCLK is selected same as MCLK, (d) CC2520-SPI interface is configured for 4MHz, (e) Default registers for CC2520 is loaded and put it Rx mode. Once the CC2520 is put in Rx mode, MCU will wait for a valid packet to be sent in the same private area network (PAN) at power on. Once, it receive a valid packet, it will retrieve the current slot information and set the MCU -periodic timer to give an interrupt (MCU on and initialization time=690us+CC2520 calibration time=192us) earlier than the actual slot and put itself in LPM3 low power mode. MCU will wake up once the set timer expires, and perform the initialization of CC2520 and ADC12 (internal ADC). ADC12 is configured for sequence of channel (8 channels) acquisition mode. The timer expiry and MCU instruction timings are adjusted in such a way that the MCU will post the CC2520 Tx command exactly 192us (Tx calibration time) before the starting of the allotted micro slot. MCU will reset the timer to receive the next WBS beacon for re-synchronization if one of the two events-8 numbers of TDMA frame or 2 seconds after receiving the last beacon-if completed. Otherwise, the timer is set to wake up in the next allotted slot.

First synchronization can take a maximum of two mini slot duration (8.6ms) plus CC2520 start up time for synchronization whereas further synchronizations will take only the duration of a micro slot plus CC2520 start up time. Sample and hold time of ADC12 is kept minimum (4 × ADC12CLK=5MHz) assuming the source resistance is more than 50kohm to reduce the power consumption. Major hardware operations and their current and timing contributions are given in Table I for a TDMA frame size of 32 mini slots and CC2520 transmit power of 0dBm.

4.2 Average Current Consumption of the Node

Average current contribution of the proposed EH-WSN is calculated from the following equation: Total lifetime of the node is given by, \[\text{Lifetime} \,[h] = \frac{\text{Battery Capacity} \,[\text{mAh}]}{\text{Average Current} \,[\text{mA}]}.\] Since the Rx Mode is only in the every 9\(^{th}\) TDMA frame, 1/8\(^{th}\) of the Rx contributions are taken per TDMA frame to simplify the calculations. Total contribution is also scaled by 1000/137.6 to get the contribution for a second. Using the values given in Table
I. battery life for both the batteries is calculated as follows:

Hours of operation with 50uAh Enerchip battery is obtained as $= 50 \text{[uA* hrs]} / 271.48\text{[uA]} = 11\text{mts}$

Hours of operation with 700uAh Enfilm battery = $700 \text{[uA* hrs]} / 271.48\text{[uA]} = 154\text{mts}$

5. Experimental results

Our experimental setup shown in fig-4 consist of the WSN-Harvester proto card, Wireless Base Station(WBS) which acts as the IEEE802.15.4.b network co-coordinator, a WSN-Radio which is powered by the harvester card, Smart RF05-CC2520 Evaluation Board which monitors network transactions and TX9150 RF power source(3W EIRP at 915MHz, kept 2m away from WSN-harvester).

![Fig. 4. (a) Top side of proto harvester card; (b) Bottom side of proto harvester card; (c) EH-WSN test setup](image)

5.1 Beaconing MAC and Current Consumption

Proposed beaconing MAC protocol is coded on MSP430 MCU which is sitting on the WSN-Radio. The current consumption of the node is measured by connecting a resistance of 10 ohm in series with the MCU supply line and monitoring the voltage across the resistor on a DSO. Current consumption corresponds to regular beacon reception and data transmissions are shown in fig-5. We can see that the actual current consumption in the plot is matching with our calculations done in section 4. Packet timing and statistics are verified using the Smart RF Studio.

5.2 Experiment1-Setting the operating point for P2110

Proper characterization of the harvester requires an RF signal to be applied directly to the P2110. We need to find the RF power required which will give the same dc power as that of harvested from the RF transmitter kept at a distance of 2m. Fig-6(a) shows the RSSI values which we have obtained from the DOUT pin of P2110 for different RF input powers from -10dBm to +10dBm. Next we have replaced the RF signal generator with a 6dBi patch antenna and found out the RSSI value with the 3W EIRP RF transmitter kept at a distance of 2m. By comparing the two results, it seen that the RF power required for 2m distance operation is around 6dBm.

![Fig. 6. (a) RSSI vs. RF power input;(b) Transmission period vs. RF power input](image)
In all our experiments, we set the RF input power as 6dBm, transmit power output of CC2520 as 0dBm and useful packet data (excluding the header) of 8 bytes so that we are able to compare the results.

5.3 Experiment2-ON-OFF Scheme

Here we have powered the WSN-Radio directly from the P2110 harvester output and the WSN firmware is coded to send a packet immediately after power ON. Harvester output will be periodic and regulated output pulses as explained in section III and the period of operation is proportional to the load WSN power consumption. Once the WSN gets powered on, it will immediately transmit a packet and shuts off itself by de-asserting the RESET pin of P2110. This is the simplest scheme and consumes the least power during inactive periods as the WSN shuts off between transmissions. Since the WSN starts from off state every time, it cannot run the beaconing MAC as it requires the WSN to synchronize with the WBS and remember the time slots. Fig-6(b) shows the period of transmission vs. RF input power received. More the RF input power, faster the capacitor can charge between the cycles and higher will be the packet transmission frequency. It is seen from the above plot that, the ON-Off scheme can transmit a packet once in every 200ms with a RF input power of 6dBm which corresponds to an operating range of 2m.

5.4 Experiment3 ON-Sleep Scheme

Here we have used a low capacity rechargeable battery (Enfilm battery) to power the WSN during the harvester off periods. During this period of time WSN will go in to ultra low power sleep mode where it will be clocked from a 32 KHz clock to reduce the power consumption. Now, WSN will be able to manage time slots by controlling sleep period timer. Power management circuit will charge the battery whenever the harvest output is present and ensure that the battery will not be over charged or discharged. During transmissions, a buffer capacitor (1000uF) connected at the output of the power manger will provide the required current.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Period of operation with RF harvesting (ms)</th>
<th>One time operation period from full battery (minutes)</th>
<th>Data rate at 0dBm (SPS)</th>
<th>Data rate at -10dBm (SPS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-Off</td>
<td>200</td>
<td>N/A</td>
<td>40</td>
<td>174</td>
</tr>
<tr>
<td>Enerchip</td>
<td>250</td>
<td>10</td>
<td>32</td>
<td>142</td>
</tr>
<tr>
<td>MAX17710 &amp; EnFilm Battery</td>
<td>290</td>
<td>125</td>
<td>27</td>
<td>120</td>
</tr>
</tbody>
</table>

We did this experiment with both the power management circuits which we have discussed in section 3. Results we got with both the schemes are compared with the on-off scheme in table 3. As expected, the on-off scheme is faster as it has no leakage during inactive periods and the software MAC over head is less. MAX17710 + Enfilm battery scheme slightly behind the Enerchip scheme as it uses discrete components and the leakage will be more in comparison to the former.

In launch vehicle applications, the actual operation period of avionics systems is very short (<2 Hrs) and so the scheme with more battery capacity is more preferable. Battery can be charged fully through RF prior to launch and operate the system at a higher data rate say 400 sps. In this case, RF power source can be switched off to avoid any interference to other systems. Fig-7(a) shows the battery voltage of Enfilm battery (shown in blue) when operated continuously at a data rate of 400 sps. It can be seen that the MAX17710 regulator voltage (shown in red) is constant throughout and the end of operation is indicated by a battery voltage of 3.6V which is more than the dropout of the MAX17710 regulator for 3.3V output.

5.5 Experiment4 Enfilm battery charging with harvested power

Unlike other Li-ion batteries, Enfilm battery charges fast and will take only 20min to charge more than 90% of the full capacity (0.7mAh) as indicated by the charging current (<100uA). However the charging time with pulsed dc power which we have with our harvester will be more than this. Fig-7 shows the charging profile of Enfilm battery with our pulsed dc output (4.2V) from (b) one harvester (c) two harvester’s. In fig-7(b), it takes around 4hrs to
charge the battery whereas in fig-7(c), when we connected two P2110 harvester ICs in parallel, charging time (2hrs) got halved and the data rate of operation for sustained continuous operation (MAX17710 + Enfilm battery) got doubled (240 sps) as expected.

6. Conclusion

This paper discusses an integrated approach to combine hardware design, synchronized wireless network programming and intelligent battery management to create a fully wireless and robust sensor network powered with RF energy for aerospace applications. Low power consumption of the sensor node is achieved by the following: proper selection of ultra low power devices, exploiting the power down modes of the devices and power management, low duty cycle operation of the node and a power efficient beaconing MAC and its optimum coding in the MCU. The experimental results show that the proposed hardware scheme along with the modifications in the beaconing MAC protocol can operate continuously (240 sps sustained data rate & sleep current < 1uA) while being in a network synchronized to a coordinator. Power consumption and hence data rate can be further improved by using ultra low power transceiver IC’s like CC2630 and/or using power gating devices to switch off devices during sleep.

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