REALIZATION OF AN AUTONOMOUS UWB SENSOR NODE POWERED BY A PIEZOELECTRIC ENERGY HARVESTER

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Abstract: This paper demonstrates self-powered ultra-wideband impulse radio (UWB-IR) data transmission using harvested vibrational energy from a piezoelectric transducer. The piezoelectric energy harvester generates an average power of 54 µW with an open circuit voltage of 5.5 V_{rms} from an input vibration of 0.45 g (4.4 m s^{-2}) at a resonant frequency of 163 Hz. When powering the UWB sensor node, it was experimentally observed that the node is able to transmit bursts of 100 pulses every 110 seconds consuming an average power of 8.2 µW and demonstrating the potential for a sub 100 µW autonomous wireless sensor node.

Keywords: Ultra-wideband (UWB), wireless sensor node, energy harvesting, piezoelectric, autonomous

INTRODUCTION

Wireless communication has become an essential technology in our environment. It not only provides flexibility and mobility but it vastly reduces the bulky, and difficult to integrate cabling required by wired systems [1]. One of the key challenges for vast wireless sensors networks is finding a sustainable power source for reliable operation. Wireless sensor nodes are typically powered by conventional batteries which have a limited lifetime and must be replaced or recharged periodically. As the number of sensor nodes in the network increase and the devices decrease in size, the replacement of exhausted batteries becomes impractical and costly. To overcome this drawback, self-powered wireless sensor nodes using harvested energy from the surrounding environment provides an alternative solution; for example, harvesting energy from ambient light, thermal gradients or mechanical vibrations [2]. Harvesting kinetic energy presented in the form of mechanical vibrations is a promising solution for the wireless sensor nodes due to the ubiquitous presence of environmental motion. To convert this motion into useable energy, piezoelectric transduction is commonly used due to its high conversion efficiency and simple integration [3]. An example of a self-powered wireless sensor node using harvested energy from piezoelectric vibrations was reported in [4]. For a short-range communication, using a ZigBee wireless protocol, 90 bits of data are transmitted every 798 seconds requiring power from a harvester capable of generating 240µW. Here, we present faster transmission, requiring less power.

Recently, there has been significant research into UWB radios which exhibit the potential for ultra-low power wireless communication. UWB signals, unlike conventional-narrow band systems, use short energy pulses spread over a wide frequency range resulting in a low power spectral density. Shortening the transmission period reduces the power dissipated per data rate making ultra-low power and high data rate communication systems possible [5-6]. Therefore, we focus on the development of an autonomous sensor system integrated with a custom made ultra-low power UWB transmitter (UWB-Tx) powered by a piezoelectric harvester. Feasibility of the wireless sensor node is demonstrated using discrete custom made blocks from which the electronics will be combined into a single integrated chip.

SYSTEM DESCRIPTION

Fig. 1 shows the system diagram of the proposed autonomous UWB sensor node. It consists of a power management unit (PMU), a microcontroller unit (MCU), an ultra-wideband transmitter (UWB-Tx) and a piezoelectric vibration harvester.

PMU (U1) and MCU (U2)

The proposed PMU (U1) converts the AC input voltage supplied by the piezoelectric harvester into a DC signal using a rectifier and a buck controller/ converter (LTC 3588-1). The buck converter allows charge to accumulate on an input capacitor (C1) until it can efficiently transfer a portion of the stored charge to the output capacitor (C2). To minimize the setting time from a cold start condition, the quiescent and leakage currents of all components in the PMU are reduced by introducing switches SW1 and SW2.

When the output voltage at C2 reaches 3.3 V, switch SW1 is closed by the 'power good' (PGOOD) pin of U1 and the MCU (U2) begins managing the power provided to UWB-Tx through SW2. The MCU is used to control the timing of the power supply (UWB_PWR) and the trigger of the UWB-Tx to maintain a sustainable pulse repetition rate based on the energy provided to the sensor node.

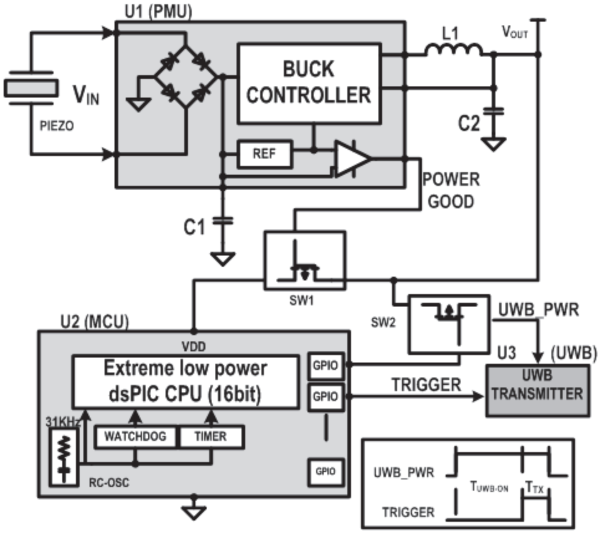


Fig. 1: System block diagram of the autonomous UWB sensor node.

The deep sleep mode of the PIC24F16KA102 in the MCU reduces consumption to only 550 nA by the 31 KHz RC oscillator and the active watchdog timer. The extremely low power consumption of the MCU is the key to reducing the system recovery time in the system. The proposed node uses a temperature sensor which is built into and interfaces directly with the MCU. It could be easily replaced by other types of sensors depending on the application.

UWB transmitter (UWB-Tx)

EPFL-ESPLAB has previously reported on an ultra-low power application specific integrated circuit (ASIC) UWB-Tx to demonstrate the feasibility of UWB technology applied to ultra-low power communication for indoor positioning applications [7]. The UWB-Tx is a state-of-the-art transmitter realized in 0.18 µm CMOS that consumes very low power making it suitable for our proposed application (range ~ 10 m and ~ KHz data rate). The schematic of the UWB-Tx is shown in Fig. 2. The ring oscillator sets the center frequency to 4.1 GHz while the triangular pulse generator is used to define the bandwidth of the UWB pulse.

Due to the linear regulators on the UWB-Tx PCB, the supply voltage is fixed at 3.3 V. Therefore, a high input voltage for U1 is needed. Since the buck converter requires 5 V_{DC} after the rectifying stage, this translates to more than 15 V_{PP} (5.5 V_{rms}) that must be provided by the piezoelectric harvester.

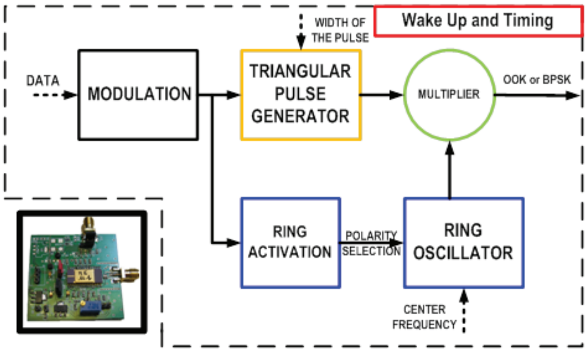


Fig. 2: Block diagram of the UWB transmitter and the associated PCB (inset).

The current consumption is 25 mA during pulse transmission (T_{Tx} ~ 2.5 ns) and 2 mA during the short setup period (T_{UWB_ON} ~ 1 ms). More details on the operation and implementation of the UWB-Tx are discussed in [7].

Piezoelectric energy harvester

Most piezoelectric harvesters consist of one or several piezoelectric layers supported by an elastic cantilever beam from which a mass is suspended. There are several piezoelectric materials available. However, the materials of interest for energy harvesting are mainly restricted to PZT (lead zirconate titanate), ZnO (zinc oxide), and AlN (aluminum nitride). In this work, the piezoelectric harvester is based on a bulk PZT sheet bonded to a silicon substrate. Bulk PZT is readily available and offers a high piezoelectric coefficient and high electro mechanical coupling which are both highly desirable in a piezoelectric energy harvester [8].

The design of the harvester was supported by the finite element method (FEM) using ANSYS to determine the electromechanical behavior of the piezoelectric harvester, such as the stress and charge distribution. A coupled-field electromechanical model was developed in ANSYS. A 3D model of a unimorph piezoelectric harvester was structured as shown in Fig. 3. The piezoelectric layer is connected to the electric circuit element CIRCU94, representing a resistor. Since most ambient vibrations are in the frequency range between 60-200 Hz, the resonant frequency of the harvester should be designed to be in this range to optimize the output power. A modal analysis is first used to define the overall shape configuration and natural frequencies of the harvester.

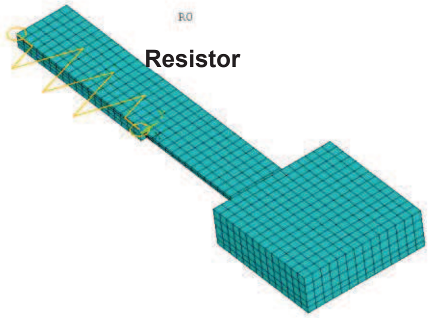
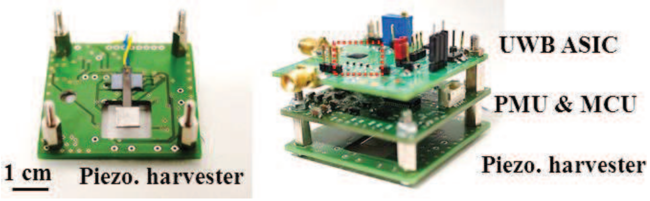


Fig. 3: A coupled-field FE model of the unimorph piezoelectric harvester.

To simulate the power generated from the structure, harmonic analysis is performed by applying a sinusoidal excitation acceleration at the fixed base of the harvester. The displacement and voltage as a function of frequency are then computed by employing a coupled electromechanical analysis. It is also practical to simulate the voltage generated as a function of the resistive load (R_L) by varying the value of resistor. The electrical power dissipated in the resistor can be calculated using $P = V^2/R_L$. A detailed description of the design and fabrication is provided in [9].

RESULTS AND DISCUSSION

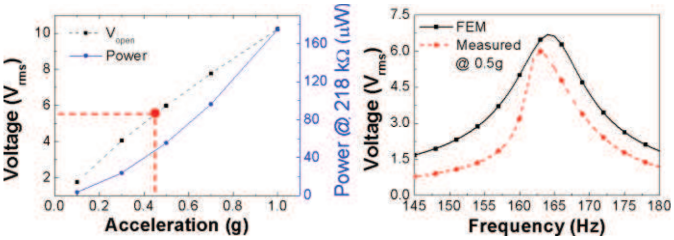
The energy harvesting performance of a single piezoelectric harvester mounted on the PCB (Fig. 4(a)) was investigated using an electrodynamic shaker to apply mechanical oscillations at varying frequencies and acclerations.



(a) (b)

Fig. 4: (a) optical image of the piezoelectric harvester mouted on the PCB (b) the proposed UWB sensor node with 3 layers (45 mm × 45 mm × 40 mm).

The harvester produced an open circuit voltage of 5.5 V_{rms} when excited at 0.45 g (4.4 m s^{-2}). A peak power of 54 µW was measured across an optimal load of 218 kΩ at 162 Hz (Fig. 5(a)). The results demonstrate that the power generated from the piezoelectric harvester is able to provide the voltage required by the PMU. A comparison between numerical simulation and experimental measurement of the open circuit voltage is given in Fig. 5(b) as a function of frequency. A good agreement is achieved in the frequency range of interest.



(a) (b)

Fig. 5: (a) Open circuit voltage and output power as a function of acceleration (b) Comparison between FEM simulation and experimental measurement.

Next, the harvester was connected to the PMU and UWB-Tx (Fig. 4(b)). The harvester was then excited with a sinusoidal acceleration of 0.45 g at 163 Hz. The voltage output (V_{out} in Fig. 1) generated by the PMU was recorded using a digital multimeter with a sampling period of 100 ms as shown in Fig. 6. Fig. 7 presents the transmitted signal from the UWB-Tx recorded using a 40 GSa/s digital oscilloscope.

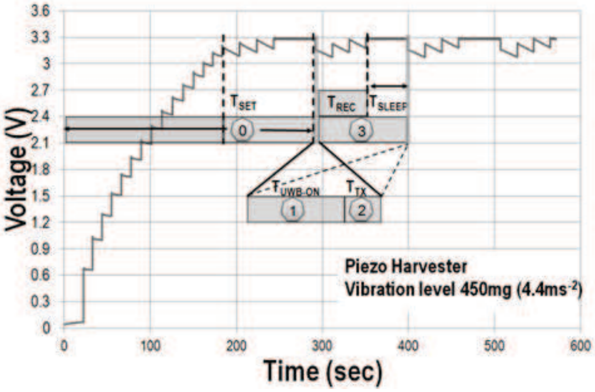


Fig. 6: PMU output voltage as a function of time from the start and different states of the PMU.

<u>State 0</u>: [Cold start / Steady State phase] This stage is controlled by the buck converter. As long as PGOOD is zero, the MCU remains off. Power is only consumed by the deep sleep mode of the MCU. In this mode, only the RC oscillator and the watchdog timer are active. The total duration is 290 s.

<u>State 1</u>: [Wait phase] The power consumption is from UWB-Tx standby power (2 mA). It was observed from the measurement that the UWB-Tx block has a setting time (T_{UWB_ON}) of ~ 1 ms. Thus, it must be powered for 1 ms before the pulse trigger is provided as shown in Fig. 7 (inset).

<u>State 2</u>: [UWB transmission phase] This phase is characterized by a large pulse of current (25 mA) due to the short duration (2.5 ns) of data transmission. A

measured pulse from the UWB is presented in Fig. 7. The value of the sensor is embedded in this signal.

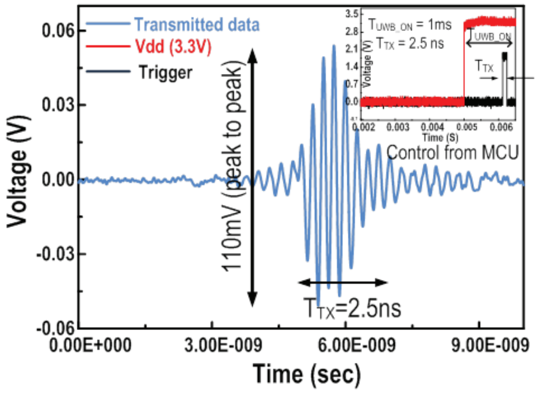


Fig. 7: Measured UWB transmitted pulses and MCU control signal (inset).

State 3: [Recover phase] Here, the system returns to steady state operation after the pulse is transmitted. The recovery phase (T_{REC}) takes around 54 s which means the system can send bursts of 100 pulses every 54 s. However, due to the resolution of the watch-dog timer in the microcontroller, the duration between two pulse bursts is set to 110 s (T_{SLEEP} ~ 56 s). The main current (5 µA) is therefore carried by the buck converter and the leakage in the capacitors.

Table 1: Current, time and energy of each phase at 3.3 V

State	0	1	2 100 pulses	3 (REC)	3 (SLEEP)
Current	-	2 mA	25 mA	5 µA	-
Time	290 s	1 ms	2.5 ns	54 s	56 s
Energy	-	6.6 µJ	20.6 nJ	891 µJ	-

Table 1 shows the energy consumption and time duration of each phase described above. The energy consumed in the transmission phase is 20.6 pJ. This is negligible compared to the energy consumed in either the wait (6.6 µJ) or the recovery (891 µJ) phases. During transmission, bursts of 100 pulses (10 bits) repeat every 110 seconds consuming an average power of 8.2 µW ((6.6 µJ + 0.0206 µJ + 891 µJ) / 110 s). The system is able to transmit data potentially twice as fast as a previously reported self-powered wireless node [4] while requiring less power from a harvester during its operation.

Since the energy supplied to the UWB pulse has to be provided by C2, the capacitance of C2 is determined by the energy consumption during state 2 and 3. A value of 220 µF was calculated using the energy stored in the capacitor. This is the minimum value of the capacitance that can be used as a storage capacitor.

CONCLUSION

An autonomous UWB sensor node powered by a piezoelectric harvester is presented in this work. It exhibits excellent potential for high speed and low power wireless communication. Integration of the PMU and the UWB-Tx on a single integrated chip is ongoing in order to reduce the necessary supply voltage allowing operation at lower vibration levels (< 0.1g).

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