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Low-Power Wireless Medical Sensor Platform

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Abstract— **Long-term, low duty cycle monitoring of patients with a variety of disabilities or health concerns is often required. In this paper, we discuss the design considerations and implementation of an ultra-low power wireless medical sensor platform, suitable for a wide range of medical and sports applications. A hardware demonstration prototype based on readily available components is presented with sensors for 3-axis acceleration, temperature and galvanic skin response. Detailed power measurements and operation results are shown, demonstrating a sensor life span of more than 10 years on a single 200 mAh lithium watch battery using low current standby techniques with an average power of less than 5 µW and a 10 second sample interval.**

I. INTRODUCTION

PATIENTS with physical or cognitive disabilities or other health concerns often need to be monitored for extended periods of time in a controlled environment [1], [2]. Basic vital signs, such as body temperature and heart rate, as well as other parameters, such as physical and emotional activity, need to be monitored. Although some conditions require continuous monitoring, many require only low duty cycle operation (e.g. one sample every few seconds or minutes). Also, for long term monitoring, noninvasive, light-weight, wireless, low-maintenance devices are needed to allow the patient to move and live normally without constraint or required attention for the sensor.

Many wireless medical sensors and systems have been studied and made commercially available in recent years [3], [4]. The primary emphasis has, appropriately, been on system considerations, such as user interfaces, real-time software architectures, sensor devices, interpretation and medical use of sensor data, potential applications, etc. The tremendous progress and interest in the area to date indicate that the future will bring a proliferation of miniature physiological monitoring products. Most devices rely on relatively large batteries (e.g. multiple AA size) for prolonged operation and require battery replacement at what may be considered frequent intervals for some applications (e.g. few days to months) [4]. It is of interest to study the sensor components in more detail and design the platform from an efficient power management perspective. The goal is to facilitate device miniaturization and offer maintenance-free operation by significantly reducing the required stored energy for long term operation.

The primary objective of this paper is to present a low power wireless sensor architecture with a detailed theoretical and experimental analysis of the power requirements for each of the sensor components. The requirements are separated into two categories: a) dynamic energy associated with each sample and transmission operation (which depends on the sensor type and amount of data collected) and b) quiescent standby losses (which dominate for low duty cycles). The design uses readily available components and leverages advances in integrated circuit (IC) technology that have produced microcontrollers, wireless transceivers, and MEMS-based sensors with low standby currents, high burst data rates [5] and small packages.

The system architecture is described in Section II. Results from an experimental demonstration are presented in Section III for a device incorporating example sensors for measurement of 3-axis acceleration, temperature, and galvanic skin response. It is shown that at sample periods greater than 5 seconds, the unit requires less than 5 µW average power, resulting in a life span of more than 10 years on a single 200 mAh lithium cell.

II. SYSTEM ARCHITECTURE

A. Overview

The system is composed of a wearable ‘sensor module’ (which is the primary focus of this paper) and a ‘receiver station’. The sensor module acquires data from various sensors with analog outputs, temporarily stores the data, then transmits it to the receiver station. The transmission frequency was selected to be in the 2.4 GHz ISM band because of the wide availability of transceivers in this band, high possible data rates, and suitable operating range.

The sensor module is controlled by an onboard microcontroller unit (MCU) optimized for low-power operation. The built-in ADC of the MCU samples the sensors and configures the wireless transceiver for transmission of the data. The ICs communicate through a fast serial peripheral interface (SPI) bus to minimize data transmission time and CPU activity.

Since the sensor operates up to 99.99% of the time in power-down mode, the components are chosen to have the lowest possible standby currents and fastest possible turn-on times and transmission speeds. Also, the system operates at a low 2.5 V supply, so the components are chosen accordingly. Figure 1 shows the overall design of the system.

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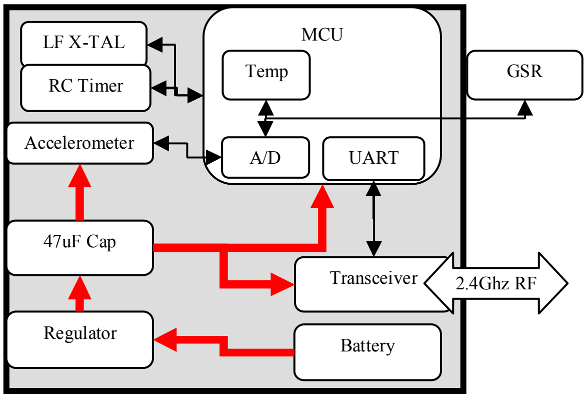

Fig. 1. Overall sensor diagram showing power flow (thick red arrows) and data flow (thin black arrows)

The sensor board also contains two different, independent timers for waking up the MCU at each sample cycle. Depending on the required sampling period accuracy, either one of the timing methods may be used. The 32 kHz low-power watch crystal is the traditional method, where the internal counter of the MCU issues an interrupt to the CPU, waking it up after a certain number of clock cycles has elapsed. This method is accurate and allows the MCU to operate at a standby current of only 0.7 µA.

The second timing method uses an RC network to produce a negative-going edge and provide the same interrupt to wake up the CPU. Without running the internal timer, the MCU can power down to a current of only 0.1 µA, which significantly reduces the total standby power of the system. The time constant of the network is chosen so that the voltage drops to about 0.9 V (the trigger threshold voltage) in 10 seconds. The significance of choosing 10 seconds is explained in Section III. Also, the resistor and capacitor are chosen to have a maximum discharge current of 0.1 µA to reduce power while providing reasonable timing accuracy. The final values chosen were 0.47 µF and 22 MΩ for the capacitor and resistor, respectively.

B. *Power*

The sensor module can be powered by a variety of external sources, such as batteries or solar cells, that supply voltages from 2.5 V to 12 V. Lithium-ion memory-backup or watch batteries are particularly well-suited for this purpose because of their long shelf-life and small self-discharge rates (less than 1% per year). The input voltage is stepped down using the Maxim MAX1726 low-dropout regulator (LDO), which was chosen for its low quiescent current and ultra low-power shutdown capability.

Figure 1 shows that the regulator has a relatively large 47 µF capacitor at its output. This capacitor provides sleep power to the MCU between sampling cycles. After the MCU samples the sensors and transmits the data, the regulator is shut down to conserve power, but enough energy remains on the capacitor to power the MCU until it wakes up again. Due to the wide operating range of the MCU (1.8 V to 3.6 V), it remains operational and can detect interrupts even though the capacitor voltage drops significantly.

C. *Microcontroller*

The MCU utilized in the sensor is the Texas Instruments MSP430F1232. This chip was chosen for its ultra-low standby current of 0.1 µA in power-down interrupt mode using the RC timer and 0.7 µA in deep sleep mode using the 32 kHz crystal for timing, versatile interface and clock capability, onboard 10-bit ADC, and fast CPU.

The MCU is programmed in ‘C’ code. The pseudo-code for the main loop is shown in Table I.

Table I: Sensor sample and transmit pseudo-code

```
-Power-up regulator
-Power-up radio
-Power-up accelerometer
-Wait for accelerometer and radio to settle
-Sample accelerometer on X,Y,Z axes using on-board 10-bit ADC
-Power-down accelerometer
-Initialize 1.5 V internal reference and settle
-Sample temperature, acceleration and GSR sensors
-Transmit Data
-Power-down radio
-Charge RC timer, enable interrupts
-Power-down regulator
-CPU off
```

First, the CPU is powered up by a digital trigger that detects the negative-going edge from the RC timer, or by a counter connected to the 32 kHz crystal. After a 100 ns power-up period, the CPU begins code execution and immediately powers up the regulator, which recharges the main 47 µF capacitor to the operating voltage of 2.5 V. Next, the various sensors are powered up, given time to settle, and sampled. The transceiver and accelerometer were chosen to minimize this settling time (see respective sections) so that the least possible energy is wasted. Next, the various signals are sampled, stored and transmitted over SPI to the transceiver, which assembles the packet, including a 16-bit CRC, and transmits the data at 1 Mbps. After transmission is completed, the MCU either recharges the RC timer or enables the 32 kHz watch crystal interrupt. Finally, the regulator is powered off and the CPU shuts down, entering interrupt mode, where it waits for the next wake-up event. The entire sense-and-transmit cycle takes only 4 ms.

D. *Sensors*

With various forms of digital I/O and analog inputs, the TI MSP430 can interface to practically any type of sensor. As a demonstration, however, the sensor module utilizes a Freescale MMA7260Q MEMS 3-axis accelerometer with 1.5 g sensitivity and built-in signal conditioning. The MMA7260Q also has a very fast start-up time of 1.5 ms and low supply current of 500 µA. The sensor measures both static and dynamic acceleration, meaning it can detect both movement and change of orientation. Due to the large designed sample interval of the whole module, this sensor will primarily detect changes in static acceleration and whether or not the patient has moved or changed orientation since the last sample.

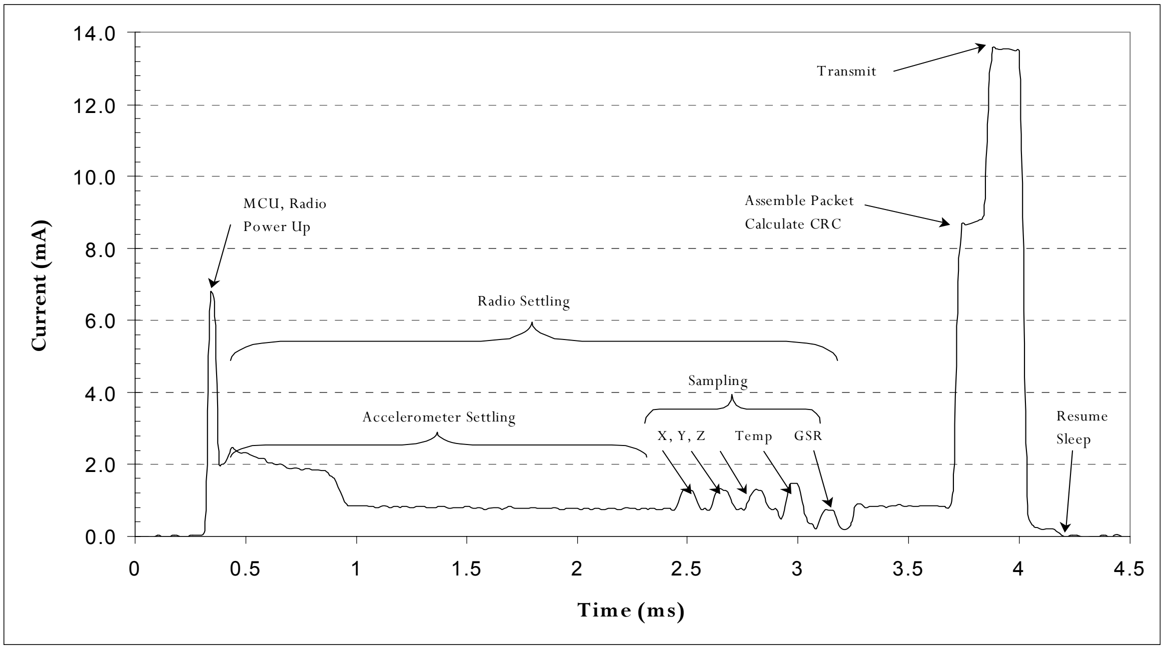

Fig 2. Measured Sensor Current Consumption During Active Phase

The on-board temperature sensor of the MSP430 is also utilized for simplicity. While more accurate body temperature measurements will require a dedicated probe, the principle and power requirements will be the same.

Finally, the sensor module also has leads for sensing galvanic skin response (GSR), or the impedance of the skin. As a person performs various activities or their emotional activity changes, the resistance of the skin will change. The GSR is a good indicator of the state of awareness of a person, and also does not require a high sampling rate [6]. This sensor is implemented as a simple voltage divider, using the internal 1.5 V reference of the MCU and a known resistor value. The exact value of the GSR is not required, only changes in impedance, so the accuracy of the resistor or voltage reference is not critical.

E. Transceiver

The transceiver used in the sensor module is the Nordic Semiconductor ASA nRF2401. This radio is optimized for low-power operation and features a 0.4 µA standby mode (register retention) and fast 3ms settling and calibration time. The radio is easily programmed via SPI and is capable of 1 Mbps transmission at 2.4 GHz. Due to the fast data rate, the on-air time of the radio is very short. This makes it possible to operate the radio at 0 dBm output power, which drains 13 mA of current. At this power level, the range is approximately 5-10 m in an office environment.

III. EXPERIMENTAL RESULTS

The operating modes and power consumption of the various sensor components were measured and verified. Table II summarizes the current consumption of each component as given by the manufacturer datasheet (for 2.5 V supply voltage). All of the values were also verified experimentally. The table gives the values for the three main operating states of the sensor module. The ‘Sleep’ state refers to the long period between sample acquisition when the MCU and radio are powered down and all of the sensors are off. The ‘Active’ state occurs when a sample begins and the CPU is acquiring data from the sensors, which are powered up. The transceiver is settling, but is not transmitting. Finally, the ‘Transmit’ phase occurs after all data has been sampled and the sensors are powered down. The power amplifier of the radio is active and transmitting.

Table II: Sensor Operating Modes

Device	Sleep Current (µA)	Active Current (µA)	Transmit Current (µA)
MSP430	0.1	200	200
MMA7260	0.0	500	0
nRF2401	0.4	12	13000
MAX1726	0.7	2	2
Total	1.2	714	13202

The current consumption of the sensor module during a complete sense-and-transmit phase is shown in Fig. 2. The measurement was made using an Agilent 34411A digital multimeter with a sampling period of 20 µs. The measurement is performed from the point of view of the regulator, without the large 47 µF capacitor, to resolve the transient waveforms. The removal of the capacitor to perform this measurement is justified, because its main function is to provide power during the sleep phase and its presence during the active phase is not critical.

Initially, the graph shows the sleep phase where the current consumption is less than 1 µA. Next, as the MCU wakes up and powers up the sensors and transmitter, there is a large transient spike of current. When the accelerometer is finished settling, the ADC is powered up and samples the sensors. Finally, the graph shows the large rise in current as the radio becomes active, assembling the packet and transmitting before entering sleep mode again.

Even though the active and transmit current consumption of the module is high, very little energy is consumed during the active phase because it lasts for such a short period of time (see Fig. 2). This is the main point of the 'burst architecture' [2]: when analog electronics are involved (such as sensors and transmitters) it is best to use the fastest possible digital components to process the data quickly and turn off the sensors and other power-hungry devices as soon as possible. The consequence of this architecture is that, because of the extremely low duty cycle of the sensor, the lifespan (how long the module will run on a given battery size) is limited by the standby-mode power. This effect is demonstrated in Fig. 3, which shows the power consumption data from Table II and Fig. 2 extrapolated to different sample periods.

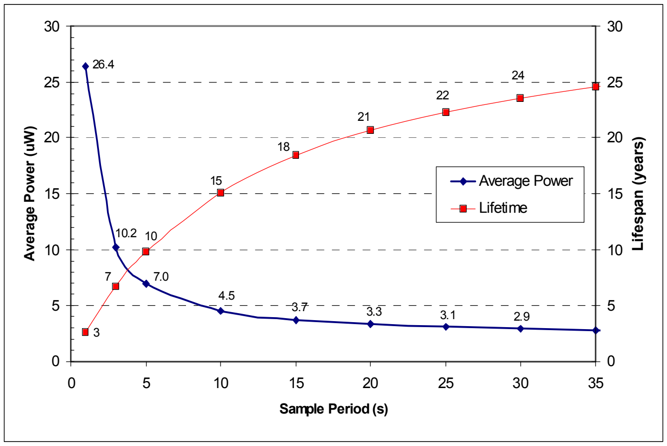

Fig. 3. Extrapolated Average Sensor Power Consumption and Lifespan Using a 200 mAh Lithium-Ion Watch Battery at 3 V.

Using numerical integration, it was possible to calculate the actual energy used during one transmit phase from Fig. 2. The consumed energy was found to be 24.3 µJ, which is close to the theoretically calculated energy of 14.4 µJ (using the datasheet numbers and Table II). Figure 3 was generated using this experimental data. The graph shows that, as the period of time between samples increases, the average power decreases, as expected. Also, the average power asymptotically approaches the standby power. Therefore, when the sampling period is larger than a certain value (about 5-10 seconds), there is little difference in average power between various sample times. For example, increasing the sampling time by 100% (from 10 s to 20 s) changes the average power by only 27% (from 4.5 µW to 3.3 µW) and so on. Thus, the sensor can operate at any sample period greater than 10 seconds with little difference in lifespan. Moreover, at large sample intervals, the average power is low enough that the sensor board could easily be powered using energy harvesting techniques, such as [7].

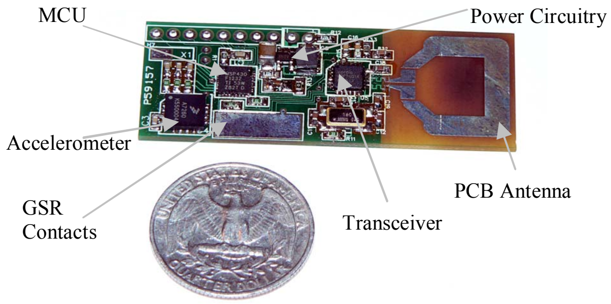

Fig. 4. Sensor Prototype

IV. CONCLUSION

During the last few years, advances in IC and MEMS technology have made it possible to build extremely low-power wireless sensor modules. The results presented above demonstrate the effectiveness of the burst architecture. Due to the fast processing times and sampling rates of the ICs used in the module, it is possible to greatly minimize the on-time of the analog electronics such that the energy used during the active phases is negligible compared to the standby phases. Thus, the limiting factor in designing low-power, low-duty wireless sensors is the standby power consumption of the processor and timer.

With this technology, a prototype sensor (Fig. 4) has been developed to demonstrate what can be achieved using commercial hardware with emphasis on low power operation. Sensors representative of long-term patient and sports monitoring applications were selected as a proof of concept. Additional sensors with similar power characteristics could easily be added to the platform with little increase in average power consumption. The prototype can operate continuously for more than 5 years at sample intervals greater than a few seconds with no required maintenance. Miniature components allow designs that do not restrict patient movement or create discomfort.

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