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Sensium: An Ultra-Low-Power Wireless Body Sensor Network Platform: Design & Application Challenges

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Abstract—In this paper we present a system-on-chip for wireless body sensor networks, which integrates a transceiver, hardware MAC protocol, microprocessor, IO peripherals, memories, ADC and custom sensor interfaces. Addressing the challenges in the design, this paper will continue to discuss the issues in the applications of this technology to body worn monitoring for real-time measurement of ECG, heart rate, physical activity, respiration and/or skin temperature. Two application challenges are described; the real-time measurement of energy expenditure using the LifePebble, and; the development issues surrounding the 'Digital Patch'.

I. INTRODUCTION

Wireless body sensor networks (WBSN) consist of sensor nodes which are used to monitor vital signals such as temperature, heart rate, electrocardiogram (EKG/ECG), physical activity and respiration. These sensor nodes gather, store and locally process vital signs data, before transmission to a central base-station node. Although prototype modules for such WBSN applications are becoming available, these devices tend to be multi-chip solutions manufactured from off-the-shelf components. As such they suffer excessive power consumption and relatively large form factors [1,2]. The development of a custom system-on-chip (SoC) can deliver improvements to the patient's quality of care through miniaturization and power consumption reduction, whilst also reducing device cost. The Sensium™ device is the first SoC specifically designed for vital signs monitoring and the platform is capable of achieving ubiquitous physiological monitoring when interfaced to appropriate external body worn sensors, an antenna and battery [3]. The chip (figure 1.) includes an ultra-low-power transceiver, full custom hardware MAC protocol, digital 8051 microprocessor, IO peripherals, memory, mircopower ADC and custom sensor interfaces. Two way communication between sensors and SoC allows for sensor bias and calibration if necessary. The ultra low power consumption is suitable for small form-factor low density flexible printed batteries or zinc air coin cells.

II. SOC CHALLENGES

A. Ultra Low Power

A key challenge for sensor nodes in WBSN is the source of

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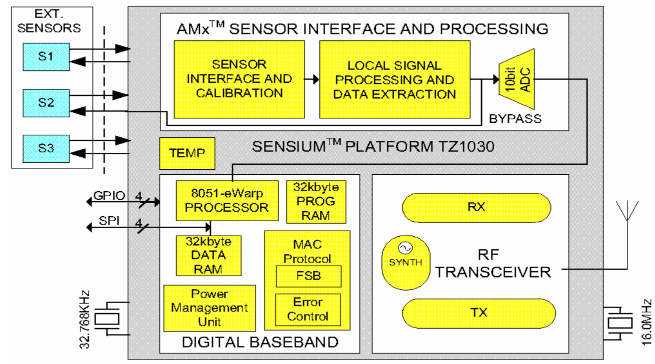


Figure 1. Sensium™ SoC block diagram

power. Flexible printed battery technologies although ideally suited to WBSN applications in terms of form-factor, cost, and environmentally friendly disposability, can only provide 1V power and 3mA·h/cm² power density [4,5]. Also to avoid battery collapse, peak power is limited to only 3mA. As such the SoC which interfaces to such a battery must minimize both peak and average power consumption. Since the peak power is usually consumed in the wireless transceiver of the sensor node, all aspects of the device design are optimized, including wireless operation frequency, data rate and over-the-air modulation scheme for efficient yet robust data transfer. Off-the-shelf wireless devices adhering to general purpose standards such as Bluetooth or Zigbee require active power consumptions which are typically an order of magnitude too large for use with paper or zinc-air coin batteries. The Sensium™ wireless link consumes 2.5mA from a 1V supply when active (receive or transmit over > 3m body area range), and an additional 0.5mA is drawn when the microprocessor is active and clocked at 1MHz.

Duty cycling of the wireless transmission can significant reduce average power consumption. This can be achieved by local processing such that only *information* is transmitted rather than just raw data. An example of how local processing can be achieved is shown in figure 2. Using local ECG template matching at the sensor node, transmit data payloads become minimal, allowing the wireless link to operate at very low duty cycle. In consequence, average power consumption is reduced, whilst still effectively providing continuous ECG monitoring.

B. Spatial Environments

The body area spatial environment in which the WBSN must work is typically a hospital ward, room in the home or local

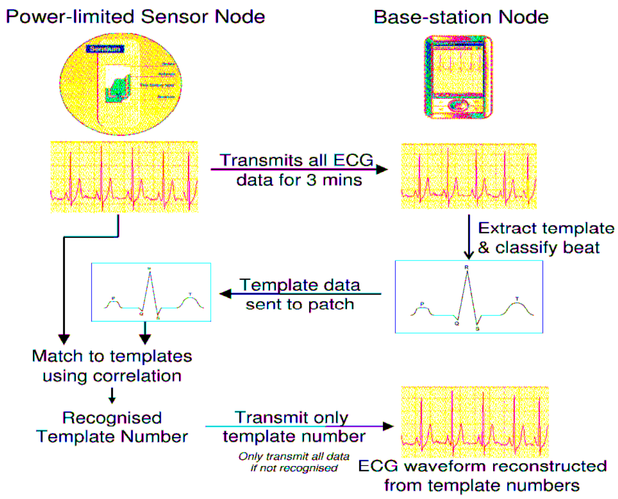


Figure 2. ECG local processing for low power

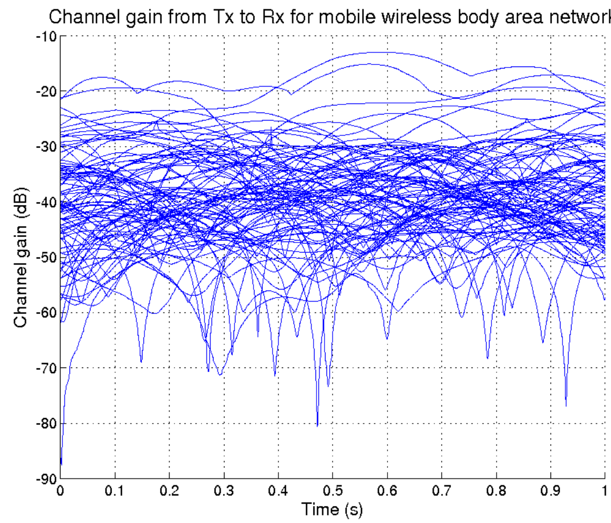


Figure 3. Channel Model Loss for Body Worn node @928MHz, d=3m

1-10m physical distance. Modeling fading and multi-path for body worn transceivers can be achieved using Doppler spread and delay spread, which provide statistical quantities describing variations due to spectral broadening and signal arrival time spread. Mathematical models based upon probability distributions exist, they rely upon various parametric assumptions which are complicated due to human body effects such as creeping waves [6], relative body movement and body absorption. An empirically based body channel model [7] run 100 times @928MHz, with body worn sensor to base-station distance of 3m and relative speed of 3km/h is shown in figure 3. As can be seen, over a 1 second period, significant wireless channel gain variation needs to be accommodated. Using an amplitude insensitive data modulation scheme (e.g. FSK), real-time automatic gain control (AGC), receiver-signal-strength indictor (RSSI) and transmit power control during transmissions can dramatically improve communication robustness whilst optimizing power efficiency.

Furthermore, a MAC protocol which is robust to rapidly changing channel conditions and interferer presence is critical to the link robustness [8]. The hardware protocol implemented encompasses all link and network management requirements and allows for use cases where the sensor node can roam, drop in and out of contact with the base-station and raise alarms.

III. Energy Expenditure Application Challenges

The Sensium™ SoC has been utilized as the WBSN platform for an ultra small size vital signs monitor (the Life Pebble), which continuously monitors ECG, heart rate, physical activity (3 axis accelerometer) and optionally skin temperature. The LifePebble's initial target application is to determine energy expenditure in real-time for diabetes type 2 patients. Typically attached to the body around the torso and the data gathered is wireless transmitted to a Sensium™ USB data logger.

By providing early stage type-2 diabetic patients with a Life Pebble, the goal is to determine, via a clinical validation study, whether the provision of real-time personalized feedback regarding their daily energy expenditure can provide encouragement for positive lifestyle modification. LifePebble provides information on heart-rate (HR), R-R interval and heart rate variability, this data together with accelerometer data can be used to calculate energy expenditure (EE). A linear relationship exists between HR and EE at normal activity levels. However, this relationship shows a wide degree of inter-individual variability so cannot be standardized for a population. Calibration of this relationship with VO_2 measurement allows EE to be calculated from 24 hour HR data for an individual [9]. This is the flex-HR method and has been validated against the 'gold standard' method known as doubly-labeled water (DLW), and also against indirect calorimetry in normal adults and children. It has also been validated in obese children, elderly subjects and disabled children. The method is equally accurate at high and low levels of daily EE and correlates well with the standard methods of DLW and indirect calorimetry ($r=0.88$, $p<0.001$) [10]. The addition of accelerometer data to the HR data allows for calculation of EE by the branched equation. This has been validated against indirect calorimetry, showing greater accuracy than HR alone [11]. The key challenges of this applications are discussed below.

A. *Electrode Movement & Muscle Noise*

Detection of ECG signals for HR calculation is a relatively simple task for a stationary patient, but when the subject is moving the ECG signals (typically 1-5mV) can be completely swamped by unwanted motion artifacts. Motion artifacts result from a change in the half cell potential of the electrode due to mechanical disturbance of the charges grouped at the "double layer" of the ions formed at the electrode-electrolyte (wet gel) interface. The most effective way to combat electrode movement is design electrodes whose connections to the lead wires are situated laterally distant from the electrode-electrolyte. In doing so, any tension applied to the wires will not alter the geometrical distribution of the gel and hence the impedance will remain constant.

Likewise muscle movement, which is accompanied by electrical signals from the muscle membrane potential, can cause electrical signals at the skin's surface of up to 20mV occupying 50 to 150 Hz bandwidth, depending on muscle type. ECG signals, whose main frequencies occur within a 1-40Hz bandwidth nevertheless do suffer from muscle noise which falls in-band. For ECG measurement, the pectoral region should be avoided and electrode placement on the sternum and laterally on the lower ribs generally results in the lowest levels of muscle noise. Out of band noise can be eliminated by filtering.

B. Electromagnetic and electrostatic interference

Unwanted electrical signals can couple directly into the body via electrostatic pick up or the antenna effect of the ECG leads. A typical interfering signal is 50/60 Hz mains hum. By minimizing ECG lead length the antenna effect is lessened, and twisting the ECG lead wires together ensures that any interference appears as a common-mode signal. Reducing the effective surface area between the electrodes also minimizes the differential interference due to electrostatic coupling. The common-mode interference is then rejected by the front-end circuitry within the LifePebble. Another effective technique to reject common-mode interference is the use of a right leg driver (RLD); this is a circuit which detects the input common-mode signal and a cancellation signal is introduced by a third electrode. Although the SoC provides a RLD output, it was decided not to implement this function in the LifePebble to avoid the requirement for a third electrode attachment. Any remaining common-mode or out-of band differential interferers can be eliminated through the use of digital filtering. Since the SoC platform contains an embedded 8051 microprocessor, custom software filters were developed to filter the ECG signals at source prior to the QRS detection. To minimize processing power, fairly simple (Butterworth and IIR) filters were implemented. Figure 4 shows indicative improvements in performance with (bottom) and without (top) activation of software filtering when the subject under test was gripping a 50Hz mains cable.

C. Antenna

A number of different antenna structures were evaluated for suitability for inclusion in the LifePebble. The goal was to achieve an average antenna gain of -10 dBi as this allows typically 5-10m range (non line of sight) for a PA output power of -10dBm at 915 MHz. A number of commercially-available, small form factor chip/ceramic antennas were measured against standard dipole and whip antennas and a custom designed inverted-F antenna (IFA). While the commercial SMD antennas showed relatively good gain,

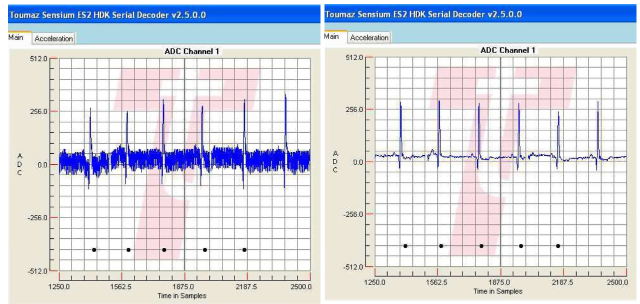
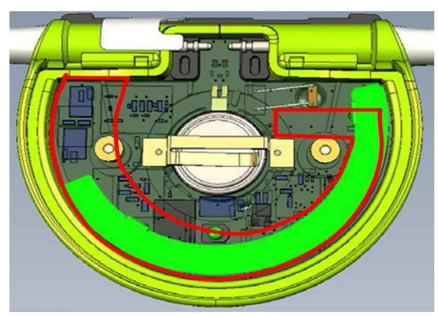
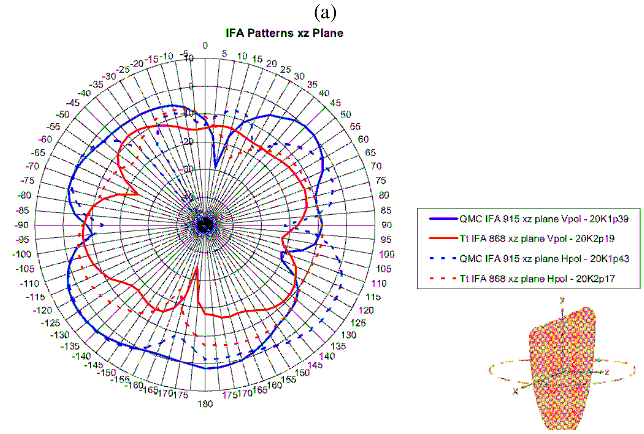


Figure 4. Rejection of unwanted ECG artifacts using digital filtering

they typically require a ground-plane free area and thus tend to detune when held close to the body. Although the initial IFA design gave adequate performance, a re-designed version gave much improved results. Both antenna designs are indicated in Figure 5a; the initial IFA is shown in green and the 'improved' IFA is outlined in red. The final antenna size is approximately 28mm*40mm. The performance improvement is due to a number of factors; the new IFA uses a counter balance to improve tuning and match; a foam support to reduce parasitic loading; the area is substantially larger and thus provides more gain; the antenna shape becomes wider away from the feed-point which has the effect of widening the antenna bandwidth. Figure 5b shows the radiation pattern of the original and improved inverted-F antennas, rotated around the vertical axis. Similar patterns were obtained for rotation around the horizontal axis and also rotated in-plane, indicating that the antenna design is robust against variations in orientation and placement.



(a)



(b)

Figure 5. LifePebble IFA (a) Design (b) Radiation Pattern

IV. Digital Patch Application challenges

Whilst the LifePebble monitor based on the embedded SoC is compact and lightweight, the 'digital patch' represents an even smaller device form factor and more functionality (respiration measurement by impedance tomography is added). Being thin and flexible, it can be disposed of after use. During the development phase of an initial 'digital patch' prototype utilizing the Sensium™ ultra-low-power WBSN platform, various issues have been encountered:

A. Electrodes

In a digital patch construction, the electrodes and leads will be incorporated into the patch packaging. Since the leads are encapsulated their movement is limited, and so motion artifacts due to lead movement will be greatly reduced. The encapsulation of the leads within the patch structure also allows the possibility for shielding which should reduce the effects of electrical interference.

B. Flexible Printed Electronics

Ensuring reliable electronic behaviour whilst providing patch flexibility requires non-rigid printed-circuit-board materials. Making the flexible PCB substrate as thin as possible actually improves the device flexibility whilst maintaining strong mechanical strength to the SoC and other electronic component mountings.

C. Batteries

For a flexible and low cost digital patch, printable battery technologies are extremely attractive. A number of flexible, low cost batteries with acceptable capacity are beginning to become commercially available [4, 5]. The main challenge, in addition to the limited low power density and peak current drain, is the limited temperature range over which they can be operated (10 – 30^{o}C) and stored (recommended storage range 0 – 5 ^{o}C). However it is expected that as this relatively new technology matures, more reliable and robust battery operation will be achieved.

D. Antenna

A reasonable area is available within the patch structure so a printed antenna on a flexible substrate (similar to RFID-type antenna structures) should give a reasonable performance. A major limitation to performance is the requirement to minimize the height of the digital plaster. This increases the mirroring effect in the ground plane as the antenna and ground plane are now very close, which limits the effective aperture area. Minimization of ground plane area below the antenna, or the use of a higher dielectric material between the antenna and ground plane to increase the effective antenna height are current options being investigated.

V. Conclusion

This paper has discussed the challenges in the design of the Sensium™ SoC. The SoC is the key enabler for ultra low power WBSN for real-time vital signs monitoring. Peak SoC active power consumption of approximately 3mW compares favourably to Bluetooth or Zigbee enabled sensor nodes which typically consume >30mW and do not include sensor interface circuitry.

The implementation of a body-worn monitor termed the LifePebble, which has been developed for real-time measurement of ECG, heart rate, physical activity (3 axis accelerometer) and optionally skin temperature, has also been presented. By tackling the issues, robust and reliable operation in a compact and lightweight form factor has been achieved. Additionally the key considerations in the deployment of a flexible disposable WBSN 'digital patch' have been covered, such applications are best suited to the Sensium™ platform's high integrated functionality and ultra-low power operation.

Acknowledgment

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