An Energy-Efficient ASIC for Wireless Body Sensor Networks in Medical Applications

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Abstract—An energy-efficient application-specific integrated circuit (ASIC) featured with a work-on-demand protocol is designed for wireless body sensor networks (WBSNs) in medical applications. Dedicated for ultra-low-power wireless sensor nodes, the ASIC consists of a low-power microcontroller unit (MCU), a power-management unit (PMU), reconfigurable sensor interfaces, communication ports controlling a wireless transceiver, and an integrated passive radio-frequency (RF) receiver with energy harvesting ability. The MCU, together with the PMU, provides quite flexible communication and power-control modes for energy-efficient operations. The always-on passive RF receiver with an RF energy harvesting block offers the sensor nodes the capability of work-on-demand with zero standby power. Fabricated in standard 0.18-μm complementary metal–oxide semiconductor technology, the ASIC occupies a die area of 2 mm × 2.5 mm. A wireless body sensor network sensor-node prototype using this ASIC only consumes <10-nA current under the passive standby mode, and < 10 μA under the active standby mode, when supplied by a 3-V battery.

Index Terms—Energy harvesting, passive RF, wireless body sensor network (WBSN), work-on-demand.

I. INTRODUCTION

RECENTLY, researchers are spending great efforts on the wireless body sensor networks (WBSNs) for medical applications, such as vital sign monitoring, the diagnose assistant, and the drug delivery [1]–[3]. Fig. 1 shows some typical applications in WBSN. In these applications, rather than the peer-to-peer self-organized network topologies, the single-hop star network topology and the master-slave protocol are commonly adopted to lower the system complexity and power consumption as well [1], [4]. A typical WBSN is usually composed of a portable device which serves as the master node for central control, and a number of miniaturized sensor nodes placed around, on, or inside the human bodies that act as the slave nodes. Compared to the master node, the slave nodes have more stringent constraints in terms of power consumption and size limitation. And this work mainly focuses on the slave sensor nodes in the WBSNs.

Typical WBSN slave sensor nodes can be used for biomedical information acquisition, signal preprocessing, data storage, and wireless transmission (sometimes direct transmission without any preprocessing). This type of slave sensor node is called the sensing node. In addition, the function of sensor nodes can be expanded to medical treatments, such as drug delivery and nerve stimulating [5], and this type of slave sensor node is called the stimulating node. One difference between the two types of nodes is that the functions of a sensing node are usually periodically performed, while the functions of a stimulating node can be either periodical or event driven.

A study has been made on these two types of WBSN nodes, and a network protocol has been proposed and implemented which meets the requirements of both, targeting the power-efficient operations. Specifically, the implemented ASIC has two standby modes. In the active standby mode, only an ultra-low-power (ULP) timer with a low-frequency clock generator is active, and it periodically power ups the sensor node. In the passive standby mode, the whole sensor node is power silent, and a secondary passive RF receiver works as the supervisor circuit. The specifically designed passive RF receiver can harvest energy from the RF signals in the space (transmitted by the master node which is not power critical), and hence, the passive standby mode consumes zero power ideally. The active standby mode can be used for the sensing and stimulating nodes. As a contrast, the passive standby mode can find its perfect use for the stimulating nodes, since the event-driven stimulating nodes can be woken up on demand without any response latency, while consuming zero power.
A low-power microcontroller unit (MCU) has been implemented for the ASIC to accomplish the network protocol and the media-access controller (MAC). The ASIC has communication ports to control an off-chip ULP half-duplex transceiver which serves as the primary communication channel of information exchanging and networking. A tradeoff strategy between the operating duty cycle and energy efficiency [6] has also been implemented for controlling the primary communication channel. The secondary passive receiver mentioned before can also provide the function of information exchanging, though the data rate is lower compared to the primary channel. In addition, a power-management unit (PMU) provides the different voltage levels needed, and the PMU is controlled by the MCU to offer several power modes in accordance with the communication nodes.

This paper is organized as follows. A work-on-demand protocol aided by a secondary passive communication channel is proposed in Section II. The ASIC architecture is presented in Section III, and the circuit implementation details are given in Section IV. The measurement results from a fabricated ASIC and a prototype system are given in Section V.

II. WORK-ON-DEMAND WBSN

As stated before, a WBSN in medical applications can have sensing nodes and/or stimulating nodes. In this section, a comparison will be made between these two types of slave nodes, and an energy-efficient WBSN protocol will be proposed with the feature of work-on-demand.

A. Sensing and Stimulating Nodes

In a WBSN, the sensing nodes and the stimulating nodes show quite different operation characteristics. A sensing node usually performs biomedical signal sensing and data transmission periodically. For example, a glucose detector wakes up and measures the blood sugar level every 5 min. Since most biomedical signals have a very low updating rate, the sensing nodes usually work in a manner of low duty cycle. A stimulating node feeds stimulus back to the human body whenever needed, such as the instant insulin injection when abnormally high blood sugar is detected in an automatic insulin pump with closed-loop control.

A typical scenario of how the sensing nodes, the stimulating nodes, and the master node operate interactively in a WBSN is described as follows.

1) The sensing nodes wake up and sense the biomedical signals periodically.
2) Once the sensing nodes detect any abnormality, an emergency event is reported to the master node immediately.
3) The master node makes the decision accordingly, and wakes up the corresponding stimulating node if needed.
4) The stimulating node performs medical treatment as demanded by the master node.

In this typical scenario, it is clearly seen that sensing nodes are activated in a periodical way, while the stimulating nodes work in an event-driven manner.

B. Work and Standby

Two states are defined for the WBSN slave nodes: 1) work and 2) standby. The two states are shown in Fig. 2. Fig. 2(a) indicates that the slave node switches between the work state and the standby state. Fig. 2(b) shows the jobs accomplished in the work state, such as signal sensing, data processing, and wireless communication. Obviously, the power consumption of the function blocks in the slave nodes varies with the node states as shown in Fig. 2(c), in which the power consumption of the MCU block is depicted. Compared to the work state, the slave nodes consume much less current.

Conventionally, a low-power timer is utilized for the standby state. This timer periodically wakes up the WBSN slave nodes. The sensing nodes work well in this way since in medical applications, the sensing nodes usually perform signal sensing periodically. However, for the event-driven stimulating nodes, periodical toggling between the work state and the standby state is not energy efficient. Since we are not sure what time the next drug delivery or stimulating operations will be as requested by the master node, the stimulating node has to be activated adequately frequently to listen to the master node. There lies the contradiction between maximizing the energy efficiency and minimizing the response delay for the stimulation nodes. The wake-up frequency directly affects the duty cycle ratio in that the slave node is in the work state. Define the duty cycle ratio as

$$C_{\text{duty}} = \frac{T_{\text{work}}}{T_{\text{work}} + T_{\text{standby}}} \approx \frac{T_{\text{work}}}{T_{\text{standby}}},$$

If a small duty cycle ratio is chosen (e.g., 100 ms/1 h), the stimulating node will have quite low average power consumption if the standby mode is designed well. However, the stimulating node might miss all of the stimulating requests within the time slot of $T_{\text{standby}}$, which lasts for one hour, and this is almost unacceptable for medical applications. On the other hand, if a relatively large $C_{\text{duty}}$ (e.g. 100 ms/5 s) is chosen, the risk of missing stimulating demands from the master node will be greatly reduced, in the cost of large power consumption, since the slave node consumes much more power in the work state than in the standby state.

Hence, the necessity arises for a “work-on-demand” solution for WBSN slave nodes, especially for the stimulation nodes. This solution should provide high energy efficiency and short response latency simultaneously.

C. Work-on-Demand With a Secondary Channel

The WBSN master node and slave nodes usually have a bidirectional communication channel to exchange information. Let us call it the primary channel. Conventionally, at the end of the
standby state, the primary channel communication is started, and the slave nodes listen to the master node.

In this paper, we propose a secondary communication channel in addition to the primary channel for the WBSN. The communication is one way, and the master node has a transmitter, while the slave nodes only have a passive receiver for this channel. This secondary channel has the following features:

1) the passive receiver in the slave node does not consume any current from its own battery; instead, the receiver has an energy harvesting block to convert the received RF signals to dc power supply.
2) the passive receiver in the slave nodes is always ready to receive any emergency commands from the master node;
3) the transmitter in the master node transmits not only useful information but also energy to the slave nodes.

With the secondary channel, the master node can wake up the slave nodes in the standby state at any time if necessary. From the slave node side, the standby state does not consume any power (no timer) and the wake-up procedure does not require any energy (no active listening).

The major differences between the primary channel and the secondary channel are listed in Table I. It is clear that the secondary channel needs simplified modules at the receiver end (slave node).

### D. Two Standby Modes

With the primary and secondary communication channels integrated altogether, the WBSN slave nodes can have two modes for the standby state: 1) the active standby mode and 2) the passive standby mode. In the active standby mode, the slave nodes use the primary channel to periodically listen to the commands from the master node. In the passive standby mode, the slave nodes only use the secondary channel for passive emergency listening. Standby mode II has much higher energy efficiency than standby mode I, in the cost of signal receiving sensitivity and communication distance.

A typical scenario of the proposed WBSN is shown in Fig. 3, with normal and emergency communications in both channels. In this scenario, we have an assumption that slave node I is a sensing node and sensor node II is a stimulating node. With the proposed architecture, sensor node I is configured to use the active standby mode, while sensor node II can be configured to use the passive standby mode in the standby state. Note that the master node and the two slave sensor nodes in Fig. 3 form a sensing-coordinator-stimulating structure that is widely used for WBSNs in medical applications. For example, in blood glucose monitoring of diabetic patients, whenever abnormal blood sugar level is detected by the sensing node, the master node should give warnings and send commands to the stimulating node, then insulin is delivered by the stimulating node.

The control procedures of the proposed WBSN protocol are listed as follows.

1) Node I (configured to active standby mode) wakes up periodically to collect biomedical information data and transmits the data to the master node.
2) The master node receives and analyzes the data from node I.
3) If the master node finds some data abnormal, it needs to decide the necessary step.
4) The master node transmits emergency command (containing node II’s ID information) through the secondary channel. Note that node II is configured to passive standby mode.
5) All of the slave nodes receive the emergency command including node I, but only node II responds after ID recognition.
6) Node II wakes up immediately and performs the function as requested (e.g., driving the insulin pump, giving nerve stimulus, etc.).

High energy efficiency has been achieved for the WBSN described before, by utilizing the proposed two standby modes properly. Also, please note that the real-time work-on-demand capability has been achieved with the additional secondary passive channel.

### III. ASIC Architecture

With the proposed protocol in Section II, a WBSN sensor node with a hybrid of active/passive RF is introduced to realize the work-on-demand capability as well as high energy efficiency. Utilizing the passive RF receiver for the secondary channel, the always-on slave sensor nodes can listen passively to the master node, and can respond to the master node’s request with a much shorter response time. The architecture of the sensor node and the ASIC will be presented in this section.

The function block diagram of a proposed WBSN sensor node is shown in Fig. 4. The sensor node can be divided into six major function blocks: 1) a digital core for controlling and processing; 2) a power-management unit; 3) an active bidirectional RF transceiver for data link; 4) a passive RF receiver for the work-on-demand capability; 5) a state/standby mode control
block for energy-efficient operations; and 6) the sensing/stimulating devices for biomedical signal sensing and stimulating.

The main task of this paper is to verify the proposed protocol with an energy-efficient work-on-demand capability. To accomplish this task, an ASIC has been designed and fabricated with the function blocks enclosed by the bold line in Fig. 4. The digital core is composed of a main control unit (MCU), a bootloader, instruction memory, and data memory. The power-management unit (PMU) is mainly composed of two low-dropout linear regulators which generate an analog VDD and a digital VDD, respectively. The state/standby mode control block contains the standby mode decision logic and an ULP timer for periodical wakeup. The passive RF receiver provides the function of RF signal receiving without quiescent current.

The interfaces between the ASIC and the remaining function blocks are compatible with the common peripheral protocols, such as SPI, I²C, general-purpose parallel, etc.

A. Control Flow

The control flow of the slave sensor nodes in the proposed WBSN is shown in Fig. 4. With the control flow, the slave nodes can accomplish the sensing-processing-communicating-executing flow under supervision of the master node. The remote master node can also configure the slave nodes’ states and modes through this control flow.

The primary wireless communication channel for the data link adopts the half-duplex contention-based protocols. The uplink (from the slave node to the master node) is for biomedical information data transmission and the downlink (from the master to the slave) is for sensor-node configuration and stimulating commands. Forward error controlling (FEC) and automatic repeat request (ARQ) are utilized to ensure communication quality.

In this control flow, the slave nodes can awake up from the standby state when triggered by two events: 1) a local timeout signal from the timer in the ASIC and 2) a remote signal from the master node, corresponding to the two standby modes. The standby mode of a slave node can be configured by the master node remotely, and the slave node can accept the wake-up trigger that matches its standby mode.

B. Power Management

The proposed sensor node is powered by a 3-V battery power supply. The PMU converts the 3-V power supply into the voltages levels as needed by other function blocks. Two programmable linear regulators are integrated in the ASIC for this function. Specifically, the digital core is supplied by a 1.8-V supply generated by one regulator, and the other analog blocks used are the 2.5-V analog VDD supplied by another regulator.

Another function of power management is to enable/disable all of the function blocks (including the linear regulators) according to the state and standby mode control and the commands from the remote master node. The power-mode control logic is powered directly by the battery. It makes the decision whether and when the other modules should be switched ON/OFF. There are only a few flip-flops in this logic circuit that consume power only when the states change.

In the work state, the power-mode control logic in the PMU will shut down part of the function blocks if there is no need to turn them on, according to the presetting stored in the register bank or any setup command from the remote master node. Proper usage of this function provided by the ASIC will greatly help to improve the system power efficiency.

In the standby state, almost all of the function blocks are disabled. For the active standby mode, only the ULP timer with a low-frequency clock generator is enabled, while in the passive standby mode, all of the circuit blocks are disabled except for the passive RF receiver listening to the master node power-silently. Table II summarizes the power-mode control for the two standby modes.

IV. CIRCUIT IMPLEMENTATION

The circuit implementation of the ASIC described in Section II will be presented in this section.

A. Digital Core

The digital core contains the MCU, bootloader, and multimode transducer interface, as shown in Fig. 6.

An MCU with the basic 8051-compatible instruction set can be adequate to implement single-hop network protocols suitable for WBSN. The control flow in Fig. 5 is implemented in software. Furthermore, for flexibility of multipurpose sensor nodes’ control flow, the program in the memory (E²PROM, FLASH, etc.) can be remotely programmable for better control of different applications. A bootloader module is implemented to complete the initializing configurations.

The bootloader initializes the MCU status, register file, and plays the role of memory arbiter. If we want to assemble several sensor nodes of different functions with the same hardware resource, we expect to rewrite the MCU program in the memory.
The bootloader can control the memory arbiter to rewrite the instruction memory through the active RF communication link or under the debug mode (wired). Every time the MCU wakes up from sleep mode back into work, its key status must be restored, guaranteed by CRC-8 verification.

The implemented digital core supports multimode peripheral interface including \( \text{I}^2\text{C} \), SPI, and general-purpose parallel ports for flexibility [17].

**B. Power-Management Unit**

The PMU in this ASIC is mainly composed of two linear regulators and the power-mode control logic. The low-dropout regulators (LDOs) regulate the battery voltage 3 V down to desired output voltages with trimming capability. Fig. 7 shows the LDO circuitry design is similar to that in [9]. It is composed of an error amplifier (M1 \( \sim \) M8); a unit-gain buffer (M9 \( \sim \) M12) [10]; a PMOS pass device; a feedback network (R1, R2); and an off-chip loading capacitance \( C_L \). An Ahuja compensation method [11] rather than Miller compensation is used. The Ahuja compensation exhibits excellent phase margin across all loads as well as higher power-supply ripple rejection ratio (PSRR) than classical Miller compensation.

An integrated bandgap reference voltage generator provides reference voltages and bias currents for the other circuit. It adopts a classical self-biased cascade structure to eliminate the dependence of supply voltage and temperature.

**C. Passive RF Receiver**

The designed passive RF receiver is mainly composed of an energy harvesting block and an on-off keying (OOK) demodulator as shown in Fig. 8. To activate the sensor node in the standby state (specifically under the passive standby mode), the remote master node transmits commands modulated onto an RF carrier to the sensor node. The energy harvesting block converts the received RF energy to a dc supply voltage for the demodulator, and uses the recovered energy for signal demodulation.

The energy harvesting block, as shown in Fig. 9(a), converts part of the incoming passive RF channel signal power to a dc voltage (VRF) which supplies all of the circuits in the passive RF module. A multistage rectifier is used to convert the received 915-MHz RF power into a dc power supply stored on a 300 pF on-chip capacitor. The rectifier has a structure of the Dickson voltage multiplier [16]. This kind of circuit needs low threshold diodes or metal–oxide semiconductor field-effect transistors (MOSFETs). The OOK demodulator mainly consists of a clock and data recovery block (CDR), as shown in Fig. 9(b). The CDR recovers a digital baseband signal together with a synchronous clock signal from the received RF signal with OOK modulation. Sequentially, the identification and command recognition operation performs digital processing, such as cyclic redundancy checks (CRC) to valid the received ID code and the control command. Finally, the passive RF module generates proper enable/disable control signals corresponding to the verified incoming command.

The passive RF uses a carrier frequency of the industrial-scientific-medical (ISM) 915-MHz band and has a data rate of...
By merging the oscilloscope, capacitor C0 and C1 are charged and discharged by turns. The 24-MHz oscillator is shown in Fig. 10(a). In this 24-MHz oscillator, the users can choose the frequencies as they want. Both use internal devices only, and do not need any external components. And both are programmable so that the users can choose the frequencies as they want.

The circuits of the two oscillators are shown in Fig. 10. The 24-MHz oscillator is shown in Fig. 10(a). In this 24-MHz oscillator, capacitor C0 and C1 are charged and discharged by turns. By merging VC0 and VC1, a saw tooth wave is generated at node N0 and compared with a reference voltage by a comparator. The T flip-flop is driven by the output of the comparator to generate a clock signal with 50% duty cycle. A second comparator U1 is used to reset the oscillator in case the frequency is too high to make a comparison by U0. The oscillator is supplied by the LDO in order to make the frequency independent of the variation of battery voltage. The 20-kHz oscillator is shown in Fig. 10(b). This ULP oscillator has a programmable RC delay cell to tune its oscillation frequency.

From simulation, the 24-MHz clock generator consumes \( \sim 250 \mu A \) current from a 2.5-V supply, while the 20-kHz clock generator consumes only \( \sim 1.3 \mu A \) current from a 3-V power supply (battery).

V. MEASUREMENT RESULTS

The designed ASIC has been fabricated in standard 0.18 \( \mu m \) CMOS technology. The ASIC occupies a die area of 2.0 mm \( \times \) 1.5 mm. The digital core takes 72.8 K equivalent gate count excluding the memories. Fig. 11 shows the photo of this ASIC on the testing printed-circuit board (PCB) with a direct chip-on-board (COB) assembly. The die photo of the ASIC is also shown in Fig. 11 (on the right side).

To validate the ASIC design, a prototype WBSN was established. An ARM7-based MCU board with a wireless transceiver served as the master node and the designed ASIC served as the slave sensor node. A commercial low-power RF transceiver working at the 433-MHz ISM band was used in this prototype for the primary communication channel. The setup of the prototype is shown in Fig. 12. Note that an extra ARM was used for field programming or debugging.

The slave sensor node was first configured to use the active standby mode, which meant that the sensor node worked and stood by periodically and was woken up by the internal timer. For the purpose of measurement, a relatively high duty cycle ratio was chosen with \( T_{\text{work}} = 0.5 \) s and \( T_{\text{standby}} = 3 \) s. To measure the current consumed by the digital core, a...
The slave sensor node was also tested with a duty cycle ratio down to 1 ms/5 min under the active standby, and the WBSN prototype worked as expected. In addition to the work-on-demand capability, the special passive standby mode offered by this design shows great advantage in terms of the standby power for the sensor node battery. Also, the secondary receiver is always on, which offers the capability of real-time work-on-demand. This secondary receiver has an energy harvesting block so that it does not consume any current from the sensor-node battery. The secondary receiver is always on, which offers the capability of real-time work-on-demand.

The standby power issue and the response latency in the WBSN have been inspected in this work, and an energy-efficient protocol with work-on-demand has been proposed for WBSN. Compared to the conventional structure, the proposed WBSN slave sensor node has a secondary wireless receiver. This secondary receiver has an energy harvesting block so that it does not consume any current from the sensor-node battery. Also, the secondary receiver is always on, which offers the sensor node the capability of real-time work-on-demand.

An ASIC that can perform the main functions of the proposed WBSN sensor node has been designed and fabricated in standard 0.18-μm CMOS technology. A prototype WBSN system was built to verify the design. The measurement results show that prototype WBSN with the designed ASIC can operate efficiently as expected. In addition to the work-on-demand capability, the special passive standby mode offered by this design shows great advantage in terms of the standby power for the sensor nodes in the WBSN for medical applications.

VI. CONCLUSION

The power consumption of the slave sensor was measured under all of the states and modes. Table IV shows the current from the battery under different states and modes. Note that the current shown in this table is the overall current of the sensor node, not just the ASIC used in the sensor node. From this table, it is clearly seen that the proposed protocol has great advantage in terms of power consumption if the sensor node is configured to use the passive standby instead of the conventional active standby, when the sensor node works with a very small duty cycle ratio. It should also be emphasized that the implemented ASIC offers the slave sensor node a work-on-demand capability, which cannot be realized with the conventional active standby mode.

### REFERENCES


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