Low Power Wake-up Receiver for Wireless Sensor Nodes

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***Abstract*—Duty cycling is a common method to reduce the energy consumption in wireless sensor nodes. Since all the nodes turn on their radio in a time slot, but only few of them actually exchange messages, energy is wasted. This can be avoided by using a separate wake-up radio. We present a new approach for a wake-up receiver that consumes 2.78 µA of current and integrates a 16 bit address coding for a selective wake-up. We use a low frequency wake-up signal that is modulated on a high frequency carrier in the main radio of the transmitting node. In the receiving node a passive demodulation circuit regains the low frequency signal and feds it to a low power low frequency wake-up IC. Four sample boards were manufactured and measured that operate at 868 MHz in the European ISM band. By using coils with high Q factors in the demodulation circuit we reached a sensitivity of -52 dBm which resulted in a wake-up distance of up to 40 meters at an output power level of +10 dBm in the transmitter. Compared to van der Doorn et. al, "A prototype low-cost wakeup radio for the 868 MHz band" Int. J. Sensor Networks, Vol.5, No.1, 2009, we achieved a 20 times farther wake-up range and a 100 times lower current consumption.**

I. Introduction

To make wireless sensor networks feasible in real world scenarios like home automation, the energy consumption of the sensor nodes must be decreased. A frequent change of the battery can increase the attendance costs of the network to a level where a wired solution is more economic. One way to reduce the energy consumption in a node is to turn off the nodes radio and to duty cycle it, controlled by an internal timer. Another way is to use a separate wake-up radio that gets triggered by an external event and that can turn on the nodes main hardware. The use of a wake-up radio permits real time behavior and avoids the overhead of time synchronization in the network.

When designing a sensor node with a separate wake-up radio some considerations should be given to the frequency range of the wake-up signal. Using high frequencies for the wake-up signal will result in a high current consumption in the receiver due to switching loses. Using low frequencies for the wake-up signal will result in a low current consumption in the receiver but in an increased antenna size and lower gain. To overcome this contradictions we present in this paper a sensor node with a separate wake-up radio that can be triggered from sleep to active mode by sending a 125 kHz wake-up signal OOK (On Off Keying) modulated on an 868 MHz carrier. In the receiving node a passive demodulation circuit retrieves the LF signal and forwards it to a LF wake-up receiver. By using this approach we combine the low current consumption of a wake-up receiver working at low frequencies with the propagation properties of a high frequency wave. Additionally a 16 bit coding in the wake-up signal is used to address only selective nodes and to avoid unnecessary wake-ups in the network. Since the wake-up signal can be sent by the main radio, every node can receive or initiate a wake-up. This makes the presented node usable in multi hop networks. Off the shelf components were used to reduce the costs of the node. The remainder of the paper is structured as follows. Section II gives an overview on related work. Section III presents the concept and the digital and analog part of the node. In section IV we present measurements in current consumption and wake-up distance. The final conclusion and a further outlook can be found in section V.

II. Related Work

Lin Gu and John A. Stankovic present in [1] a radio-triggered hardware to wake-up a sleeping node. The hardware extracts energy from the radio signal and uses a charge pump circuit to rise the voltage of the signal. Since it does not use any external power supply the wake-up range is limited. The paper compares the radio-triggered wake-up to time slot wake-up scheme and calculates the energy savings for a chosen application. Furthermore a selective wake-up approach is presented by sending the wake-up signal on multiple frequencies at the same time. A set of radio-triggered circuits which work on different frequencies is put on one node. The outputs are fed to AND-gates so that the circuit only wakes-up the node when all the corresponding frequencies are present. The number of possible addresses is very limited. When using six different frequencies, between twenty different nodes can be distinguished.

Wang et al. present in [2] a radio-triggered wake-up circuit. The signal of a transmitted wave is passed to a multistage voltage multiplier and is then used as an interrupt source for a microcontroller. The circuit presented in the paper has sensitivity of -27 dBm when sending the wake-up signal over a distance of 40 meters with a sending power of 4 Watt. Since in the European ISM band the maximum permitted sending power is at 500 mW in a 10 % duty cycle, the presented solution is not feasible for the majority of applications.

LIANG et al. present in [3] a sensor node with the low power wake-up radio ATA5283 fabricated by Atmel. The wake-up radio reacts to a 125 kHz Signal, composed of a preamble and a header, and interrupts a microcontroller from its low-power mode. The main communication is done by a CC1100 radio transceiver. The sensor node presented is a pure slave. It is not capable to transmit the wake-up signal and to wake-up neighbors by itself. This is done by a power independent node which has access to unlimited energy source. There is no comment about the achieved wake-up range.

In [4] THOMAS WENDT and LEONHARD REINDL describe different methods to wake-up a sleeping sensor node. One of the presented methods is a Frequency Diversity Wake-Up scheme in which also an Atmel wake-up receiver operating at 125 kHz is used. Wendt calculates the lifespan of a sensor node with such a wake-up receiver up to 4-5 years.

ANSARI et al. describe in [5] a TelosB sensor node with an attached wake-up radio operating in the 868 MHz ISM band. An incoming signal on this frequency pases through an impedance matching network, followed by a five stage charge pump that multiplies the low voltage so that a subsequent comparator IC can shift them to the high and low levels of the microcontroller. The transmitted wake-up signal contains address information that the microcontroller can use to state if the message was destined for it. The address decoding is done by the microcontroller and therefore leads to needless current consumption in case the message is not intended for the triggered node. The authors allude reached wake-up distances of 10 meters.

The paper from VAN DER DOORN et al. presents a sensor node equipped with a wake-up circuit working at 862MHz frequency [6]. The wake-up signals consists of an amplitude modulation of the carrier signal. An incoming signal gets amplified by three cascading low-power low-gain amplifiers and is then fed to a PIC12F683 microcontroller, which filters out residual interferences and also detects the wake-up signal. If a wake-up signal is detected, the controller interrupts the main microcontroller Atmega128 from its low-power mode. The overall power consumption in wake-up mode is measured to be 819 μW and the achieved wake-up range is 2-3 meters.

III. SENSOR NODE DESIGN

A. Concept

Figure 1 shows a block diagram of the senor node. The node has two receiving paths, one for processing a wake-up signal and one for communication with the nodes main radio. Which path is activated depends on the antenna switch situated directly behind the antenna. It is controlled via an output port of the microcontroller. Before entering the low power mode the controller sets the switch so that all incoming signals are routed to the demodulation circuit. After impedance matching, rectifying and low pass filtering only the envelope signal remains and is fed to the input of the wake-up receiver IC. In case of a valid wake-up signal and a positive correlation of the sent address with an internal saved bit sequence, the wake-up receiver interrupts the microcontroller from its sleep mode. When entering active mode the controller toggles the antenna switch and can establish a regular communication link with the nodes main radio.

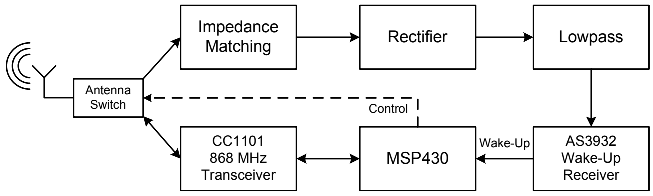

Fig. 1. Schematic of the complete node. In sleep mode, incoming signals are directed to the upper path and reach the wake-up receiver after impedance matching and demodulation. In active mode, in and outgoing signals are routed to the main radio transceiver chip for data communication.

The node can send a wake-up signal itself by configuring the main radio to amplitude modulation with infinite packet length. It then can modulate the 868 MHz carrier with a 125 kHz square signal, which itself is additionally modulated with preamble, header and address information. Figure 2 shows a drawing of the OOK carrier modulation.

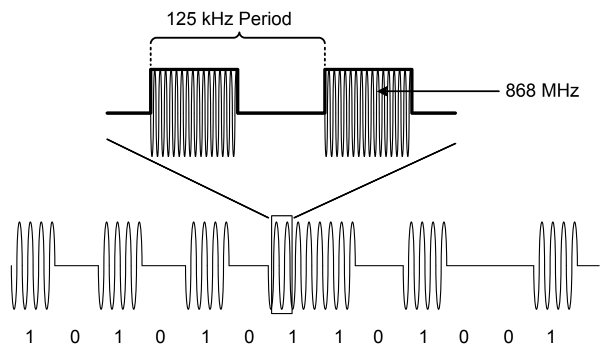

Fig. 2. The 868 MHz carrier is turned On and Off so that the resulting envelope represents a 125 kHz square signal. Additionally the square signal is modulated with an address information.

B. Digital Domain

1) Microcontroller: The used microcontroller is a MSP430F2350 by Texas Instruments. It was chosen because of the current consumption of 0.5 µA in its Low Power Mode 4 (LPM4) where the CPU as well as all components are disabled. Switching time from sleep to active mode is calculated to 32 µs [7]. While in sleep mode, the controller can still react to an external interrupt on one of its I/O-pins. The lower limit in RAM was defined to at least 2 KByte in order to have flexibility in testing different MAC protocols.

2) Radio Transceiver: Texas Instruments CC1101 Transceiver IC is used as the nodes main radio. It is one of the low power transceivers available in the 868 MHz ISM (Industrial, Scientific, Medical) band in Europe and is verified to work properly with the MSP430 devices. The CC1101 supports different modulation schemes as well as simple On Off Keying and is able to send data packets with infinite length. According to the CC1101 datasheet [8] the current consumption in active mode with +10 dBm output power is at 30 mA in transmit mode and at 15 mA in receive mode.

3) Wake-up Receiver: Low power wake-up receiver are used for keyless-go entry systems in automotives. They are build to work a long time without a battery change and therefore operate at low frequencies. The short wake-up range of about 3 meters due to inductive coupling is of no limiting factor for the keyless-go application. In our node we used the AS3932 wake-up receiver from Austriamicrosystems [9]. It consumes in one channel listening mode 2.7 µA current and has a wake-up sensitivity of 100 μV_{RMS} as well as a high input impedance of 2 MΩ. One of the main reasons for choosing the AS3932 is, that it has an integrated correlator which compares the received signal to a byte pattern saved in a configuration register. When the two signal match, the "wake" output of the chip changes its logic state and a connected microcontroller can receive the signal on an interrupt capable input port.

4) Antenna Switch: There are two routes in our node which data signals can propagate from the antenna to the node hardware. One ways is directly to the main radio transceiver, the other way is through the analog circuit. In order to avoid having two antennas on one node we integrated a low power antenna switch to manage the propagation of incoming signals. The ADG918 switch from Analog Devices has a high off isolation of 43 dB at 1 GHz and consumes less than 1 µA current. A digital input port sets the output direction.

C. Analog Domain

The analog domain is an important factor in the performance of the wake-up receiver since non-ideal impedance matching will result in a shorter wake-up distance. The analog domain of the presented node consists of a matching network, two demodulation diodes and a low pass filtering circuit as can be seen in figure 3.

The impedance matching network and the demodulation diodes were simulated with Agilents Advanced Design System (ADS) software. In the sample boards capacitors from Muratas GJM series and wire wound coils from Coilcraft were used.

IV. Experimental Results

A. Current Consumption

In the design for the sample board pin connectors were inserted at the Vcc line of the ICs and at the battery. To measure the current consumption a Keithley 6514 System Electrometer was inserted in series. All measurements were repeated on four identical manufactured sample boards. Table I shows the individual current consumption of the ICs as well as the overall current consumption measured for four nodes.

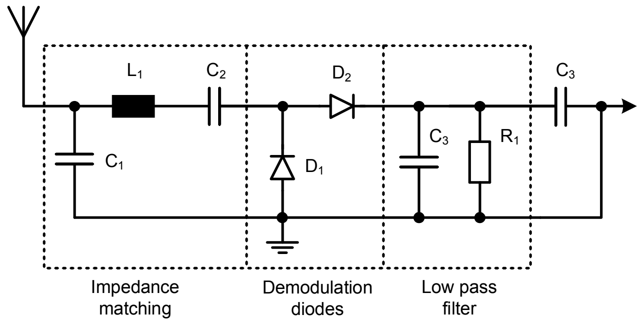

Fig. 3. Schematic layout of the analog circuit. After impedance matching, the signal is demodulated by the diodes D1 and D2, and low pass filtered by C3 and R1. The capacity C3 removes the DC offset.

TABLE I
CURRENT CONSUMPTION OF NODE IN SLEEP MODE

Node	MSP430	CC1101	ADG918	AS3932	Total
1	143 nA	6 nA	4.0 nA	2.586 μA	2.743 μA
2	152 nA	11 nA	5.0 nA	2.567 μA	2.742 μA
3	190 nA	13 nA	5.0 nA	2.610 μA	2.840 μA
4	189 nA	7 nA	6.7 nA	2.590 μA	2.800 μA
$\bar{x}$	169 nA	9.3 nA	5.2 nA	2.588 μA	2.781 μA

The Total measured current is about equivalent to the added single currents of one node. A sensor node manufactured like the one presented here has an average current consumption of 2.78 µA in idle mode.
Table II shows the current consumption when sending the wake-up signal. The wake-up signal was transmitted in an infinite loop without any delays with the nodes main radio.

TABLE II
CURRENT CONSUMPTION OF NODE WHILE SENDING THE WAKE-UP SIGNAL

Node	MSP430	CC1101	ADG918	AS3932	Total
1	460 μA	14.6 mA	3.0 nA	2.59 μA	14.9 mA
2	470 μA	14.4 mA	3.2 nA	2.61 μA	14.7 mA
3	500 μA	14.7 mA	4.0 nA	2.62 μA	14.9 mA
4	490 μA	14.5 mA	4.0 nA	2.59 μA	14.8 mA
$\bar{x}$	480 μA	14.5 mA	3.5 nA	2.60 μA	14,8 mA

The current consumption of the whole node while sending the wake-up signal is dominated by the current consumption of the main radio transceiver IC. The measured currents correspond to the values in the datasheet of the transceiver for transmission at +10 dBm output Power with a consumption of 33.4 mA. Since we periodically turn on and off the transceiver to get a 125 kHz signal the measured current consumption is about half of this value.

B. Sensitivity

The sensitivity has been measured by using a Rhode & Schwarz signal generator SMA-100. The wake-up receiver was configured to detect a continuous 125 kHz signal without address information. A wake-up of the node was signaled by an led on the sample board that was turned on by the micro-controller. The minimum power level of the signal generator, while still waking up the node, was measured to -53 dBm.
To measure the sensitivity with an active address correlation two nodes were connected directly to each other with a variable attenuator in between. Both nodes were programmed with the same address information, one as a sender, the other as a receiver. A successful wake-up was observed up to an attenuation of -52 dBm.
To verify an optimum impedance matching a frequency sweep from 800 MHz to 900 MHz was done and the reflections were measured using an Agilent E5071B network analyzer. As can be seen in figure 4 the fewest reflections can be measured at 868 MHz which is the nodes main radio operating frequency.

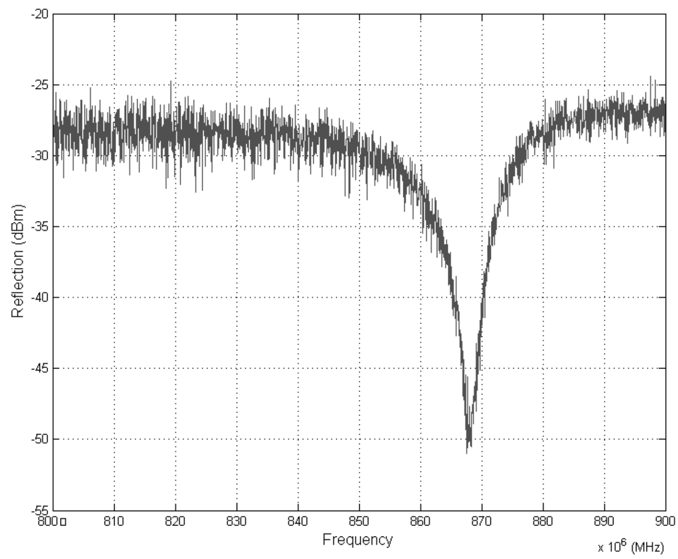

Fig. 4. This figure plots the reflection against a frequency sweep between 800 and 900 MHz. The fewest reflections are reached at about 868.3 MHz which is the operating frequency of the radio transceiver.

C. Wake-up Distance

The wake-up distance is an important factor in the design of a wake-up receiver. A wake-up distance of only a few meters would mean that more sensor nodes are needed to pass information between two specific points. This results in increased costs. We measured the wake-up distance of the wake-up receiver in an open air test site. One node was configured as a transmitter sending the wake-up signal with included address information at variable output powers in an infinite loop. Two other nodes (Node 1 and Node 2) were configured as sleeping receiver nodes. We used two receiver nodes at the same time in this experiment to compensate possible manufacturing errors. The sending node had a fixed position whereas the receiving nodes were moved successively away. We measured the farthest distance the receiving nodes would still wake-up for an output power from -30 dBm up to + 11 dBm at the transmitter. Packet error rate (PER) was accepted up to 5% which means that in one of twenty sended wake-ups it was tolerated if the sleeping nodes did not wake-up. Sending and receiving nodes were attached to poles with a height of 1 meter. Measurement place was an open air field with line of sight. The results can be seen in table III.

TABLE III
WAKE-UP DISTANCE AGAINST SENDING POWER

	Distance	
Power	Node 1	Node 2
-30 dBm	0.38 m	0.37 m
-20 dBm	1.33 m	1.32 m
-10 dBm	3.70 m	3.70 m
0 dBm	16.8 m	15.2 m
+10 dBm	38.8 m	37.8 m
+11 dBm	45.0 m	44.9 m

D. Lifespan

A sensor node reaches the end of its lifespan either when one of the components of the node breaks down due to aging or environmental effects or because the power source of the node is drained out. The lifespan is an important parameter of a sensor node since it is directly connected to the longterm costs of a wireless sensor network. This longterm costs originate from the expenses needed to change the batteries in the nodes. Our node is powered by a standard CR2032 coin cell with a capacity of 230 mAh at 3V. The nominal capacity of 230 mAh is determined to an end voltage of 2.0 V when the battery is allowed to discharge at a standard current level at 23° Celsius [10]. We measured the node operable down to a voltage of 1.8 V in idle as well as receive mode. Therefore we can assume, that we have the full 230 mAh charge of the coin cell at our disposal. The maximum life span T_{maxidle} of the node can be calculated using equation 1.

$$T_{\text{maxidle}} = \frac{230\, mAh \cdot d \cdot a}{3.23\, \mu\text{A} \cdot 24\, h \cdot 365\, d} = 8.13\, a \tag{1}$$

The node has a theoretical standby time of about 8 years, if we assume that it does not get waken up during that time. When using a coin cell of type CR2477 with 950 mAh the maximum lifetime of the node can even be stretched to about 33 years.
In a typical application a node will wake-up more than once in its lifetime. Therefore the calculated values above do not match with real scenarios. We define an interval T_{int} in which the node wakes up once. The reciprocal value of T_{int} is

the wake-up frequency f_{int}. Time T_{send} is the time period it takes for one node to send the wake-up signal. T_{idle} is the difference between T_{int} and T_{send} and defines the idle time in which the node is in sleep mode ($T_{\text{idle}} = T_{\text{int}} - T_{\text{send}}$). We then can calculate the total charge needed in T_{int} by $Q_{\text{int}} = (T_{\text{send}} \cdot I_{\text{send}}) + (T_{\text{idle}} \cdot I_{\text{idle}})$. The total charge of the battery is $Q_{\text{bat}} = 230\, mAh = 828\, As$. When divided by the charge of one interval Q_{int} we get the quantity of intervals that can be send with the capacity of the battery. This quantity multiplied by the duration of the interval T_{int} gives the total lifetime in seconds for the sensor node till the battery is depleted. Divided by the factor 3600 gives the lifetime of the node T_{dnode} in days. We can sum this up in equation 2.

$$T_{\text{dnode}} = \frac{Q_{\text{bat}} \cdot T_{\text{int}}}{(T_{\text{send}} \cdot I_{\text{send}} + (T_{\text{int}} - T_{\text{send}}) \cdot I_{\text{idle}}) \cdot 3600} \qquad (2)$$

If we plot the duration of the time interval in which the wake-up signal is sent once on the x-axis of a chart and the corresponding calculated T_{dnode} values divided by 365 on the y-axis using the values in table IV we get figure 5. The figure plots the lifetime for three different types of batteries in years.

TABLE IV
PARAMETERS IN T_{DNODE} CALCULATION

Symbol	Description	Value
Q_{bat}	Battery capacitance	var.
T_{send}	Wake-up signal send time	13 ms
I_{send}	Current sending wake-up signal	15 mA
I_{idle}	Current in sleep mode	3.23 μA

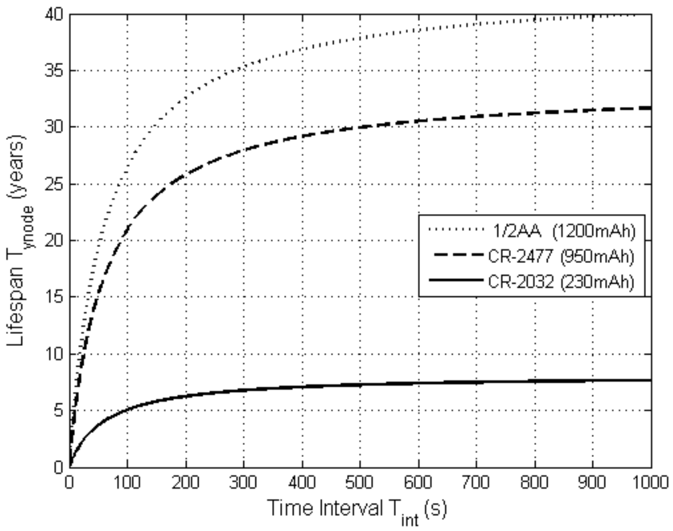

Fig. 5. This figure plots the lifespan of the node in years against the time interval in seconds in which the node wakes-up once for different types of batteries.

The longer the time interval in which the wake-up signal is sent once, the less weight gets the T_{send} value compared to the T_{idle} and the curve gets flattened.

E. Overall System

We built four sample boards including the analog and digital part as well as a cell coin battery on one single PCB board. Additionally we placed two push buttons, a programming interface and three LEDs on the board. An SMA connector was used to plug in a $\lambda/2$ antenna for 868 MHz. For the sample boards two layer PCBs in FR4 material were used. One of the assembled boards can be seen in figure 6.

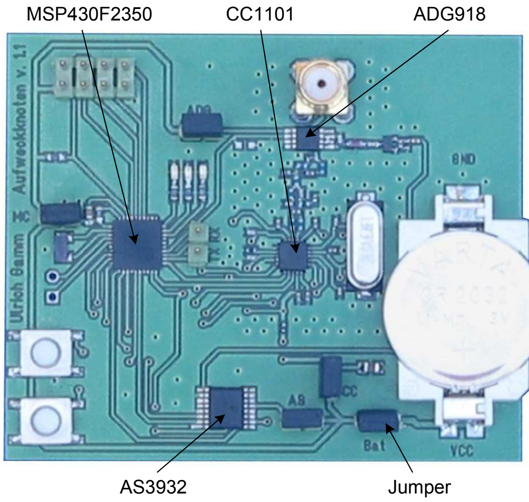

Fig. 6. Assembled node using SMD components and a two layer PCB-board.

The sent wake-up signal with included address pattern was logged with an oscilloscope and can be seen in figure 7. The first part of the signal is the carrier burst followed by a 10 bit header. The final part is the 16 bit address pattern. The total length of the wake-up signal is measured to 13 ms.

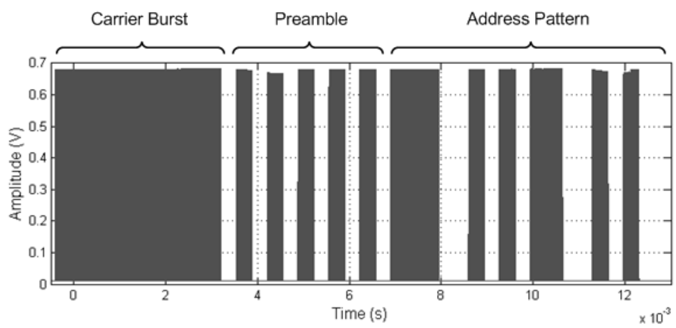

Fig. 7. Wake-up signal consisting of carrier burst, header and address pattern.

V. CONCLUSION AND OUTLOOK

Wake-up receiver provide a promising approach to reduce the current consumption and latency in wireless sensor networks. The disadvantages of current wake-up receivers in form of a short wake-up range and a high idle current consumption could be improved by the presented design. The main radio of the sensor node is used to send a wake-up signal with OOK modulated low frequency 16 bit address information. In the receiving node the incoming wake-up signal is passively demodulated, filtered and fed to a low frequency wake-up receiver IC. The combination of a high frequency carrier for the wake-up signal with the low frequency of the wake-up receiver IC leads to a standby current consumption of 2.78 µA. An improved impedance matching and demodulation circuit produced a sensitivity level of -52 dBm for the receiving node. When sending a wake-up signal with the nodes main radio at +10 dBm output power a wake-up distance of nearly 40 meter was achieved. The theoretical maximum standby time of one node powered by a CR2032 coin cell was calculated to 8 years. The next steps in further development are to reduce the size of the node and to integrate a PCB antenna. More effort can be done in the impedance matching to improve the over all sensitivity of the wake-up receiver. Longterm aim should be to level the nodes main radio distance with the wake-up distance. A more advanced step would be to integrate the microcontroller, the RF-radio and the wake-up receiver on one single chip. The resulting decrease in size and cost would accelerate the use in many applications.

Acknowledgment

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