Ultra-Low-Power Sensor-Node with Wake-Up-Functionality for Smart-Sensor-Applications

Felix Pflaum #, Robert Weigel #, and Alexander Koelpin *

#Institute for Electronics Engineering, Friedrich-Alexander-University of Erlangen-Nuremberg,
Cauerstrasse 9, 91058 Erlangen, Germany, Email: felix.pflaum@fau.de
*Chair for Electronics and Sensor Systems, Brandenburg University of Technology (BTU),
Siemens-Halske-Ring 14, 03046 Cottbus, Germany

***Abstract*— In this paper a complete mobile sensor node which has the ability to monitor temperature, atmospheric pressure, relative humidity, brightness and magnetic fields is presented. Very low power consumption is achieved due to deliberate component selection, cyclic and/or on-demand-operation made possible by a low-power wake-up circuit with improved sensitivity, which allows the controller, transmitter and sensors to be in a battery-saving inactive mode for most of the time. Additionally, the sensor node can also be localized within a previously calibrated area.**

I. Introduction

Smart houses and factories are trending topics nowadays aiming at improving life quality and production processes as well as saving costs and valuable resources. For these purposes wireless sensor networks (WSNs), which deliver the information needed to optimize parameters like heating, ventilation or illumination levels in a given environment, are key. However, it has to be taken into account that they should not consume more energy than they help saving. Therefore smart concepts for energy management are essential for the development of modern WSNs, which in many cases still rely on battery power due to absence of solar light or energy harvesting possibilities. Reliable performance in combination with long battery-lifetime is very important for acceptance among users. Maintainability is also a big issue regarding modern WSNs, which often can contain a three-digit-number of nodes running on batteries, as well as network traffic. Therefore it is desirable to be able to explicitly specify, when a certain node should transmit its data, so data collision – and the accompanying useless battery drain on two or more nodes – can be avoided. Targeting this issue wake-up-receivers (WuRXs) with low power consumption allow for long-lasting mobile battery-powered nodes because all other devices can be powered down while waiting for a wake-up call.

II. Sensor Node

The proposed sensor node to acquire environmental parameters either based on a time-based schedule or on demand was designed for sensor and automation applications in home or industry environments where data from different places have to be collected at a central point.

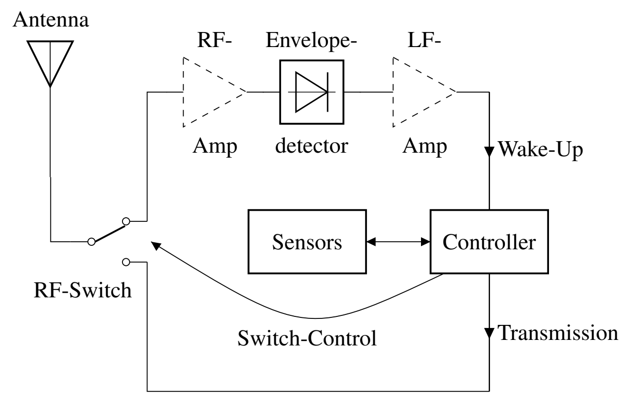

Fig. 1. Block diagram of the sensor node's functional units

It is managed by an Infineon PMA5110, which includes an 8051-microcontroller as well as a transmitter operating in one of the license-free bands around 434 and 868 MHz in Europe or 315 and 915 MHz in the USA and a WuRX with an operating frequency in the low frequency (LF)-domain at 125 kHz [1].

For data aquisition the sensors Bosch BME280 (temperature, air pressure, relative humidity) [2], Vishay VEML6030 (brightness) [3], and Honeywell HMC5883L (magnetic field) [4] are connected to the microcontroller through an Inter-Integrated Circuit (I^2C)-bus. To minimize energy consumption all sensors were selected with particular focus on current consumption and could be measured to draw less than 1 µA when inactive at room temperature. To further increase battery lifetime as few calculations and operations as possible – besides data acquisition and transmission – are performed on the sensor node and the highest data rate possible is chosen for wireless data transmission to minimize the on-time of the transmitter.

Figure 1 shows the sensor node's operation principle in a block diagram without the matching networks necessary for minimizing reflections between components: If a wake-up-call is received, the sensors are activated and read out before the antenna gets switched to the transmission path and data are transmitted. Afterwards, the antenna will be switched back to the receiver path. Optionally, if only data transmission with a fixed update rate is needed and there a only few nodes in the network, which makes data collision unlikely, the WuRX can be disabled in software for further energy-saving at the cost of flexibility. The wake-up-path with its amplifiers and the envelope detector will be described in detail in section III.

The sensor node transmits its data to a base station, which consists of multiple receivers. Although a single receiver would be sufficient for data exchange, the multi-receiver setup offers the possibility to not only acquire sensor data but also to localize the position of the mobile sensor node. The localization algorithm based on multivariate statistic techniques only relies on previous calibration of possible locations and draws necessary information from the data signal, so no further effort from the node's side is necessary. Still, the algorithm already has been presented in [5] and is not the focus of this work.

III. Wake-Up-Receiver

A. State of the art

WuRXs offer great potential for applications in WSNs due to their low energy consumption while monitoring wireless channels. Unfortunately, operating frequencies of commercially available WuRXs like [6] are mostly limited due to proportionality between frequency and power consumption. Commercially available receivers operating in frequency ranges over 100 MHz consume a sizeable amount of energy during on-times, even if they are branded as "low current" [7]. Sensitive WuRXs at radio frequencies have been presented in recent years [8] but are not available from distributors yet.

B. Signal generation

The PMA5110's built-in wake-up-receiver operates on On-Off-Keying (OOK) with a carrier frequency of 125 kHz with a current consumption of only 1 µA. However, as antenna size is proportional to wavelength, which amounts to 2.4 km at 125 kHz, a direct over-the-air transmission at low frequencies is not always feasible on compact nodes.

Therefore, the 125 kHz-OOK-signal is modulated on an 868 MHz-carrier for over-the-air-transmission and recovered by an envelope detector. According to its specifications the PMA5110's receiver expects an amplitude-modulated signal with a carrier frequency of 125 kHz and a data rate between 2 $\frac{\text{kbit}}{\text{s}}$ and 4 $\frac{\text{kbit}}{\text{s}}$. Thus, on the wake-up-transmitter side an OOK-signal with a carrier frequency of 868 MHz and a data rate of 250 $\frac{\text{kbit}}{\text{s}}$ is generated.

To illustrate this method the simulation in figure 2 shows the bit sequence "11010110" in OOK-modulation where a "1"-bit is represented by a $\frac{1}{250\,\text{kHz}}$-long high-frequency-burst followed by an equally long period of silence, whereas a "0"-bit just consists of silence. As can be seen, the rectified envelope can be interpreted as

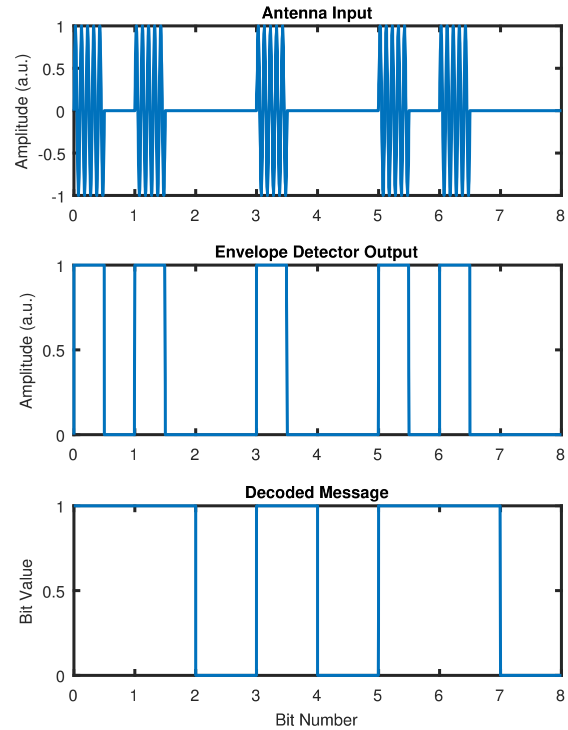

Fig. 2. Simulation of creating an LF-OOK-signal from higher frequency OOK-bursts

a rectangular oscillation at 125 kHz that represents the sequence. For purposes of presentation data rate and LF carrier frequency are chosen equal in this example.

C. Signal decoding and analog pre-processing

The approach of modulating the LF-signal on an radio frequency (RF)-carrier has the advantage that the same antenna can be used for data transmission and wake-up-call-reception at the sensor node. The low-power two-way RF-switch CG2179M2 [9] by default connects the Rx-path to the antenna but is switched to the Tx-path as soon as sensor data are due to be transmitted after a wake-up-call has been registered. PMA5110's built-in WuRX is specified with a minimum sensitivity of 2.5 mV peak-to-peak, which corresponds to a necessary input power of −48 dBm to wake up the controller. Taking into account Friis' equation (1)

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2, \tag{1}$$

with unity gain for Tx- and Rx-antennas a maximum range of 22 m can be achieved under ideal conditions for a 868 MHz assuming a transmission power of 10 mW. As this range is very unlikely to be actually reached in an indoor environment with omnipresent shadowing and

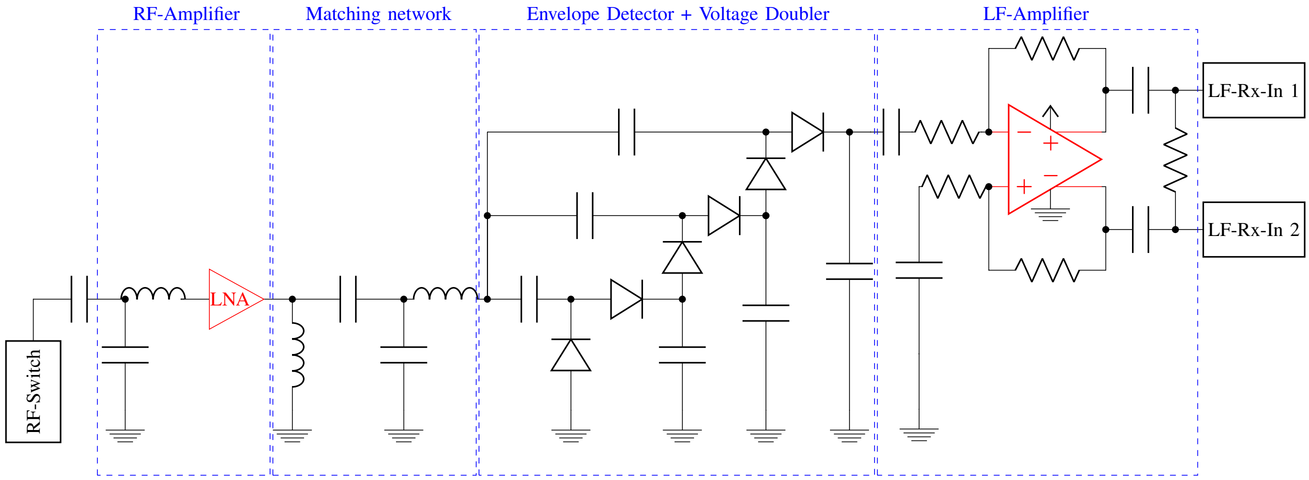

Fig. 3. Signal processing circuit for the wake-up-receiver with LNA, matching, envelope detection, voltage doubling and LF-amplification

shielding obstacles the node was designed with a potential to increase the wake-up-sensitivity through additional amplification in the LF- and RF-domain before and after envelope-detection, respectively.

The circuit used to process the received data for maximum sensitivity consisting only of commercial “off the shelf”-parts is shown in figure 3. It can be divided in four major blocks and active components are drawn in red. First the input signal is amplified in the RF-domain by a low noise amplifier (LNA) whose in- and output have to be matched to the surrounding circuits for minimal reflections. The LNA is a Maxim Integrated MAX2643 [10], chosen due to its low shutdown-current, short turn-on time, and high amplification. Afterwards, the envelope detector built with three zero-bias Schottky-diode pairs SMS-7630 from Skyworks [11], which has been designed for a limiting frequency of 1 MHz, will restore the 125 kHz-signal. As proposed in [12] the envelope detector also acts as a charge pump to amplify the input voltage. In the following block a fully differential operation amplifier THS4531 from TI [13] – also chosen due to implemented shutdown-switch and low power demand – with ac-coupled in- and outputs acts as an amplifying single-ended to differential converter for the differential inputs of the WuRX. Both amplifiers are optional taking into account the compromise between sensitivity requirements and energy consumption as will be shown in sections IV-B and IV-C.

IV. Measurements

A. Input return loss

The measured input reflection coefficient S_{11} for the Rx-path is shown in figure 4. At the carrier frequency 868 MHz the input return loss is bigger than 11.4 dB, so less than 7.5 % of incident power are reflected.

B. Wake-up sensitivity

To determine the sensitivity of the wake-up-circuit in different configurations a 868 MHz OOK-signal with a data rate of 250 $\frac{\text{kbit}}{\text{s}}$ was injected into the Rx-path through the antenna connector. The RF-power-level was turned up until a light emitting diode signalized the awakening of the node.

The smallest power at which the sensor node could still be activated from sleep mode without any amplification in the RF- or LF-domain was −37 dBm, which is equivalent to a theoretical maximum distance of only 6.2 m to the central base station assuming a transmission power of 10 mW.

Using the LF-amplifier while bypassing the LNA boosted the sensitivity threshold to −62 dBm, equivalent to a distance of 97 m. With lower RF-input-power the output

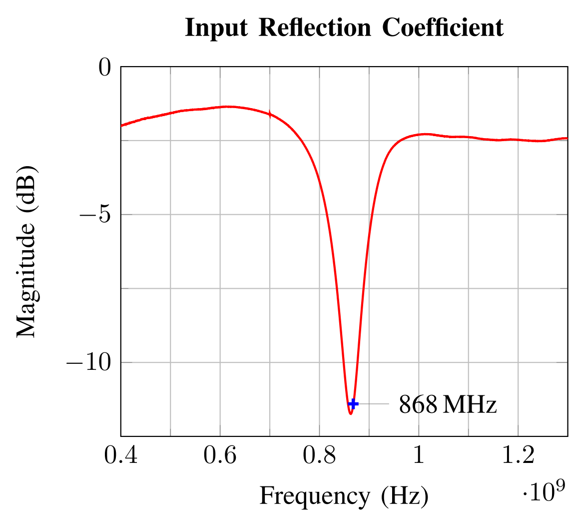

Fig. 4. Input reflection coefficient S_{11} of the Rx-path

of the envelope detector is dominated by noise and the carrier at 125 kHz cannot be restored any more.

Therefore, before the signal passes the envelope detector, pre-amplification is performed in the RF-domain, which provides an additional sensitivity boost, so the node is still waking up at an RF input power of −71 dBm, which corresponds to a peak-to-peak voltage of 3.7 µV. This means a maximum sensitivity boost of 63.5 compared to [6] and leads to a theoretical maximum wake-up range of more than 300 m.

C. Energy consumption

The node must be supplied with at least 2.7 V to make all of its parts work properly. As typical coin cells like CR2032 deliver a voltage of 3 V this value was applied for all measurements.

The current I_{supply} drawn by the node during power down mode while waiting for a wake-up receiver call without any of the amplifiers active adds up to 2.7 µA. If the wake-up receiver is disabled, too, and the node thus simply works on a certain time schedule, its current intake reduces even further to 1.7 µA, which is lower than in comparable approaches [14].

The MAX2643 and THS4531 draw 5.8 mA and 200 µA when permanently active and less than 1 µA in total when inactive, respectively. As they can be turned on and off within 5 µs, they can be operated in duty-cycled mode controlled by an ultra-low-power timer, the TPL5010 from TI, which only needs 35 nA to operate [15]. The average current consumption I_{avg} can then be calculated depending on off-time and on-time as:

$$I_{\text{avg}} = \frac{I_{\text{on}} \cdot t_{\text{on}} + I_{\text{off}} \cdot t_{\text{off}}}{t_{\text{on}} + t_{\text{off}}} \tag{2}$$

If the node is synchronized with the base station and listening at highest sensitivity for 10 ms at a frequency of 1 Hz the average current drawn by the amplifiers is 61 µA. If the RF-amplifier is not used the amplifier current consumption reduces to 3 µA for the same scenario, which results in a supply current of 5.7 µA for the node in total. The current consumption during data acquisition from the sensors and transmission is 1.96 mA and 12 mA for 6.4 ms and 6.54 ms, respectively.

Thus, a sensor node acquiring and transmitting data every minute without wake-up-function draws an average current of 3.2 µA, allowing it to run more than eight years on a CR2032-battery with 230 mA h. A wake-up-driven node consumes more energy in the inactive state but can be operated in a more flexible way, so the operation mode has to be determined according to the application scenario. For the highest sensitivity still a theoretical lifetime of 140 days can be calculated.

V. Conclusion

This paper presented a low-power sensor node to measure environmental parameters for potential application in smart-home or smart-factory environments, which has been designed with special focus on low energy consumption and remote on-demand operation with an improved wake-up-circuit. The latter can detect signal levels down to an input power of −71 dBm. An average current consumption of 1.7 µA and 2.7 µA could be achieved during power down mode when the wake-up amplifier was inactive and active in the least sensitive state, respectively. Depending on the update rate and sensitivity demands the node can either be triggered from long distance or run several years on a single coin cell.

Acknowledgment

The authors wish to acknowledge the support of Infineon Technologies AG and thank for providing the hardware equipment.

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