A highly sensitive and ultra-low-power wake-up receiver for energy-autonomous embedded systems

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Abstract. This article presents the design, optimization and characterization of an ultra-low-power wake-up receiver for embedded wireless sensor nodes. The RF part of the circuit is based on an optimized diode detector for an amplitude-modulated (AM) 315 MHz RF carrier, followed by an ultra-low power low-frequency (LF) amplifier for the demodulated signal, and a commercial ultra-low-power wake-up receiver IC. Special emphasis has been put into optimizing the RF part with respect to its input sensitivity and selectivity. With two different versions of this circuit part, RF reception sensitivity could be raised from -52 dBm to -63 dBm. Power consumption is 7.4 µW at a minimum supply voltage of 2 V.

1. Introduction

Today, the development of embedded wireless sensor systems is driven by a number of up-coming - or already present - target applications, like medical assistive devices and implants, Internet-of-Things (IoT) technologies and distributed sensor systems in smart buildings, structural health monitoring, industrial sensing, automotive or aircraft applications. In many of these application areas a large number of sensor nodes are deeply embedded into their respective application sites. This calls, inevitably, for selective wireless communication between nodes and respective base stations, as any wired connectivity would severely reduce flexibility in application, deployment, modification or service. Also, communication is frequently bidirectional and non-synchronized: A base station must, for instance, be able to address an individual wireless sensor node (WSN) at deliberate times to reprogram the WSN’s tasks or to retrieve information on demand.

In this situation a serious problem arises from the fact that every WSN has to listen, more or less continuously, to potentially incoming messages. In a conventional system design this would require, at least, regular and frequent up-times of the WSN and its RF transceiver. The system will wake up for a short time, activate its wireless communication interface and listens to potentially incoming messages. If no message arrives, this effort is fruitless and wastes energy. The unnecessary power drain from the system battery or energy harvesting unit is considerable and will reduce the WSNs operational lifetime and reliability, especially if it is not easily accessible for service.

In this situation, energy-autonomous as well as battery-operated WSNs do greatly benefit from the integration of a wake-up receiver. This unit listens continuously for incoming wireless communication while consuming an absolute minimum of electrical power and wakes up the system from its power-saving sleep mode only if a valid communication request is detected. Its task is merely to receive basic information at a low data rate, e.g. the address of a specific WSN to be accessed. Therefore, energy-saving receiver concepts are conceivable.
2. Wake-up receivers: Requirements and state-of-the-art

The premier requirement for a wake-up receiver is ultra-low-power operation. Moreover, its RF frequency range should allow for long-range communication in order to reach a WSN over a larger distance. Receiver sensitivity must be high from the same reason. With a widespread commercial application in mind, the use of a license-free frequency range, like one of the available ISM bands, is preferable. As these frequency bands may be highly covered, selectivity must be good enough to suppress interferences from neighbour RF channels. Finally, the wake-up receiver should be available in a highly compact form, e.g. as integrated circuit.

Taking the measures of that time, low-power receivers have been available as integrated circuits in the 1970s already: For instance, an AM medium wave receiver of the company Ferranti was operational from a supply voltage of 1.1 V only, with 200 µA supply current [1]. High RF sensitivity (typ. 50 µV) was achieved through the integration of a multi-stage amplifier for the demodulated audio signal. Automatic gain control was realized for receiving signals from both weak and strong transmitters.

These design elements are also present in all modern commercial wake-up receiver ICs [2,3,4]. Similar to [1] they operate at low frequencies (LF, typ. 125 kHz) for the sake of low power consumption (typ. a few µW). This does, however, require large electrical antennas or magnetic pickup coils. High-frequency wake-up receivers usually consume much higher power if realized as ICs. Gamm et al. [5] have shown a solution for this design trade-off: By modulating a high-frequency carrier with a pulsed LF signal, they combine the advantages of high frequency communication (smaller antennas, larger distances) with the low power draw of integrated LF wake-up receivers. The same concept is found in [6], others use the WSN’s microcontroller for data decoding [7,8].

In all cases RF transmission is based on amplitude modulation (AM), and all receivers use a diode detector as RF frontend. The main reason for this choice, despite its limited channel resolution and noise immunity, is again power consumption: Frequency or phase modulation are more reliable and tolerant against interferences, however would require a much more power-hungry circuitry, whereas a detector radio is using the energy present in the RF signal itself for demodulation.

3. Design concept

Combining the benefits of the concepts outlined above, the wake-up receiver realized within this study uses a diode detector as RF stage with a LF amplifier for improving overall reception sensitivity [1] and a commercial LF wake-up receiver IC for further signal amplification and data decoding [5]. The receiver operates within the 315 MHz ISM band and requires a pulsed, amplitude-modulated signal.

Figure 1 shows the circuit diagram with two different implementations of the RF detector circuit.

Figure 1. Schematic circuit diagram of the wake-up receiver.

The detector output signal is fed into a two-stage LF transistor amplifier and, from there, into the input of the LF wake-up receiver IC [10]. The LF amplifier is made from two high-gain bipolar transistors (BC 860 C) with a current mirror at their collector terminals. Gain and bias set-point of both transistor
stages are adjusted via respective collector-emitter feedback resistors $R_2$. Capacitive AC coupling is realized between all stages. The amplifier and all other active circuit parts operate at VDD = 2V.

The commercial wake-up receiver IC in use is designed for ultra-low-power and low-frequency operation within upper and lower corner frequencies of 180 kHz and 30 kHz, respectively [4]. To match this frequency range, a pulsed modulation frequency of 32.768 Hz was used for digital data transmission. At the transmitter every data bit representing a logical “1” will turn on the 32 kHz modulation, whereas a logical “0” will lead to the transmission of an unmodulated carrier signal. After demodulation and amplification, a pulse train of 32 kHz bursts will appear at the input COIL of the wake-up receiver IC to be further amplified, decoded and presented as serial data stream at the output N-DATA. The maximum power consumption for this IC is approximately 2.8 µW at 2 V.

A global or an address-dependent wake-up can be performed as required: Global wake-up occurs after a valid signal has been present at the input COIL for a fixed latency period. Then, a digital wake-up detection signal appears at the output WAKE-UP for e.g. activating a connected microcontroller. Now, additional data, e.g. an address, can be transmitted and will appear as serial data stream at the output DATA to be decoded by the activated microcontroller. The WAKE-UP signal is latched and has to be cleared via the ICs input RESET. This could be done easily by the microcontroller. As an alternative and as safety feature, a logic circuit has been implemented instead with four NAND Schmitt trigger gates to enable - after a pre-set time - an automatic reset of the wake-up receiver and the system’s microcontroller (output µC RESET). Microcontroller reset can be prevented via the input INHIBIT. This allows the automatic reset of a non-responding microcontroller by simply sending a wake-up signal. As this logic circuit is optional, its power consumption is not taken into account in table 1.

4. Implementation, optimization and characterization
The RF detector circuit and the LF amplifier have been optimized with regard to their performance and power consumption. Fig. 2 shows the frequency-dependent gain of the LF amplifier as a function of its supply current, with an obvious trade-off between both. Finally, voltage gain was set to appr. 10 at 32 kHz, with a power consumption of 4 µW at a supply voltage of 2 V. Therefore, a demodulated signal with 100 µVRMS amplitude is sufficient for wake-up, taking the input sensitivity of the wake-up receiver IC (1 mVRMS) into account.

The RF detector was optimized step-wise towards higher sensitivity. Characterization was done by applying an amplitude-modulated RF signal (100% modulation depth) directly at the antenna input and by recording the minimal RF input power required for detecting a valid wake-up. As a starting point, the non-optimized version 1 uses a LC tank ($L_1$, $C_1$) for frequency tuning, a RF Schottky diode (Agilent HSMS 285) for demodulation and the capacitor $C_3$ for filtering. Although not optimized, the RF sensitivity of version 1 does already reach -52 dBm.

In contrary to that, version 2 was optimized with respect to maximal power transfer from the antenna to the detector, using an antenna matching network composed from $L_2$ and $C_2$. As a result, the input impedance of version 2 is close to the desired 50 Ohm, which represents the typical impedance of an ideal whip antenna. The input reflection coefficient $s_{11}$ of version 2 is given in figure 3. At resonance, version 2 of the detector circuit has an input sensitivity of -63 dBm.

Practical implementation was made on standard double-sided printed circuit boards (PCB, FR4 with 0.8 mm thickness). For comparison of RF detectors, exchangeable test boards were built with a common shield layer on one side and the SMD components placed on the other side. SMA connectors were used for the antenna input and an edge connector to connect these boards to the rest of the circuit.

Figure 2. Voltage gain of the LF amplifier as a function frequency and of supply current, with a supply voltage of 2 V. Resistor $R_1$ is used to adjust the supply current (see fig. 1).
In addition, an integrated version was built with the wake-up receiver on one PCB side, as visible in Figure 4. All digital logics are placed onto the backside for the sake of small board dimensions.

### 5. Discussion and Conclusions

As shown in table 1, the input sensitivity of the non-optimized version 1 is already in the typical range known from a number of other publications. The sensitivity of version 2 is significantly higher. A power consumption of 7.4 µW is typical for the majority of wake-up receivers presented so far. This value could, however, be reduced by operating the LF amplifier at lower power: Taking the same input impedance at the RF input, a LF voltage gain of only 5 at 32 kHz, with a total power consumption of approximately 3.5 µW, would still result in a calculated RF sensitivity of approximately -60 dBm. This leaves the user with the freedom to decide whether low power consumption or high RF sensitivity is preferable. Also, a further optimization, e.g. by choosing a lower modulation frequency in conjunction with suitable wake-up detection, leaves additional room for a reduction of power consumption.

### 6. Acknowledgement

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