A narrow-band and ultra-low-power 433 MHz wake-up receiver

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Abstract. For the design of wireless sensor nodes (WSNs) the inclusion of a wake-up receiver becomes interesting as soon as an asynchronous bidirectional communication between the WSN and its host is mandatory, to e.g. reprogram the WSN or to trigger the delivery of data. For these purposes the use of the WSNs standard RF interface is not suitable in most cases, as the high power consumption of the same may drain the WSNs battery or overload the capabilities of an integrated energy harvesting module. To solve this principal conflict between flexibility and power consumption, we present the design and characterization of an ultra-low-power wake-up receiver. The concept is based on an optimized modulation/demodulation concept, to achieve a high RF sensitivity and narrow-band operation at the same time. The final device works in the license-free 433 MHz frequency band, with a high RF sensitivity of -63.4 dBm, an ultra-low power consumption of 8.7 µW, and with a low supply voltage of 2 V only.

1. Introduction
Today, we see an emerging number of wireless sensor systems - battery-operated or energy-autonomous - in applications like medical implants, personal assist devices, building automation or environmental monitoring. New wireless protocols, like e.g. LoRa®, allow for a bidirectional communication with embedded wireless sensor nodes (WSNs) at a reasonable energy expense per transmitted bit. However, if such a RF transceiver has to be kept in continuous listening mode for incoming calls, the WSN may rapidly drain its battery or overload its energy harvesting capabilities. An alternative would be the definition of regular communication time slots, where individual nodes of a wireless sensor network will wake up at their pre-programmed time, listen to potentially incoming calls through their standard RF interface and fall back into deep sleep, either directly, if no incoming call is detected or after execution of the received commands. It is obvious that such a polled receive strategy will drain the more power the shorter the intervals between these time slots are chosen, thus creating an unavoidable conflict between accessibility and internal power consumption of a WSN. Also, every wake-up and power-down of an RF interface may consume additional energy by itself. As the internal real-time clocks of a WSN and its host may run out of synchronization, time slots for transmission and reception have to be provided with a certain overlap, which again may increase the WSN’s internal power consumption. Finally, a large number of WSNs serviced by one host will inevitably prolong the time interval between two accesses to a certain sensor node.
Therefore, wake-up receivers are considered as an alternative for enabling a truly asynchronous and much more flexible, yet power-effective communication. They perform either a continuous - or again polled - ultra-low-power listening to incoming RF communication. In contrary to the time slot approach described above, polling of a wake-up receiver could be done in a much more flexible way. In any case, the WSN will start communication via its high-power main RF transceiver only when a communication request is detected. In all other cases, deep sleep is either maintained or interrupted only briefly and with minimal power consumption, to e.g. detect whether the address of a wake-up call is valid. This can be done either by the WSNs microcontroller or even in the wake-up receiver itself.

2. State-of-the-art

Commercial wake-up receiver ICs available today are mostly working at low radio frequencies (LF, typ. 125 kHz) to maintain low-power consumption [1][2][3]. Usually, a ferrite antenna is used for such an LF receiver, as any antenna for the electric component of the RF field, e.g. a dipole, would take a huge size unacceptable for the requirements of most WSNs. The internal circuitry of these devices is similar and also used in this study: Frequency tuning, reception and demodulation of an amplitude-modulated (AM) or on-off-keyed (OOK) RF carrier is done via a diode detector circuit coupled to a multistage amplifier with internal automatic gain control to avoid overload of the receiver by high field-strength RF signals. The demodulated and amplitude-adjusted signal is digitized and may then be analysed in the wake-up receiver itself, using an internal address decoder [1][2]. Simpler devices, as also used in this study [3], do only feed out the received data stream and a digital wake-up signal.

Aside from these low-frequency devices, several concepts of high-frequency wake-up receivers have already been studied. In general, these wake-up receivers will consume a much higher power than LF receivers when realized as integrated circuit. Discrete concepts of such devices use e.g. ultra-low-power operational amplifiers, comparators and logic gates in conjunction with, again, a diode detector to deliver a demodulated digital data stream. One example [7] couples a diode detector to a low-power amplifier for creating digital data directly from the demodulated signal. The amplifier gain is set by the WSNs microcontroller to achieve maximal sensitivity for different RF signal strengths. Instead, other wake-up receivers use a comparator with an automatic threshold adjustment [8][9] or with a fixed threshold [10]. Two other studies [5][6] modulate a high-frequency carrier with the low-frequency signal required by a commercial LF wake-up receiver IC to use the low power consumption and all signal processing capabilities of the same for a wake-up at higher frequencies. In our own research we have recently realized a wake-up receiver based on the same concept [4]. However, one common drawback of all these solutions turns out to be the high modulation bandwidth required by the respective LF wake-up receiver ICs, which ranges from 30 kHz [4] up to 125 kHz [5].

3. Device concept and implementation

Figure 1 shows the circuit schematic of the wake-up receiver realized in this study. The basic concept behind is to combine signal amplification with mixed signal pre-processing in such a way that a low-bandwidth modulation can be used to feed a commercial LF wake-up receiver requiring a much higher low corner frequency.

![Figure 1. Circuit diagram of the wake-up receiver](image-url)
The RF transmitter’s encoding scheme and typical signals in the wake-up receiver are depicted in figure 2. In the RF transmitter the modulation signal encodes a logical “1” as a time-equivalent sinusoidal signal at 4.681 kHz, whereas a logical “0” is encoded with zero amplitude. The 433 MHz RF carrier is amplitude-modulated with 100% modulation depth for all logical “1” bits. For logical “0” bits the carrier is turned off completely. This allows for narrow-band operation of the transmitter, will however also enforce a data rate significantly below 4.681 kHz. Such a low data rate may seem as detrimental, it is however in conjunction with the actual state-of-the-art in commercial low-power transmission protocols, where, e.g., the LoRa® protocol also sets a minimum data rate of 300 bits/s.

In the wake-up receiver, an optimized diode detector does RF reception and demodulation. The demodulated signal is fed into an ultra-low-power and low-frequency (LF) amplifier made from two high-gain bipolar transistors. The amplifier’s gain is in direct relation to its supply current and input frequency, as shown in Figure 3. With the set current of 2 µA gain is appr. 35 dB at 4.681 kHz. This shows the benefit of using a low modulation frequency in comparison to a modulation with higher frequencies as required by LF wake-up receiver ICs. In [5] a 125 kHz square wave signal is applied for OOK modulation, suitable for the wake-up receiver IC used in this study [2]. In a similar approach we have used a 32.768 kHz modulation signal [4] to trigger the respective wake-up receiver IC [3] directly, with the LF amplifier shown above as intermediate stage. However, for this higher frequency its gain is only 21 dB, which translates into a significant loss of receiver sensitivity. For nevertheless obtaining the required 32 kHz signal, a comparator at the amplifier output performs DC offset cancellation and converts the demodulated sinusoidal signal into a high-amplitude square wave signal. The seventh order harmonic of this square wave signal is extracted by means of a 32.768 kHz quartz bandpass filter to trigger the wake-up receiver IC above its 30 kHz low corner input frequency [3].

Figure 2. Data encoding and modulation in the RF transmitter (left) and signal pre-processing in the wake-up receiver (right). The encircled numbers of the graphs describe the respective points in the wake-up receiver schematic, see figure 1. All graphs not drawn to scale.

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Figure 3. Gain of the LF amplifier as a function of frequency and supply current
The total gain in the subsequent signal chain can be calculated from a Fourier analysis of the square wave signal: With a 2Vpp square-wave signal at the comparator output the seventh order harmonics at the filter input has an amplitude of 182 mV. The quartz bandpass filter shows a damping of 26 dB at 32.768 kHz, therefore a signal with 9 mV amplitude is present at the input of the wake-up receiver IC. As this device requires a minimum signal amplitude of only 1.4 mV [3] a sufficiently high safety margin is created for a reliable wake-up. In addition, the quartz filter’s steep characteristics helps to prevent that erroneous radio signals will generate a faulty wake-up.

As a second safety feature a digital reset circuit at the outputs of the wake-up receiver IC performs an automatic reset of the wake-up receiver and of the WSNs microcontroller after a pre-set time interval. The automatic system reset can be prevented by an active WSN. If, however, the WSN is in a deadlock situation from any reason, this feature allows an external reset via the power-saving and fail-safe wake-up circuitry.

Figure 4 shows a photograph of the wake-up receiver. Implementation was done on standard FR4 printed circuit boards in a modular fashion, i.e. the diode detector and all other circuitry were placed onto separate boards for an easier individual optimization of both.

4. Characterization and measurement results
Device characterization was done with a commercial RF signal generator (SMA100A, Rhode & Schwarz). To find the receiver’s RF sensitivity the signal generator was used as 433 MHz RF transmitter and was modulated with the scheme shown in figure 2. In the experiment, the generator’s RF output power was reduced down to the limit where no valid wake-up could be detected by the connected receiver. In comparison to our own previous research [4] the wake-up receiver showed an improved RF sensitivity (-63.4 dBm vs. -52 dBm) at a higher RF frequency (433 MHz vs. 315 MHz). Power consumption was measured at the device’s supply line, using a precision current meter. In comparison to our previous study [4] it is only moderately increased (8.7 µW vs. 7.4 µW) at the same minimal supply voltage of 2 V. Power consumption of the digital reset circuit was not taken into account within both studies, as this unit is optional and not required for operation.

Essential key data of different wake-up receivers are presented in table 1 together with the results of this work. The frequency range chosen for this comparison (up to 1 GHz) covers several ISM (ISM: Industrial, Scientific and Medical) and non-ISM bands available for open access in a large number of countries worldwide. Especially the ISM bands at 433 MHz and above offer a sufficient compromise between small antenna size, wireless transmission range and worldwide access, and are therefore the predominant target of most studies on wake-up receivers.

In comparison to other wake-up receivers with internal digital signal processing the realized circuit excels in its RF sensitivity. Power consumption is comparable and supply voltage is at the lowest limit of all relevant studies [4][5][6]. The power consumption of pure RF receivers and signal conditioners [7][8][9][10] is lower. This comes however with the drawback of e.g. a lower RF sensitivity [10] or with the need of operating the connected microcontroller in a mode with higher power consumption, e.g. for a continuous interaction with the wake-up receiver [7]. Also, power figures could not be verified for all studies, as specifications for components used there were not available (e.g. [9]).

| RF frequency [MHz] | 433 | 315 | 868 | 868 | 300 | 868 | 433 | 868.5 |
|-------------------|-----|-----|-----|-----|-----|-----|-----|-------|
| RF sensitivity [dBm] | -63.4 | -52 | -52 | -52 | --- | -55 | -52.1 | 4.37 |
| supply voltage [V] | 2 | 2 | 3 | 2 | 3 | 2 | 1.5 | 3 |
| minimal power consumption [µW] | 8.7 | 7.4 | 7.77 | 7.59 | 4.8 | 1.2 | 0.27 | 2.63 |
5. Discussion and conclusions
Within this study an ultra-low-power wake-up receiver has been realized and tested. The device concept is based on a modulation/demodulation scheme that has been specially tailored to combine a narrow band RF transmission with high RF sensitivity and low power consumption of the wake-up receiver. For this purpose the transmitter is operated in an AM mode, using a low-frequency sinusoidal modulation for every digital “1” bit. Within the receiver, this chain of sinusoidal signal bursts is pre-amplified and then shaped into a square-wave burst signal with the same basic frequency, however a much higher amplitude. An overtone of this square wave signal is filtered and fed into the input of a commercial low-power wake-up receiver IC.

This concept allows for a high RF sensitivity of -63.4 dBm at a frequency of 433 MHz, i.e. within an ISM band that is license-free in a large number of countries worldwide. With a power consumption of 8.7 µW at 2V the required supply current is 4.35 µA. Minimal modifications of the receiver circuitry could guarantee this value also for higher supply voltages. Therefore, a standard 3V lithium coin battery (e.g. CR 2032 with 230 mAh capacity) could supply this wake-up receiver over a period of 6 years, which is acceptable for many WSNs that use batteries with much higher capacity. Only a slightly higher supply current of the LF amplifier (see figure 2) could further rise RF sensitivity and transmission distance, if acceptable from battery lifetime considerations. This study has been done with off-the-shelf components and standard printed circuit board technology. A future implementation as integrated circuit would allow for a further increase of performance with a decrease of device size and power consumption.

6. References
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