Radio-Triggered Wake-ups with Addressing Capabilities for Extremely Low Power Sensor Network Applications

Junaid Ansari, Dmitry Pankin and Petri Mähönen
Department of Wireless Networks, RWTH Aachen University, Kackertstrasse 9, D-52072 Aachen, Germany
Email: {jan, dpa, pma}@mobnets.rwth-aachen.de

***Abstract*— Sensor network applications are generally characterized by long idle durations and intermittent communication patterns. The traffic loads are typically so low that overall the idle duration energy consumption dominates. Low duty cycle MAC protocols are used to reduce the idle duration energy consumption. However, lowering down the duty cycle in favour of energy consumption results in increased latency, which makes it undesirable for many applications. In this paper, we propose Radio Triggered Wake-up with Addressing Capabilities (RTWAC) that allows suppressing the idle duration current consumption. Our solution consists of an external low-cost hardware wake-up circuit attached to the microcontroller of a sensor node. In order to communicate with a sensor node, a special kind of out-of-band modulated wake-up signal is transmitted. The modulated signal contains data that enables to distinguish between differently addressed nodes in order to avoid undesired node wake-ups. Furthermore, we augment this solution to a MAC protocol running on the normal radio on the sensor node in an advantageous way to achieve high energy gains and low latency for data communication.**

I. INTRODUCTION

Owing to the severe resource constraints, sensor network applications do not use the available resources continuously all the time. One of the common techniques is to use controlling mechanisms that turns off the unused hardware peripherals. Since the available battery power is the most precious resource and directly effects the lifetime of the network, energy aware techniques have their peculiar importance. In typical Wireless Sensor Network (WSN) applications, data communication has the highest power consumption budget. Since the data traffic is generally very low in sensor networks, reducing the idle duration power consumption by the radio resource has very high importance. Radio duty cycling is a popular solution, where the radio is turned on and off according to a predefined scheme [1], specific to each MAC protocol. However, there is a tradeoff between energy consumption and the latency in duty cycling MAC protocols. Lower duty cycles result in lower energy consumption but at the same time increases the latency in the data communication which is unaffordable in many applications.

In this paper, we present a radio triggered wake-up circuit attached to a sensor node that allows it to keep its radio module completely switched off until it is required to be used for data communication. An out-of-band modulated signal is sent. Upon receiving this signal, the wake-up circuit interrupts the microcontroller from sleep mode to the active mode in order to interpret the data inside the wake-up signal. The data contains the address information and command messages, which allows the sensor node to shortly switch back to sleep if it is not addressed. On the contrary, an addressed receiver is able to execute the command message transmitted in the wake-up data packet. For instance, it may include turning on the normal radio of the sensor node for data communication. A sensor node uses the normal radio with a sophisticated MAC protocol running on it for data communication. In this way, RTWAC solution combines the advantages of the radio triggered wake-ups by avoiding idle listening to the medium and that of sophisticated MAC procedures for data communication. We believe that this solution, which brings together the advantages of both the radio triggered wake-ups and MAC protocols and offsets their disadvantages, will be beneficial in many low power applications.

The rest of the paper is organized as follows: we give an overview of the related research in Section II. Section III describes the design and implementation details of the RTWAC. In Section IV, a detailed experimental performance evaluation of the RTWAC is presented and a performance comparison with a widely used duty cycle MAC protocol [2] is made on various duty cycles. Finally, in Section V, the article is concluded and the future work directions are outlined.

II. RELATED WORK

One of the most widely used approaches for reducing power consumption at sensor nodes is to use power management in order to avoid energy wastage by unused hardware peripherals and radio resource. While it is easy to define when transmission is required, reception is usually unpredictable and asynchronous to a sensor node. Either continuous listening or duty-cycling schemes are used at the receiver. An evident drawback of all the duty cycling schemes is the increased latency compared to the always on mode. One of the possible alternatives to minimize latency is to use an additional wake-up radio hardware, which is thoroughly optimized for negligible power consumption and is capable to react instantly on an event of interest i.e. radio transmission.

PicoRadio [3], [4] uses a carefully designed very low power transceiver module (build as a prototype IC), which is capable of monitoring radio environment. It can be used either as a stand-alone radio module on the sensor node or as an additional wake-up module used in combination with a more advanced radio transceiver. The total power consumption of the module in the receive mode is 380 μW with a supply voltage of 1 V and receiver sensitivity of -75 dBm. In the transmit mode, it consumes 1.6 mW with an output power of 0 dBm. Although the power consumption ratings are much less than many state-of-the-art normal radio transceivers used in sensor nodes (using typically 2-3 V supply voltage and consuming 10-30 mA current consumption), this solution still consumes significantly high power consumption while staying always-on.

Lin Gu *et al.* proposed to use radio triggered wake-ups for wireless sensor networks [5]. The idea is to use only passive components in order to collect energy from on-going radio transmissions, as it is done in RFID technology. When the power induced at the receiving antenna is large enough, it interrupts the microcontroller, which wakes-up the "normal" sensor node radio for data communication. Due to simplicity of the wake-up hardware, it reacts to any strong electromagnetic field in the operating frequency. Having no addressing mechanism in its design leads to undesired node wake-ups. In order to avoid the unwanted node wake-ups, Radio-Triggered-ID (RTID) was proposed, where different nodes are addressed by performing transmissions simultaneously at several different frequencies. This solution involves practical difficulties such as the need for an additional wake-up hardware corresponding to each frequency and a transmitter capable to transmitting at different frequencies simultaneously. Furthermore, it has a very limited addressing space.

M. Malinowski *et al.* developed a direct amplifying RF detector, operating in 300 MHz as a part of CargoNet project [6]. The main building blocks of this RF detector are antenna matching network, envelope detector and micropower amplifier. The receiver sensitivity and power consumption of the circuit are -65 dBm and 2.8 μW, respectively. The RF detector is able to detect an OOK signal modulated with baseband square pulses of 25 Hz.

WISP is a wirelessly powered platform for sensing and computation [7]. Although WISP is not directly related to WSNs, its hardware components and research philosophy are close to our work. WISP is a wireless battery-free platform for sensing and computation. A standard UHF-RFID reader is used to power it wirelessly and control its sensing and data transmission capabilities. WISP's main building blocks are passive power harvesting hardware, demodulator, microcontroller unit and sensors. The main point of interest in WISP for our study are the passive power harvester and demodulator circuits.

III. Design and Implementation

In this section, we describe our solution which alleviates the need for periodic wake-ups of the radio module on a sensor node as govern by duty cycling MAC protocols. The radio remains completely switched-off and the microcontroller can operate in low-power mode. By using an additional hardware attached to the sensor node, the microcontroller on the sensor node can be waken-up from sleep state by sending a specific RF signal. This additional hardware circuit is either completely passive or active with an extremely low power consumption (just a few μA). This results in many years of sensor node operation in the sleep mode and also allows instantly waking-up upon the need for data communication over the normal radio of the sensor node. We use a modulated RF signal to wake-up sensor nodes, unlike the approach in [5], where no modulated signal is used in the node wake-up process. The "data modulation feature" in our design allows to uniquely address different nodes or groups of nodes and send additional data (e.g. command messages) in the wake-up signal.

We aimed at the following goals by introducing new wake-up scheme with additional hardware attached to the sensor nodes:

- Avoiding radio duty cycling in order to suppress the idle listening power consumption significantly by keeping the normal radio on the sensor nodes completely switched off and the microcontroller in the sleep state
- A sensor node must consume only negligible power in the sleep mode
- Instantly waking-up the nodes from the sleep state, i.e. as soon as a sensor node completely receives a wake-up signal, it should be ready to communicate over its normal radio
- Unique addressing capabilities, i.e. possibility to wake-up one dedicated sensor node or group of nodes. The wake-up addressing is common with the MAC addressing space.
- Command capabilities, i.e. possibility to send a command to a sensor node together with the wake-up signal
- Maximizing operating range of the wake-up hardware

In order to achieve the above objectives, the most difficult engineering task is to have a good communication range and at the same time keeping a negligible power consumption. With a completely passive structure, a communication range of more than one meter is difficult to achieve under the frequency regulations in Europe. By introducing some active components in the wake-up hardware circuit, we were able to increase the operating range to more than 10 m and still keeping power consumption of the wake-up circuit at an extremely low level. We designed dedicated hardware circuits for the wake-up process. This includes the wake-up signal transmitting module and the wake-up signal receiving module. In the following, we describe in detail the prototype hardware circuits consisting of commercial off-the-shelf discrete components.

A. Wake-Up Signal Transmitter

The wake-up signal transmitter consists of a TelosB node, a CC1000 radio transceiver and, optionally, a ZHL-2010 radio frequency amplifier. The CC1000 radio generates a wake-up signal in 869 MHz band; the radio frequency amplifier can be used to increase the communication range. The wake-up signal transmitter block diagram is shown in Fig. 1.

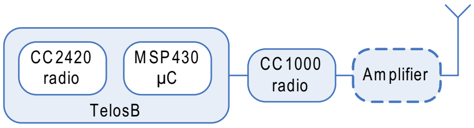

Fig. 1. Wake-up transmitter block diagram.

B. Wake-Up Signal Receiver

The wake-up signal receiving node (we call it a hybrid node) consists of a TelosB node and a wake-up hardware circuit. The wake-up hardware circuit is intended to interrupt the microcontroller, when it receives a wake-up signal. The block diagram of the receiving wake-up circuit is shown in Fig. 2. The main building blocks include an impedance matching network, a voltage multiplier and a digital comparator. The power induced at the antenna is extremely low due to the path loss during radio waves propagation, thus the task of the matching network is to transfer as much power as possible from the antenna to the voltage multiplier circuit. The matching network is built on two lumped reactive elements: a parallel capacitor and a series inductor, in order to provide maximum power transfer from the antenna to the rest of the circuitry. The induced power at the output of the antenna and the matching network is potentially very small. Usually the induced voltage is not sufficiently high enough to interrupt the digital logic of the microcontroller; moreover the voltage alternates at the radio frequency. Our design includes a five stage VM structure (also known as charge pump) to increase the voltage to sufficiently high level and to detect the slowly varying envelope signal from the modulated high frequency carrier. The diodes are chosen carefully to be able to turn on at very low forwarding voltages and operate at high frequencies. We use low threshold RF Schottky diodes HSMS-2852 [8] from Avago Technologies. Digital comparator is the only

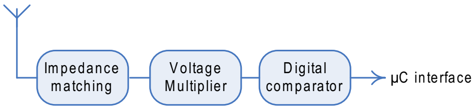

Fig. 2. Wake-up receiver block diagram.

active element in the wake-up circuit. It is used to digitize the analog signal and shift the voltage levels to "high" and "low" logical levels of the microcontroller. Digital comparator also performs an over-voltage protection for the microcontroller because it is likely that voltage multiplier in the close vicinity to the transmitter will produce voltages higher than even 10 V. The complete schematics of the wake-up circuit is shown in Fig. 3.

The resistor, R1 is a main load for the VM part of the circuit because the load of digital comparator input pin is negligible. R1 constantly drains out the current from the charging capacitors C2-C11. When the power induced by the antenna is decreased, the voltage at the output of the VM is also decreased. Thus VM and load resistor R1 form a

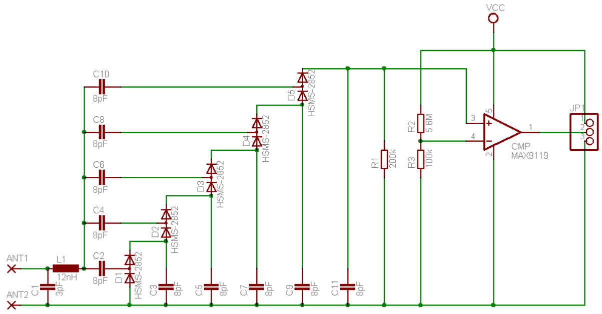

Fig. 3. Schematics Wake-up Board.

simple envelope detector. The obtained amplitude envelope is compared to a predefined threshold of the digital comparator to determine the transmission of high or low level. The predefined threshold level is configured by the voltage divider consisting of resistors R2 and R3. A threshold level is selected well above the noise level to avoid false interrupts at the microcontroller. Decreasing the threshold level can lead to an increase in the operating distance but this also causes an increase in the number of false positives. We empirically found out the noise threshold to be 50-60 mV, which gives a reasonably good operating range of more than 10 m. Fig. 4 shows the hybrid node consisting of the wake-up PCB attached to TelosB node.

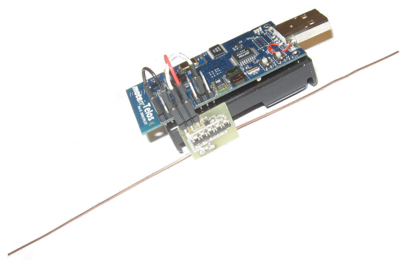

Fig. 4. A hybrid node consisting of an external wake-up circuit interfaced to a TelosB sensor node platform.

There are only two sources of the power consumption in the wake-up circuit. The first is the extremely low power digital comparator. The chosen MAXIM's MAX9119 [9] comparator consumes only 350 nA of supply current at 3 V. The second source of power consumption is the voltage divider that forms the threshold voltage (reference voltage for the comparator). Voltage divider is composed of two resistors, R2 and R3, and consumes 526 nA. The total current drained by the wake-up circuit is therefore,

$$I_{\text{wakeup}} = I_{\text{comp}} + I_{\text{div}} = 350\text{nA} + 526\text{nA} = 876\text{nA}. \quad (1)$$

Since the wake-up circuit interrupts the microcontroller externally, we use the deepest sleep mode (LPM4) of the MSP430 series microcontroller, which consumes a current $I_{\text{TelosB}} = 3.3\,\mu\text{A}$ on TelosB.

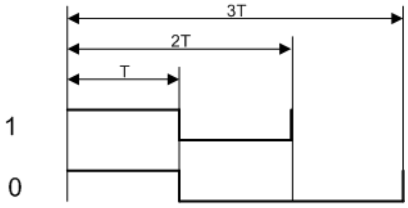

Fig. 5. Pulse Interval Encoding (PIE).

C. Wake-Up Signal Protocol Packet

We designed a very simple lightweight protocol for the wake-up signal transmission. CC1000 radio chip is used to perform OOK by simply turning on and off its power amplifier. These turn-on and turn-off periods are controlled completely by external microcontroller (MSP430 of the TelosB node in our case). For the encoding of digital data we have chosen to use Pulse Interval Encoding (PIE). PIE scheme is presented in Fig. 5. Encoding of 0 and 1 starts with a fixed interval T of high level transmission, after it a low level period varies from T for 1 to 2T for 0. The total bit transmission time is from 2T to 3T.

The preference of PIE compared to Manchester encoding in our implementation is because of the less required number of interrupt events during decoding of a single bit by a microcontroller. In order to decode data sequence from Manchester encoded signal, the microcontroller has to track all transitions from low-to-high and from high-to-low. In PIE, it is enough for the microcontroller to track only low-to-high transitions and time intervals between them to successfully decode the data sequence. The reduced number of interrupts saves power consumption required to invoke and process additional interrupt service routines. A synchronization sequence of zeros and ones is sent at the beginning of each packet. This sequence allows dynamic calculation of the timing characteristics of zero and one transmissions, i.e. determine 2T time for "1" and 3T time for "0". Thus the receiver has no hard build-in timing values, rather it can adapt to transmitter timing characteristics using the synchronization sequence. At the link layer, we designed the following packet structure for the wake-up signal transmission. A packet starts with 8 bits synchronization sequence (SYNC), followed by 16 bits address (ADDR), 16 bits command (CMD) and 8 bits CRC value. The total packet size is six bytes. It may be noted that the address space of the wake-up packet is shared with the MAC addressing scheme running on the normal communication radio. The packet structure is shown in Fig. 6.

SYNC	ADDR	CMD	CRC
1byte	2bytes	2bytes	1byte

Fig. 6. Wake-up packet structure.

IV. Performance Comparison with Duty Cycle MACs

In this section, we compare and analyze the power consumption and latency of our prototypic RTWAC implementation on the TelosB sensor node platform with B-MAC operating at various duty cycles running on the same platform. The power consumption of RTWAC is calculated in the sleep mode whereas that of B-MAC is calculated while performing only low-power listening (LPL) or channel polling operation without packet receptions. This is justified because it represents the most common state of a sensor node. In the sleep mode, the current drawn by the RTWAC enabled node is the sum of the currents drawn by RTWAC circuit board and the current consumed by TelosB node and is given by

$$I_{\text{RTWAC}} = I_{\text{TelosB}} + I_{\text{wakeup}} = 3.3\mu A + 876nA = 4.176\mu A \quad (2)$$

Hence the operating power consumption of an RTWAC enabled node is P_{RTWAC} = 12.528 μW. Unlike the constant power consumption of an RTWAC enabled node, the power consumed by a MAC protocol strongly depends upon the operating duty cycle. We calculated the power consumption for the reference implementation of B-MAC in TinyOS 2.0 at various duty cycles with the default channel polling interval of 1 ms when CC2420's hardware acknowledgements are disabled. The power consumption is calculated by

$$P_{\text{LPL\_MAC}} = P_{\text{TelosB\_sleep}} + \text{DutyCycle} \cdot P_{\text{listen}} \quad (3)$$

Fig.7 shows a comparison of the power consumption during the idle duration of the RTWAC enabled node and the B-MAC protocol on TelosB platform. It is evident that the RTWAC enabled node has a remarkably low power consumption. Only the MAC duty cycles of below 0.001 % have comparable power consumption but impart a very large latency. In order

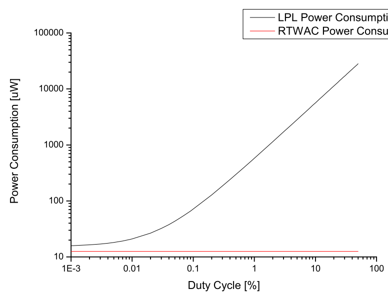

Fig. 7. The average power consumption comparison of RTWAC against a Low-Power-Listening (LPL) MAC protocol at different duty cycles, implemented on CC2420 radio. The channel polling time for the MAC protocol is 1 ms.

to calculate the latency of the RTWAC solution, we need to measure the time required to transmit a complete modulated signal containing the data. Since RTWAC uses PIE at the PHY layer, the latency depends upon the number of zeros and ones contained in one complete wake-up packet. The transmission time of "1" and "0" are 2T and 3T, respectively.

In our reference implementation, T=530 μs. So the average transmission time for 6 bytes of packet is 63.6 ms.

We use the average latency for data communication on the reference B-MAC implementation. The maximum latency for a particular packet is given by

$$\text{B-MAC\_latency}_{\text{max}} = T_{\text{duty-cycle}} + T_{\text{packet}} \tag{4}$$

The minimum latency is equal to the time that is required to transmit a complete packet and is actually dependent on the packet size:

$$\text{B-MAC\_latency}_{\text{min}} = T_{\text{packet}} \tag{5}$$

The average latency of the B-MAC is:

$$\text{B-MAC\_latency}_{\text{avg}} = \frac{\text{B-MAC\_latency}_{\text{max}} + \text{B-MAC\_latency}_{\text{min}}}{2} \tag{6}$$

In order to calculate T_{packet} of B-MAC, we use the raw packet size with default payload size of 28 bytes. The MAC layer overhead is 12 bytes, and the synchronization header of the IEEE 802.15.4 PHY layer is 5 bytes. For the CC2420 raw data rate of 250 kbps, we calculate:

$$T_{\text{packet}} = \frac{45\,\text{bytes}}{250\,\text{kbps}} = 1.44\,\text{ms} \tag{7}$$

The average latency comparison of the RTWAC enabled node and B-MAC's implementation on TelosB is shown in Fig. 8. It may be observed that the latency imparted by RTWAC is comparable to that of the B-MAC protocol with 1 % duty cycle. However, RTWAC consumes significantly less power at this duty cycle of B-MAC. It may be noted that the latency of the RTWAC can easily be improved by sending the RTWAC data packet more quickly. In our reference implementation, it is restricted by the software implementation of the SPI bus on the MSP430 microcontroller.

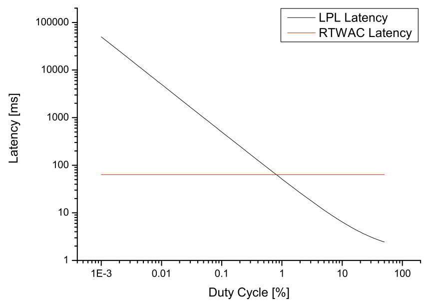

Fig. 8. The average latency comparison of RTWAC against a Low-Power-Listening (LPL) MAC protocol implemented on CC2420 radio at different duty cycles.

V. Conclusions and Future Work

In this paper, we have presented radio triggered wake-up solution with addressing capabilities. We have described the rationale behind various hardware aspects and the protocol architecture in detail. RTWAC not only helps sensor nodes to avoid idle listening to the medium but also suppress unnecessary wake-ups because of having the addressing information in the wake-up signal. We have found that by combining RTWAC with a duty cycle MAC protocol on TelosB sensor node platform can result in remarkably low power consumption and latency on TelosB sensor node platform. We have also conducted comparative studies against duty cycle MACs and have shown that duty cycle MACs consume large amount of power consumption and have high latency, because radio communication can only take place during the short active periods. Either a long preamble needs to be transmitted before the data packet or a high synchronization overhead has to be paid in the duty cycle MACs. On the contrary, our solution allows keeping the power consumption of a node at a negligible level when communication is not required and instantly waking-up when it is needed. RTWAC wake-up circuit works in 869 MHz ISM band and complies to the power level and duty cycle constraints by the frequency allocation operators in Europe. We have also integrated RTWAC into an extremely low power asset tracking system, which was demonstrated in [10].

In the future, we would like to further improve the operating range of the RTWAC. In our current design, we have selected a bit higher noise floor threshold in order to avoid undesired microcontroller triggers coming from the adjacent GSM band. Increased range can be achieved by using a band pass filter to suppress unwanted signals in the operating band. This will, however, require an additional power consumption to the circuit board.

Acknowledgment

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