Wake-Up-Receiver in energy efficient Wireless Sensor Networks for security applications

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Abstract – Wireless sensor networks are especially interesting for event-based applications (e.g. security applications), which present low and variable data rate, but a vital low latency requirement. In this case, an innovative solution using wake-up receivers allows purely asynchronous operations with low latency. A wake-up receiver is a low power radio-triggered device used to continuously monitor a channel and which activates the node on demand for incoming communication. Such a modular, small sized and good performing (-15 dBm input sensitivity and only 6µW power consumption) wake-up receiver module has been developed from off-the-shelves components. A new software communication protocol taking advantage of the wake-up on radio functionality is proposed, successfully demonstrated and compares well against standard low duty cycle MAC protocols.

1. Introduction

1.1 Wireless Sensor Networks

Wireless Sensor Networks (WSNs) have emerged in the last ten years as a revolutionary technology for querying the physical world and provide manifold opportunities in a wide variety of applications. Basically it can be seen as a group - from a few up to a large number - of small low-energy units, with limited computational and memory resources that operates autonomously to accomplish a specific task.

Wireless Sensor Networks are easy to deploy and this is an important selling point: no wires, cables or other infrastructure is necessary to begin operation. Nodes are indeed self-supportive meaning that sensing, processing, storage and communication capabilities are from the start all included.

1.2 WSNs for security applications

As a result WSNs can be used to build very efficient, powerful solutions for security applications. Security applications are generally event-driven, meaning that the distributed sensors only inform the sink of the network when a specific event occurs. Typical examples are fire or smoke detection systems [1], target tracking or surveillance systems [2] whose duty can be trespassing detection (building or border for instance).

The Fraunhofer Ernst-Mach-Institute (EMI) has already seen the need for the development of such WSNs in security projects such as AISIS [3] (a BMBF Project www.aisis-innovation.org). Here energy self-sufficient nodes are being equipped with pressure sensors, placed in a railway-tunnel, and triggered in case of any catastrophic event such as explosion for example. The collected data is then being used to evaluate the integrity of the structure. This information is critical to plan evacuation and rescue operations.

Event-driven applications do have specific requirements regarding the network, namely low and variable data rates, and WSNs in general pose formidable challenges, the fundamental one being power management.

2. Energy consumption review

Current-generation node hardware usually relies on batteries for operation. Since this energy resource is fundamentally constrained by the small device form factor, power consumption is a critical issue.

When looking at the nodes operating scheme, the most effective way to save power consists in simply decreasing the activity level of the nodes in favor of inactive or sleep states, drastically reducing their power consumption. This scheme can be applied to the node as a whole or it can target specific components, usually the most power hungry ones.

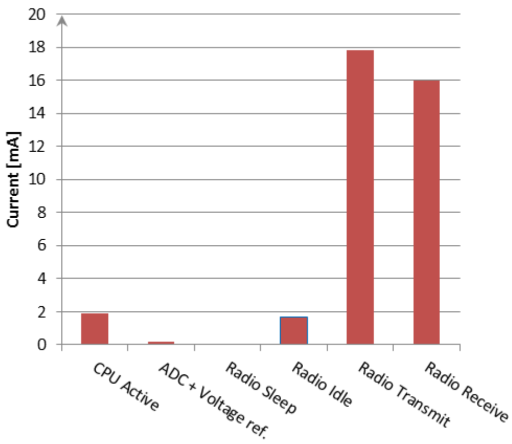

Figure 1: CC430 current consumption figures [4]

Our node platform is an MSP430-CCRF development board. This board comes with a Texas Instrument CC430F5137 [4] low-power microcontroller, which has an integrated RF transceiver connected to a built-in PCB antenna with the 868/915MHz radio frequencies supported. From the CC430 datasheet, the given current consumption numbers are illustrated in figure 1. An actual energy consumption model is hard to build with these figures since it is strongly application-dependent. However two observations can be made:

1. Although sensing and data processing could be energy-consuming, the energy consumed for communication is often a very significant contributor to the overall energy consumption.
2. Transmit, receive and idle currents are of the same order of magnitude. The radio consumes considerable power except when completely turned off.

As a result, a very efficient way to reduce energy waste is to minimize the time the communication module is being switched on (idle, receive or transmit modes). Whenever there is no RF traffic, energy efficient approaches should put the node’s radios in the deepest sleep state available. These approaches can be roughly divided into two main categories: the first is software based and relies on MAC protocols with low-duty cycles, while the second one is hardware based and uses a dedicated wake-up module.

3. State of the art energy efficient schemes

3.1 Software based approach

In the literature, the concept of a low duty cycle is represented as a periodic wake-up scheme. A node periodically switches between an active communication epoch (regardless if transmitting data, receiving data, or idly listening to a clear channel), and a power-efficient sleep state. Low-duty cycle MAC or wake-up protocols are then being built on top of these periodic wake-ups in order to enable RF communication.

Although diverse in nature, the main disadvantage of low duty cycle MAC protocols is that even with a balanced duty cycle, the enforced regularity rarely matches an application’s needs, compromising energy efficiency or performance. The fundamental uncertainty of when an incoming message is to be expected has a negative impact on all software-based approaches to power management.

3.2 Hardware based approach

An alternative, hardware-based technique implements a pure asynchronous *rendezvous*. With pure asynchronous *rendezvous*, sensors are not duty cycled anymore, but reside in deep sleep most of the time and can be woken up by their neighbors on demand.

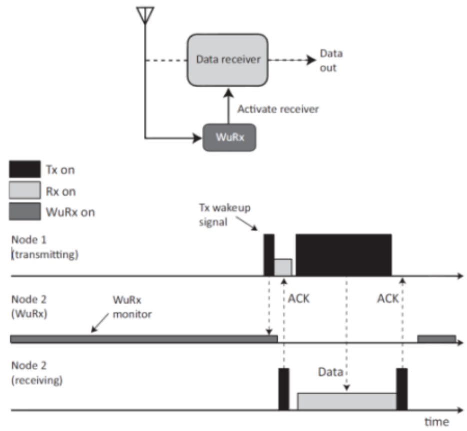

Figure 2: Asynchronous *rendezvous* scheme [5]

Instead of having each node maintain a communication schedule, each node is equipped with a low power wake-up receiver (WUR) module which monitors a given channel continuously, as seen on figure 2. When a node wishes to communicate with a neighbor, it first sends a wake-up call. After successful reception and decoding of the wake-up call, the WUR sends an interrupt signal to the node itself, which can then fire up its primary radio to engage in efficient high-speed communication with the sender. After the transmission, both nodes resume their usual activities and go back to sleep, activating their WUR before doing so.

Even if a WUR module adds cost and hardware complexity, it can enable significant energy savings while enabling a low latency communication scheme. For these reasons an operating scheme based on WUR is developed.

4. Hardware design

4.1 System design selection

The choice is made to look for solutions built using off-the-shelves components because this type of circuitry provides fast and satisfying results for many applications. The commercially available AS3932 chip [6] is a 3-channel low power receiver that is able to generate a wakeup upon detection of a data signal which uses a LF carrier frequency between 110 - 150 kHz.

With a 3 volts supply voltage, the standard one channel listening mode power consumption equals 6 µW. Attached to a CC430 development board which only consumes about 4 µW in the deepest sleep mode available, the whole system would still only consumes 10 µW. Moreover the AS3932 very low wake-up sensitivity, addressing capabilities, fast wake-up capabilities and low cost (2.45$ per chip) makes it the perfect choice for the desired wake-up receiver module.

Several frequency bands (ISM 13.56 MHz, 433 MHz, 2.4 GHz; SRD 868 MHz; RFID 125 kHz) have been investigated and the 868 MHz frequency range turned out to be the most suitable design choice.

4.2 Hardware architecture

The 868 MHz frequency band is used as wake-up channel in order to combine the low current consumption of a wakeup receiver working at low frequencies with the propagation properties of a high frequency for RF transmission. By sending a 125 kHz wake-up signal OOK (On Off Keying) modulated on an HF 868MHz carrier, the wake-up receiver chip will be triggered from sleep to active mode thanks to a passive demodulation circuit that retrieves the LF signal from the HF signal.

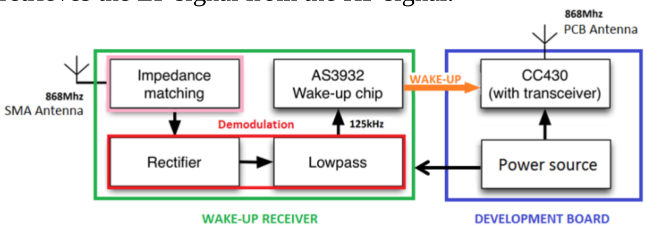

Figure 3: The hardware receiver architecture

The wake-up receiver circuit consists of an impedance matching part, two zero bias Schottky rectifying diodes and a low pass filter. This circuit is capable of extracting the low frequency wake-up signal from the high frequency carrier. The wake-up signal is then fed to the AS3932 for further processing. Since all these components are passive, no external power is required.

The RF impedance matching network is vital to obtaining the best performance possible from a given diode circuit, by maximizing the power transmission of the signal coming from the antenna. Non-ideal impedance matching will result in shorter wake-up distances. The whole electronic circuit has been modeled in an electronic simulation tool in order to simulate the input reflection coefficient of the diodes and properly design the impedance matching part.

The PCB layout is designed according to the previous simulation results and built in the electronic lab of the Fraunhofer EMI:

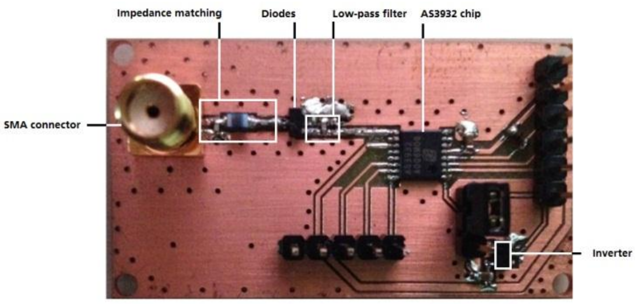

Figure 4: Printed circuit board of the wake up receiver

The wake-up receiver module built from off-the-shelves components is proved to be fully functional and performs well with -15dBm input sensitivity, and 6 µW power consumption in wake-up mode. This results in a maximum wake-up distance of more than 8 meters (wake-up signal sent on the 868MHz frequency, 10dBm output power). This module is very modular and can be easily attached to sensor nodes so that the resulting network can benefit from the wake-up on radio functionality.

5. Software design

A communication protocol using the wake-up on radio functionality is proposed and implemented.

5.1 Network topology

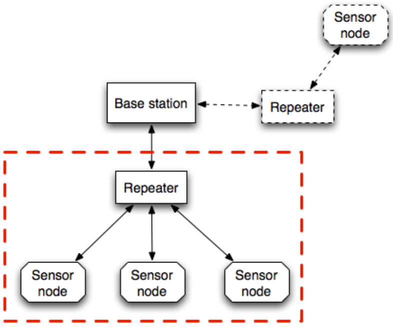

Figure 5: Hierarchical network architecture

A hierarchical structure is proposed and pictured in figure 5. All nodes are equipped with wake-up receivers. The sensor node detector is the simplest monitor, which must connect to a repeater to report its monitoring information. The repeater not only monitors its area, but also provides network access for detectors. The focus will be on the communication in a single cluster (highlighted in figure 5) in the network.

In the network every transmission only occurs after a clear channel assessment (to check if the channel is free) and unnecessary idle states are avoided thanks to node time-outs.

5.2 Network cluster initialization

By default, all the WUR are configured with the same wake-up address, namely {0xAA, 0xAA}.

As seen in figure 6 (left), the repeater starts the network initialization by sending a default wake-up message, waking-up all sensor nodes in the neighborhood. The repeater then immediately sends a network binding request, which tells all sensor nodes its intention to build a cluster and it’s ID. The repeater then stays in the receive mode until time-out, and every time a network binding confirm message is received, memorizes the ID of the new child. The repeater finally sends acknowledgment messages back to all discovered children in order to confirm to them that they have been properly recognized.

After being awoken by a wake-up interrupt coming from the WUR, a sensor node waits for the network binding request message. After reception and processing, the node backs off for n*ID ms (in order to avoid answers collisions) before replying with a network binding confirmation addressed to the repeater. After acknowledgment the repeater ID can be set as parent.

The cluster is then properly initialized and all nodes finally reprogram their wake-up addresses with their identifiers in order to enable addressing in the cluster.

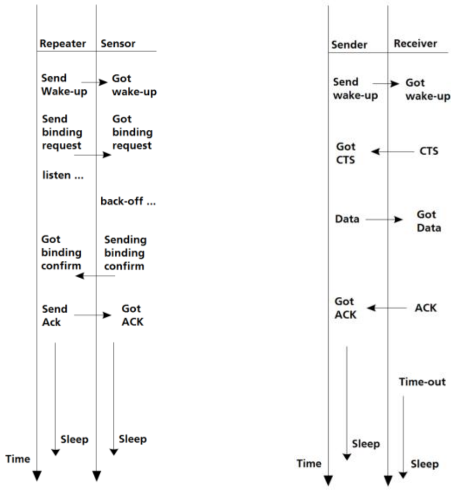

Figure 7: Network initialization (left) and communication (right) schemes

5.3 Data exchange in a network cluster

In this section it is assumed that the cluster is already initialized, so that the sensor node knows its parent ID and the repeater knows all of its children IDs.

As pictured in figure 6 on the right, after sending the wake-up message addressed to the destination node, the sender waits for a clear to send answer. If the node successfully receives the clear to send answer, it sends the data and waits for the final acknowledgment frame. After getting the acknowledgment, the node goes back to sleep.

The receiver, after wake-up, directly broadcast the clear to send message – since it does not know the sender's ID yet – and then switches to receive mode and wait for the actual data to be transmitted. After getting a data packet (and knowing which is the sending node), the node replies with an acknowledgment message and goes back to sleep.

The communication protocol has been successfully implemented in a proof of concept network (3 nodes).

5.4 Communication protocol evaluation

Mathematical analysis using simple models [modified from 7] capturing first-order effects are used to compare an operating scheme based on WURs with the synchronous low duty protocols WiseMAC and SCP-MAC. A cluster of seven nodes is considered, and a basic data packet with acknowledgment (universal for all operating schemes) transmission scheme is analyzed. The focus is on low data rates and the performance metric of interest is the average power consumption of a node in the network.

The wake-up receiver clearly outperforms (figure 8) both MAC protocols. The wake-up receiver operating scheme outperform the Wise-MAC protocol by 10% for a 0.1 message rate and up to 55% for a 0.01 message rate.

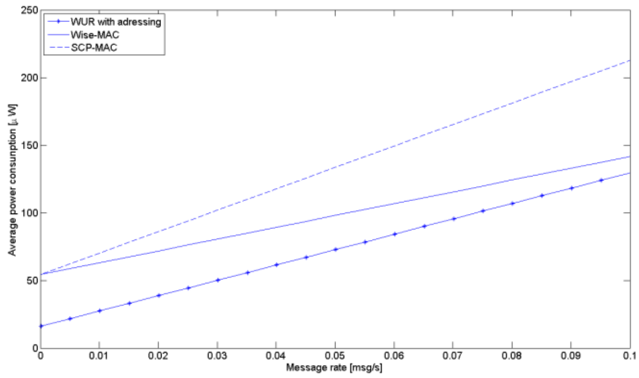

Figure 8: Average power consumption of a node in a 7 nodes network for a WUR system, SCP-MAC and WiseMAC

Notably for a certain message rate higher than 0.1 a pseudo-asynchronous MAC protocol such as Wise-MAC will theoretically become more energy efficient than the wake-up receiver scheme. The WUR technique is very effective with low data rates applications, but not necessarily with higher data rates applications.

6. Conclusion

A fully functional and well performing wake-up receiver module with -15 dBm input sensitivity and 6 μW power consumption in wake-up mode has been developed from off-the-shelves components.

The proposed new software communication protocol which takes advantage of the wake-up on radio functionality has been implemented and successfully demonstrated in a proof of concept network.

An operating scheme based on wake-up receivers is compared to standard low duty cycle MAC protocols and outperforms them.

References

[1] **Qifen Dong et al.**: *Design of Building Monitoring Systems Based on Wireless Sensor Networks.* Wireless Sensor Network, Vol. 2 No. 9, p. 703-709, 2010.

[2] **I. F. Akyildiz et al.**: *Wireless sensor networks: a survey*. Computer Networks, Vol. 38, 393-422 (2002)

[3] **M. Erd et al.:** *Self-Synchronized Energy Efficient Event Detection with Wireless Sensor Networks.* 9th International Multi-Conference on Systens, Signals and Devices Chemnitz, Germany (2012)

[4] **Texas Instrument:** CC430 Family Guide (SLAU259B, 2010)

[5] **Nathan M. Pletcher:** *Ultra-Low Power Wake-Up Receivers for Wireless Sensor Networks.* PhD Thesis, University of California, Berkeley (2008)

[6] **Austriamicrosystems:** AS3932 3D Low Frequency Wakeup Receiver Datasheet v1.4

[7] **K. Langendoen***: Analyzing MAC protocols for Low Data-Rate Applications.* ACM Transactions on Sensor Networks, Vol.7, No. 2 (2010)