Energy Efficient Communication using Wake-up Receivers

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***Abstract*—For many years duty-cycling protocols in its various forms have been the standard way of achieving low energy consumption for communication systems. They do, however, lead to an increased delay and communication complexity and suffer from the inherent clock drift of the communicating nodes. Therefore the achievable energy savings and performance is limited. In recent years a new technology, called wake-up receivers (WuRxs) have been proposed that can solve these problems with an additional ultra low-power radio chip. In my PhD thesis I investigate how this technology can be used in various applications ranging from wildlife monitoring using sensor networks to low-power wireless LAN (WLAN) for Internet of Things (IoT).**

I. Introduction

Energy efficient communication has long been a main concern in the field of wireless sensor networks, where a strict energy budget is one of the main limiting factors. With recent advantages in miniaturization and the reduced energy consumption of communication hardware new applications for distributed sensing and communication have evolved. The trends of connecting more and more devices to the internet are known as Internet of Things (IoT) and Industry 4.0. Here an energy efficient communication technology is also crucial as many devices are usually powered by battery.

Many solutions proposed to mitigate energy wasting by idle listening and overhearing are based on duty-cycling. With this technique the main transceiver can be disabled during an inactive period to save energy and only be enabled for a short period of time for communication. This has proven to save a lot of energy but has some inherent problems [1]: For a successful transmission receiver and transmitter have to be in an active state at the same time. This requires tight synchronization between the nodes, which adds additional communication overhead to the system. Also an inherent tradeoff between delay and energy consumption has to be made: longer inactive times reduce the required energy but increase the delay as nodes have to wait longer for the next active period. A shorter duty cycle would reduce these waiting times but increase the power consumption as nodes have to enable their receiver more often.

Because of these shortcomings a new technology called wake-up receiver (WuRx) has been investigated in the past years. The core idea is to add an additional radio receiver that has a low data rate but also a very low power consumption. Because of this the WuRx can be turned on all the time, even if the node is in it's inactive state. For a successful transmission a node now does not have to wait for other nodes to wake up and enable their main transceiver. Instead a special WuRx signal can be send which is received by the WuRx. Upon the reception of this signal, the receiving node can wake up (change to an active state), power on it's transceiver and normal communication over the main radio can commence. As no synchronization between nodes is required, the communication protocols can be much simpler and unnecessary overhead is prevented. The delays can be greatly reduced because the intended receiver can directly be woken up.

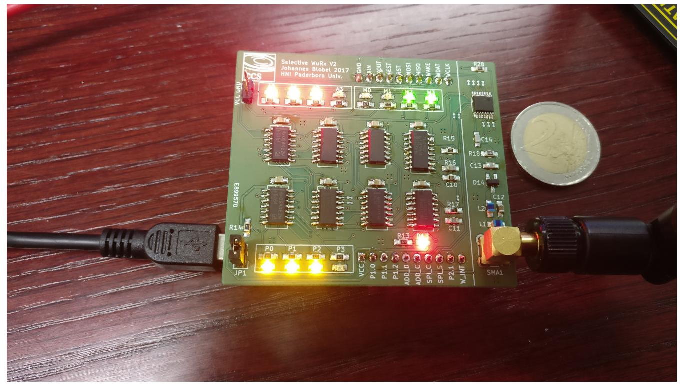

Fig. 1. Hardware prototype of our selective wake-up receiver.

II. State of the Art

Duty-cycling protocols have long been used in wireless sensor networks [1]. Depending on the use case different MAC protocols have been proposed. The main drawback of these protocols however is that they trade delay and throughput for energy efficiency.

Wake-up receivers have the potential to overcome these limitations and to provide low-delay, low-power asynchronous medium access. In the past years there has been much research on the field of new hardware solutions for wake-up radios and also on the networking aspects of wake-up based systems [2], [3]. The main research challenges are energy consumption, data rate and sensitivity for the hardware designs and addressing and medium access schemes for the network protocols.

While most of the research in this field focuses on wireless sensor networks, it has become clear that there are also other applications that can profit from this technology. A new IEEE task group (IEEE 802.11 ba) has just been formed to develop a new power saving mode for wireless LAN (WLAN) that uses wake-up receivers and first hardware solutions have already been presented [4].

III. Research Topics and Methodology

My research approach combines hardware prototypes and real world measurements with extensive simulation studies. With the prototypes and measurements I can prove the feasibility of my proposed technologies and algorithms and cross validate the simulation results. Based on these results, the simulations allow to analyze the system in larger scale and under varying conditions. I am investigating three main topics: Sender based addressing, WuRx based communication protocols and low-power WLAN using WuRx

A. Sender Based Addressing

Already for the very first WuRx-systems addressing capabilities have been proposed. With these schemes, each node can have a unique id which is encoded in the wake-up signal. This allows to wake up specific nodes instead of all nodes in communication range.

In [5] we propose a novel addressing scheme, called *selective wake-up receiver*, that includes an address and a mask. The decoding is done without the support of a microcontroller using only standard logic gates. This allows the *sender* of the wake-up signal to determine whether a specific node (unicast), all nodes (broadcast) or a subset (multicast) of nodes should be woken up. With this flexibility, communication protocols can use the wake-up capability of nodes in a fine-granular way.

We created a hardware prototype using off-the-shelf hardware and a commercially available wake-up receiver, which is shown in Figure 1. The prototype includes an RF-frontend with an impedance matching circuit and an envelop detector, a wake-up receiver and the address matching logic.

B. WuRx based communication protocols

Communication protocols using wake-up receivers can be much simpler than duty-cycling protocols because there is no need for tight synchronization between nodes. Still, many different protocol options can be investigated and medium access between main and wake-up radio has to be taken care of.

In the BATS project [6] we use wake-up receivers for ultra-low power communication for wildlife monitoring of bats. As bats are very small animals, the developed sensor nodes have to be very lightweight and tight energy constraints have to be met. In [7] we investigated different protocol options for the downlink communication from the sensor nodes to the ground station networks.

Wake-up receivers can also be used for routing in a stationary sensor networks. With the addressing capability described in Section III-A a geographic, energy-efficient routing scheme can be implemented. When forwarding packets to a destination, a node can select the next hop based on its geographic location. The chosen node can then be woken up with a unicast wake-up packet and receive the data packet via its main radio. Similarly, Geocasting protocols could be implemented using the multicasting capability of the proposed wake-up receiver.

C. Low-power WLAN using WuRx

Another application for wake-up receivers are IoT devices. For these class of devices, different wireless communication technologies like Zigbee or Bluetooth LE are available that can achieve low power consumption. The drawback of these technologies, however, is the rather low data rates that can be achieved and the incompatibility among each other. WLAN on the other hand is already available in nearly every household and provides fast and reliable data transmissions but requires way to much energy for battery powered IoT devices.

A combination of wake-up receivers with WLAN could combine the best of both worlds. An additional wake-up receiver could be used to extend the existing power-save modes in WLAN while being backwards compatible with existing installations. While the basic concept is rather simple, the implementation of such a system raises many research questions that I want to investigate in the future. Especially the compatibility with existing systems requires a careful adaption of the existing protocols and a thorough analysis. When the main radio and the wake-up system use the same frequency band, interference will become a problem. The wake-up signals could also be used to transmit additional data, without having to use the main radio. Also the sending of the wake-up When the main radio and the wake-up system use the same frequency band, interference will become a problem. The wake-up signals could also be used to transmit additional data, without having to use the main radio. To investigate all these options I also want to follow the approach of building hardware prototypes and create simulation models.

My research will help to build future communication systems that need little energy while still being fast and reliable.

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