Ad Hoc Networks 000 (2017) 1–19

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

T-ROME: A simple and energy efficient tree routing protocol for low-power wake-up receivers

T. Kumberg[a,*], M. Schink[a], L.M. Reindl[a], C. Schindelhauer[b]

[a] University of Freiburg – IMTEK – Laboratory for Electrical Instrumentation, Georges-Koehler-Allee 106, 79110 Freiburg, Germany
[b] University of Freiburg – IIF – Computer Networks and Telematics, Georges-Koehler-Allee 51, 79110 Freiburg, Germany

ARTICLE INFO

Article history:
Received 15 April 2016
Revised 17 January 2017
Accepted 13 February 2017
Available online xxx

Keywords:
Wireless sensor network
Wake-up receiver
Cross-layer
Routing protocol
Markov chain model
Low latency
Energy efficient

ABSTRACT

Wireless sensor networks are deployed in many monitoring applications but still suffer from short lifetimes originating from limited energy sources and storages. Due to their low-power consumption and their on-demand communication ability, wake-up receivers represent an energy efficient and simple enhancement to wireless sensor nodes and wireless sensor network protocols. In this context, wake-up receivers have the ability to increase the network lifetime. In this article, we present T-ROME, a simple and energy efficient cross-layer routing protocol for wireless sensor nodes containing wake-up receivers. The protocol makes use of the different transmission ranges of wake-up and main radios in order to save energy by skipping nodes during data transfer. With respect to energy consumption and latency, T-ROME outperforms existing protocols in many scenarios. Here, we describe and analyze the cross layer multi-hop protocol by means of a Markov chain model that we verify using a laboratory test setup.

1. Introduction

Wireless sensor networks are used in many applications like environmental monitoring, home automation, smart manufacturing, infrastructure monitoring and many others. In this context, a wireless sensor network usually consists of many small self-powered sensor nodes that measure their environment, process data and communicate it to other nodes or to a base station [1]. Message transmission can be done via single-hop transmissions or via multi-hop communication resulting in complex network topologies.

The most critical parameter of a wireless sensor node is its energy requirement [2] which is vastly dominated by the power required for communication. A lot of research was already done on efficient MAC protocols to reduce power consumption and collisions and to increase the throughput of a wireless network [3]. The authors of [3] categorize MAC protocols into four groups: asynchronous, synchronous, frame-slotted, and multi-channel protocols. Asynchronous and synchronous protocols are based on duty-cycling, where nodes switch between sleep and active states in order to save energy. To establish a communication link in synchronous protocols like S-MAC or T-MAC, each participating node has to be awake at the same time. This necessitates clock synchronization messages. Asynchronous protocols like B-MAC or WiseMAC nodes use preamble sampling in combination with duty-cycling to detect the beginning of a communication. To minimize collisions frame-slotted protocols allocate different time slots to nearby nodes. Multi-channel protocols use cross-channel communication to realize higher throughput. All these MAC protocols have in common that their energy requirement is linked to the duration of their sleep periods. Longer sleep periods result in lower energy consumption but also in communication latencies. In addition, these MAC protocols require a certain amount of overhead to organize themselves [2].

Recently, wireless sensor networks [4–8] have been upgraded with low-power wake-up receivers. These wake-up receivers have marginal power consumption and wake up the sensor node if a dedicated signal has been received. So, low-power wake-up receivers can greatly reduce the power consumption of wireless sensor nodes, by eliminating the idle listening time and at the same time reduce communication delays to achieve an almost latency free communication [9].

According to [2], wake-up radios can be categorized into two groups, active and passive wake-up receivers. Passive wake-up receivers harvest their wake-up energy directly from the wake-up message itself, whereas active wake-up receivers require a permanent, yet very low, power supply. In this approach, a wireless sensor node usually incorporates two radio receivers, the main radio

* Corresponding author.
E-mail addresses: timo.kumberg@imtek.de, timo.kumberg@imtek.uni-freiburg.de (T. Kumberg).

http://dx.doi.org/10.1016/j.adhoc.2017.02.003
1570-8705/

Table 1
Receiver (RX) sensitivity at 868 MHz and transmit (TX) currents at +10 dBm for some typical RF transmitters.

RF transceiver	RX sensitivity [dBm]	TX current [mA]
Si4468	−104	19.7
CC1200	−107	36
CC1101	−95	30
SPIRIT1	−105	21

Table 2
Non-exhaustive list of wake-up receivers, their sensitivity and power consumption.

Wake-up receiver	Sensitivity [dBm]	Power [μW]
Magno and Benini [11]	−55	1.3
Nilsson and Svensson [12]	−47	2.3
Gamm et al. [13]	−52	5.6
Hambeck et al. [14]	−71	2.4

for data communication and a second one for receiving wake-up messages [2]. A sensor node wakes up only when it receives a wake-up message and then it turns on its communication radio.

Another advantage of wireless sensor nodes with wake-up receivers is their enhanced robustness. Clock synchronization is obsolete and nodes may be reset at any time, for example, if a fatal software error occurred. Existing networks can be easily enhanced by new nodes, even if the network is running on low duty cycle periods [6]. Furthermore, extracting data from the network can be done without much delay, as messages are transmitted almost instantly.

Although [10] speak of a paradigm shift for wireless sensor protocols with integrated wake-up transceivers, there exist two major challenges [2,10]: First, active wake-up receivers show a higher sensitivity compared to passive ones [2], but their sensitivity is still lower compared to that of state-of-the-art main communication radio transceivers. Secondly, sending wake-up messages may cost more energy than sending of communication messages. Table 1 shows the typical sensitivity of some commonly used radio transmitters and their current consumption during transmit state. In Table 2 sensitivity and power consumption of some state-of-the-art wake-up receivers are shown. The discrepancy between main radio and wake-up receiver sensitivity is clearly obvious as is the power consumption.

Here, we present a cross-layer multi-hop wake-up routing protocol that combines wake-up and communication radios. The wireless sensor nodes are based on the works of [13,15]. Due to the smaller transmission range of wake-up receivers compared to that of the main radio, data and wake-up transmissions are realized by a multi-hop routing protocol that supports sending wake-up messages and data. The protocol stack consists of several layers. The lowest layer is responsible for the waking up of neighboring nodes. The second layer handles single-hop message transmissions and the top layer routes messages and forwards wake-up signals along multiple hops.

The presented work in this paper is organized as follows. In Section 2 we review existing network protocols that support the use of wake-up receivers. In Section 3 we take a look at current wake-up receiver designs and present the wireless sensor node that is used in this research. In Section 4 we introduce the proposed multi-hop wake-up routing protocol in detail and analyze its current consumption as well as the occurrence of false wake-ups in Section 5. In Section 6, we introduce Markov models of the proposed algorithm as well as for CTP-WUR and a naive communication algorithm. The models are verified and performance and energy requirements of the aforementioned protocols are compared

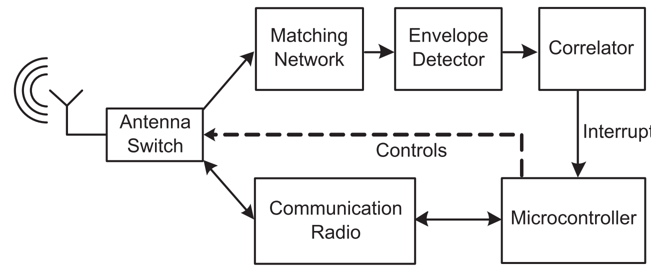

Fig. 1. Schematic of wireless sensor node including a wake-up receiver.

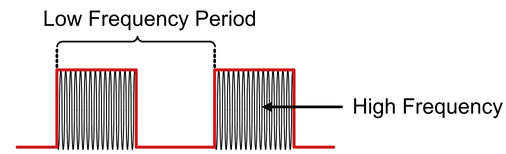

Fig. 2. The low-frequency wake-up message (red) is modulated on the high-frequency carrier signal by on-of-keying. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and analyzed in Section 7. Finally, outlook and conclusions can be found in Section 8.

2. Related work

2.1. Wake-up transceiver

Generally, a low-power wake-up receiver consists of an envelope detector and a correlator as sketched in Fig. 1 that shows schematically a wireless sensor node including a wake-up receiver. The envelope detector demodulates the high-frequency (HF) carrier signal to achieve a low-frequency (LF) wake-up signal as sketched in Fig. 2 [13] that depicts an on-off-keying modulated wake-up signal. The correlator analyzes the LF signal, to verify the validity of a wake-up message. In that case, the main microcontroller of the sensor node is woken up by an interrupt and, depending on the embedded software, a sensor reading might be initiated or the antenna is connected to the main radio to establish further communications. A matching network might be necessary to match the impedances of antenna and wake-up receiver.

Blanck et al. presented [9] an overview of current low-power transceivers. In respect to energy consumption the range goes from highly integrated concepts that require 0.1 μW [16,17] to several solutions between 10 and 1000 μW [9]. Only a few receivers are in the range of 1 to 10 μW. Common to all receivers in the range below of 10 μW is that they use on-off-keying modulated wake-up messages. This is due to the simplified and energy efficient hardware design that can be used in this particular case. For example, the envelope detector is merely composed of diodes and capacitors and as a correlator, a comparator is used [11,18–21].

2.2. Protocols

Although wake-up receivers have many advantages and writer frequently reported devices in wireless sensor networks [4–7], there do not exist many MAC or routing protocols that support their use and the majority of existing protocols are only limited to simulations. Some existing protocols for wake-up receivers support single-hop communication only, like E2RMAC [22], WUR–MAC [23], RTWAC [19] and GWR–MAC [24]. These protocols show superior energy requirements compared to synchronous or asynchronous MAC protocols but their performance is only based on simulation results. The main feature of E2RMAC and WUR–MAC protocols is

Please cite this article as: T. Kumberg et al., T-ROME: A simple and energy efficient tree routing protocol for low-power wake-up receivers, Ad Hoc Networks (2017), http://dx.doi.org/10.1016/j.adhoc.2017.02.003