Computer Networks 69 (2014) 51–65

Contents lists available at ScienceDirect

Computer Networks

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

BailighPulse: A low duty cycle data gathering protocol for mostly-off Wireless Sensor Networks

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ARTICLE INFO

Article history:
Received 22 September 2013
Received in revised form 6 April 2014
Accepted 28 April 2014
Available online 6 May 2014

Keywords:
Wireless Sensor Networks
Mostly-off
Data gathering
Low duty cycle

ABSTRACT

Mostly-off sensor network applications alternate between long periods of inactivity (ranging from minutes to hours) and short periods of activity (normally a few seconds). From an energy consumption point of view, it is desirable that the network switch off completely during application inactive periods and wake-up efficiently at the start of application active periods. The fundamental problem preventing this is the inter-node clock skew arising from the network being off for a long period. Existing solutions maintain synchronization during the inactive period or use the radio excessively to enable asynchronous wake-up. Herein, we propose BailighPulse, a low duty cycle data gathering protocol for mostly-off WSN applications. BailighPulse incorporates a novel multi-hop wake-up scheme that allows for energy efficient recovery of network synchronization after long off periods. The scheme uses a staggered wake-up schedule and optimized channel polling during wake-up based on knowledge of the pre-defined application-level schedule. Herein, we provide an extensive assessment of the protocol's performance including an analytic model, simulations, and testbed results. We show that, for a homogeneous schedule with collection period greater than 2 min, BailighPulse reduces radio duty cycles by at least 30% and 90% compared to Dozer and B-MAC, respectively. We also show that BailighPulse is able to reduce radio duty cycle by to 68% for a heterogeneous schedule under similar conditions.

1. Introduction

In data gathering applications Wireless Sensor Network nodes periodically sample their sensors and transmit the measurements back to a single node (the sink). In *mostly-off* WSN applications [1], the application alternates between long periods of inactivity (ranging from minutes to hours) and short periods of activity (normally a few seconds). Examples of these applications include predictive maintenance [2], utility metering networks [3], and environmental research [4].

From an energy consumption point of view, it is desirable that a Wireless Sensor Network follows application characteristics and switches off completely during application inactive periods and switches on efficiently at the start of application active periods. This mode of operation where a network is completely switched off between short on periods is referred to as *disconnected mode* [5]. Clearly, to preserve energy, the time for which the sensor network is on should be as short as possible. Dutta et al. [5] showed that, in principle, a network using this mode of operation can operate at a duty cycle of 0.01%. In practice, however, achieving this goal has proven difficult due the fundamental problem of inter-node clock skew arising from the network being off for a long period [6]. Clock skew results

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http://dx.doi.org/10.1016/j.comnet.2014.04.018
1389-1286/

from crystal oscillator instability which is mainly caused by temperature variation. In outdoor environments this can lead to clock drifts of 125–400 ms/h (35–110 ppm) [7]. Due to the resulting clock skew, nodes wake-up at different times and need to wait until the whole sensor network is ready before communicating. This increases the network on time, increasing the nodes' duty cycle.

The problem can be addressed at the hardware or software level. At the hardware level, a temperature compensated crystal oscillator (TXCO), which has minimal clock drift can be used, so that nodes wake-up at almost the same time [6]. Another hardware approach uses an out-of-band wake-up radio that allows efficient asynchronous network wake-up [8]. Hardware approaches, however, are rarely used since they require additional electronics which increase sensor node cost and size. Hence most research focuses on the software level in the form of energy efficient data gathering protocols.

Data gathering protocols can be categorized according to whether they use synchronous or asynchronous wake-up methods. In the case of synchronous wake-up, either explicit or implicit synchronization is used during the application inactive period. In the case of asynchronous wake-up, the sensor network is kept on so that the drift does not matter. Both approaches require energy which is wasted from the application point of view. As a result, no previously proposed protocol achieves the theoretical duty cycle target.

Typically, in mostly-off sensor network applications the application schedule (the times of sensor sampling and data collection) is determined by a domain expert and fixed *a priori*. An application schedule might, for example, set the network to sample sensors less often during the day and more often during the night. In the protocol presented herein, we take advantage of this property to propose a different approach to dealing with the clock skew problem. In BailighPulse the network is switched off completely when the application is inactive. Fine grained network synchronization is then recovered at the beginning of the active phase using a novel multi-hop wake-up scheme. This wake-up scheme uses a staggered wake-up schedule and optimizes channel polling based on knowledge of the pre-defined application-level schedule. Using this approach energy consumption during wake-up is minimized.

To the best of our knowledge, BailighPulse is the first data gathering protocol for mostly-off sensor networks utilizing coarsely synchronized multi-hop wake-up. BailighPulse is suitable for use with complex scheduling algorithms such as those described in [9–12]. These algorithms derive sampling schedules based on criteria such as sensing converge and data correlation. For completeness we propose a compact notation for specifying the application level schedules. The notation allows for expression of application activity, i.e. sampling and collection, in a simple and compact way.

The results of analytic and simulation based evaluations show that, for low data collection rates, the proposed protocol significantly reduces the average radio duty cycle of the network. We show that in mostly-off applications BailighPulse outperforms Dozer, which is a state-of-art data gathering protocol.

2. Related work

A large number of techniques aiming to reduce energy consumption in WSNs have been proposed [13,14]. The solutions most closely related to the proposal are data gathering protocols, i.e. protocols specifically designed for collecting data from the entire network. Typically, data gathering protocols are cross-layer, integrating MAC layer, routing layer, and energy management mechanisms. From the point of view of mostly-off sensor network applications, these protocols can be divided according to whether they use synchronous or asynchronous wake-up.

A simplified overview of both approaches is shown in Fig. 1. In the first case (Fig. 1a), nodes are not synchronized and periodically poll (check) the wireless channel for a wake-up beacon. The polling period is typically in the range of 100–1000 ms. However, energy is wasted when the application does not require transmission of data. In the second case, nodes are synchronized (Fig. 1b) and time synchronization is maintained in the network. This means that clock drift is kept low. This allows the nodes to wake-up at scheduled times and send data immediately. Although less energy is wasted than in the case of asynchronous wake-up, energy is still wasted on maintaining time synchronization.

Most proposals based on asynchronous wake-up are focused on the MAC layer. Protocols such as B-MAC [15], Wise-MAC [16], X-MAC [17] use periodic channel polling to reduce energy consumption. For data gathering applications, these protocols must be used with a collection protocol which provides packet routing. One of the most recognized collection protocols is the Collection Tree Protocol (CTP) [18], which is a standard data gathering protocol distributed with TinyOS [19]. The main drawback of CTP, when used in mostly-off sensor network applications, is that it requires the network to be active during the application inactive period. This is required in order to maintain the routing state of the data gathering tree. The duty cycle of CTP is thus directly related to the duty cycle of the underlying MAC protocol, with typical values of 1%. In DISSense [20], the authors added an adaptation layer to CTP which allows the network to switch off between active periods. Thanks to this, DISSense is able to achieve a duty cycle of 0.1% for a collection period of 60 min.

Koala [21] is a data gathering protocol strictly designed for mostly-off sensor network applications. Koala uses an asynchronous wake-up technique called Low Power Probing (LPP). In LPP nodes actively probe the channel in order to detect a wake-up message sent by the sink. This allows for data collection to be initiated by the sink at any time. Unlike CTP, Koala does not maintain the routing state between application inactive periods. Instead, the data gathering tree is recreated at the beginning of the active period. The approach used by Koala, is beneficial in applications with collection periods greater than tens of hours. In this way, the considerable overhead of establishing the data gathering tree is amortized.

Protocols using synchronous wake-up have been proposed both as MAC protocols and cross-layer data gathering protocols. Synchronous MAC protocols include well known protocols such as S-MAC [23], Z-MAC [24],