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Enhancing performance of wireless sensor networks in glacial environments using wake-up receivers

Vana Jelicic[1], Daniel Cesarini[2] and Vedran Bilas[1]

[1] University of Zagreb, Faculty of Electrical Engineering and Computing, Unska 3, 10000 Zagreb, Croatia

[2] University of Pisa, Department of Information Engineering, Largo Lucio Lazzarino 1, 56122 Pisa, Italy

E-mail: {vana.jelicic, vedran.bilas}@fer.hr, daniel.cesarini@iet.unipi.it

Abstract. Development of radio telemetry enabled long-term monitoring of hard-to-reach and harsh environments. This paper compares two WSN deployment projects for gathering sensor data in glacier monitoring application — GlacsWeb and PermaSense, in terms of system design and wireless communication. We discuss the potential benefits of energy-efficient event detection using wake-up receivers together with duty-cycled communication. We show that adding a WURx would increase the average power consumption of Dozer protocol for 10%, but it would reduce the delay from 2 minutes to several milliseconds. Besides for event detection, WURx could be used for synchronizing the beginning of the TDMA communication, which would eliminate the need for clock drift compensation, making the protocol simpler and lighter.

1. Introduction

Environmental monitoring was one of the first telemetry applications to attract attention, due to the need of unattended and unobtrusive measurements interesting to a wider community (e.g. weather and climate monitoring and forecast), as well as field scientists (biologists, zoologists, geologists, etc.). Monitoring hard-to-reach and harsh environments, like glaciers, has posed a special challenge, since the measuring equipment has to survive extreme conditions (low temperatures, wind, ice...) and there is a high maintenance cost in case of a failure. Automatic Weather Stations (AWSs) are measurement units developed and deployed in various locations in the past 30 years. They provide a single point of measurement, usually for temperature, humidity, wind speed, etc. To collect the data, the location has to be visited, or the data can be communicated wirelessly (e.g. via WiFi or satellite) [1].

Although field scientists benefit significantly in understanding many phenomena from data collected by AWSs, they are also interested in obtaining dense spatial distributed measurements [2]. Technology enabling that requirement is called Wireless Sensor Networks (WSNs) [3]. WSNs are suitable for long-term monitoring of various phenomena on a large area (temperature, humidity, snow height, etc.). To reduce high energy consumption of the transceivers, but ensure reliable communication at the same time, various low power medium access control (MAC) protocols for WSNs have been developed [4]. Their main characteristic is duty-cycling of the radio, that reduces consumed energy, but introduces latency. Many phenomena in glacial environments are quite slow, but there are some events where precise timing is interesting for scientists (start of snowing, subglacial movement, etc.) or safety related, e.g.

rock falls or avalanches. A promising solution for eliminating latency and keeping low energy consumption of the communication unit are wake-up receivers (WURx) [5].

By now, only two projects had WSN deployments in glacial environments. They gather spatially distributed sensor data at a low frequency (<1 Hz). In order to detect interesting events in WSNs, we propose to use WURxs, that would enhance the performance of by-now used TDMA (time division multiple access) protocols, and communicate the event to the user in real-time, enabling timely reaction in case of safety-critical events. Another benefit introduced by WURx in MAC protocols is synchronization of the nodes for beginning of TDMA communication. The remainder of the paper is organized as follows. Section 2 presents requirements of WSN monitoring in glacial environments, with comparison of two real-life deployments and their TDMA communication protocols (Dozer and GWMAC). Section 3 presents the benefits of using the WURx technology in low-power TDMA MAC protocols, for event detection in glacial environments, and for TDMA synchronization. Section 4 concludes the paper.

2. Monitoring glacial environments with WSNs

Environmental sensor networks [6] have evolved from passive logging systems that require manual downloading, into intelligent sensor networks that comprise sensor nodes which communicate their sensor data to a network server. The first widely famous environmental WSN application was in 2002, and it monitored bird habitats. Besides habitat monitoring, WSNs are often developed and deployed in agriculture [7]. Harsh environments like glacial areas pose even bigger challenges for WSN development and deployment because of more extreme weather conditions and more difficulties (i.e. costs) to reach the equipment for maintenance. In this section, we provide an overview of glacial monitoring with WSNs, focusing on two most famous research projects using WSNs in this field: PermaSense and GlacsWeb. We also survey the low-power MAC protocols they developed (Dozer and GWMAC).

2.1. PermaSense

The PermaSense project investigates the influence of climate change on permafrost. The main scientific research goal is to understand the heat transport in frozen rock walls and its influence on the stability, as well as large scale mass movements (rock glaciers) [8]. From 2006 by now, there were 2 deployments in Swiss Alps, at 3500 m a.s.l. Although there were various modifications of the system over time, the main principle has remained the same: sensor nodes placed on the surface, and the probes with sensors (temperature and crack meter) placed in the ground. The WSN comprises TinyNodes (with TI MSP430 MCU and Semtech XE1205 transceiver) as sensor nodes and an embedded computer, running the Linux OS, as base station.

2.1.1. Dozer incorporates a MAC layer (TDMA), topology control, and a routing protocol [9]. It builds a data gathering tree on top of the underlying network topology and provides nodes with precise wakeup schedules for all communication only relying on local synchronization (without a global schedule). Nodes are organized in parent-child relationships. Parents schedule precise rendezvous times for all communication with their children. While in theory wakeup times can be calculated perfectly at both parent and children, clock drift has to be considered in real-world applications. In Dozer, the receiver node is responsible for clock drift compensation and worst-case guard times are used to guarantee a prior wake up of the receiver before the sender starts its transmission. Furthermore, Dozer addresses the problem of temporary network partition and energy efficient tree adaptation in case of local link failures. Despite these additional considerations, Dozer attains low radio duty cycles in both single-hop and multi-hop networks. The Semtech XE1205 radio transceiver operates at 868 MHz using 0 dBm transmission power and a bandwidth of 75 kbps. The obtained range is about 300 m. Using a sampling period of two minutes, Dozer achieved an average duty cycle of less than 0.2% on all nodes.

2.2. GlacsWeb

GlacsWeb project uses a WSN to understand subglacial processes, and relationship between glacier dynamics and climate change [10]. They had several deployments from 2004 to now (in Norway and in Iceland), with different improvements of the system design. The latest deployment in Iceland is a heterogeneous sensor network consisting of: probes in the ice and till layers, geophones embedded within the ice and a differential GPS network in order to produce precise measurements of movement distance. The nodes deployed into the glacier are based on the Energy-Micro ARM Cortex-M3 MCU and Radiometrix RPM1 transceivers. Geophones, on the other hand, communicate the data over the air from their probes to the base station using the TI CC1120 transceiver. Sensors used on the probes and/or geophones are: temperature, pressure, strain, accelerometer, compass, gyroscope and conductivity. The base station is a platform with TI MSP MCU and a Beagle Bone Linux computer [11].

2.2.1. GWMAC is a centralised TDMA-based protocol, designed for unreliable networks where contention is completely eliminated and control packets are minimised [12]. Since in GlacsWeb latency is secondary, GWMAC reduces the duty cycle of the nodes to almost zero, providing only one small communication window (few minutes) per day. Even during the communication window, nodes have their transceivers turned off for the major part and only turn them on either during time slots in which they are expected to receive data or slots uniquely assigned to them for transmission. A centralized algorithm is used to synchronise the entire network at boot phase and, additionally, each time a command packet is received. In GlacsWeb deployment, the base station is connected to some of the nodes in the ice (called anchor nodes) via a serial cable. The anchor nodes communicate wirelessly with other nodes deployed even deeper under the surface. In order to get the nodes synchronised, the base station first synchronises its own RTC with the average of the closest RTCs of the anchor nodes. The remaining nodes are synchronised through the diffusion of any message packet initiated by the anchor nodes. When a node receives a message packet, it can uniquely determine its clock by considering the time stamp value embedded within the packet, the time of flight and time of processing.

3. Enhancing communication with wake-up receivers

Extremely low duty cycles of Dozer and GWMAC are implemented because the data delivery latency is not considered to be important, i.e. it is important to deliver the data, but it doesn't matter if it occurs immediately or the day after. In case of GlacsWeb, glacial and sub-glacial movements were monitored. Instead of moving continuously throughout the year, the movement of a glacier occurs through a series of slip events ("stick-slip" motions), but it is a rather slow process and the glaciologist are satisfied to receive the information rarely (once a day). PermaSense project studied heat transport in frozen rock walls and its influence on large scale mass movements and stability. For now the benefit of the WSN system was to gather the data from a wider area and use it for offline analysis. They used an average duty cycle (D) of 0.2%. There are, though, some events that require prompt reaction to avoid catastrophes (e.g. avalanches or rock falls), that can't be detected with such low duty cycles. Wake-up receivers are a suitable solution to optimize delay, since they are continuously monitoring the communication channel and wake up the node upon message reception.

In 2007, when both PermaSense and GlacsWeb projects published their low-power MAC solutions (Dozer and GWMAC, respectively), WURxs were only at their beginning. Just in 2009 and after, there have been some significant attempts of designing WURx prototypes [13]. In this section, we will analyze the benefits of a wake-up receiver in glacial monitoring WSNs on a case study of enhancing Dozer behavior with AS3932 WURx.

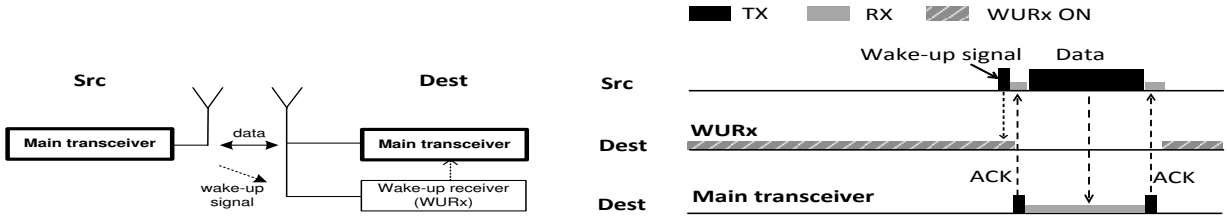

Figure 1. Implementing wake-up receivers on wireless sensor nodes

Table 1. Characteristics of low-power MAC protocols (DOZER, GWMAC) and AS3932 WURx

Name	Frequency	D [%]	Rate [kbps]	P [μW]
Dozer	868 MHz	0.2	75	82
GWMAC	173 MHz	~ 0	5	386
AS3932	125 kHz	100	5.5	~ 8

3.1. Wake-up receivers

A wake-up receiver (WURx) is a simple, very low-power receiver added to a transceiver, that continuously monitors the communication channel and wakes up the transceiver upon message reception to receive the data (Fig.1 left). Fig.1 (right) shows communication between two nodes when employing a WURx. The main radio is turned off most of the time, both for the source and the destination node. When a node wants to communicate, it sends a wake-up signal, usually containing the address of the destination node to awake only the desired neighbor.

WURxs have been a hot topic in the last couple of years, but are still under development. Since it is a new component with quiescent power consumption added to the radio circuitry, it is important to reduce its power consumption as much as possible. As a consequence, the downside of WURxs is the low reception range and low throughput [5]. Low throughput is not a problem, since for wake-up signal only a short message is used. Low reception range could be solved by placing nodes in smaller distances. One of the very few commercially available is a low-power, low-frequency wake-up receiver chip with addressing capability AS3932 [14]. Gamm *et al.* [15] designed a low-power WURx circuitry around it. The main transceiver produces a 125 kHz wake-up signal OOK (On Off Keying) modulated on an 868 MHz carrier. They report communication range of 45 m when transmitting with main high-consuming transceiver with +11 dBm and over 15 m when using 0 dBm output power.

3.2. Benefits of WURx combined with Dozer protocol

Table 1 compares the characteristics of AS3932 WURx to Dozer and GWMAC protocols. For Dozer and GWMAC, power consumptions are average values simulated from the tests and current measurements on the nodes [9, 12]. Average power consumption of the WURx depends on the number of received wake-up signals. But, since the duration of the wake-up signal is very short, the power consumption of the idle state dominates in practical applications. Unfortunately, the Dozer and GWMAC have not been implemented on the same platform, making it difficult to compare their performance. Current consumption of TinyNodes and GWnodes while in sleep, receive (RX) and transmit (TX) state, as well as of AS3932 WURx in idle and while receiving, are shown in Table 2. Hereafter, we discuss the benefits that the WURx would introduce in Dozer protocol, in terms of asynchronous and synchronous communication.

Table 2. Current consumptions of a TinyNode, GWnode and AS3932 WURx

	GWnode	TinyNode	AS3932
RX	18 mA	13 mA	12 μA
TX	35 mA	16 mA	-
sleep/idle	1 μA	6 μA	2.7 μA

Table 3. Time duration: communication period in Dozer, data message (t_{data}) and wake-up signal (t_{wup})

Dozer period	t_{data}	t_{wup}
2 min	5 ms	1 ms

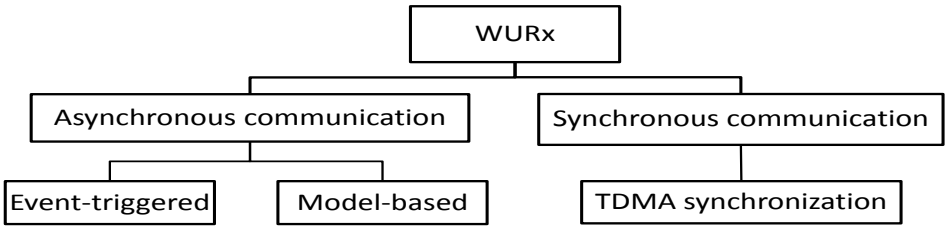

Figure 2. Benefits of using a WURx in a WSN with TDMA protocol

3.2.1. Asynchronous communication: Table 3 shows the times in Dozer communication: period and data message. Since the time necessary to transmit the data is about 5 ms, we can approximate the maximal delay in the communication to be 2 minutes. If we use the AS3932 WURx in addition to the main nodes transceiver, we can reduce that delay to orders of milliseconds. Since the detected event can be important for the whole network, it is not necessary to include addressing in the wake-up signal, but to wake all the nodes within the communication range, instead. That means that the wake-up signal has to be at least 550 μs long (by the specifications). We will suppose it is 1 ms long, as a worst case. Let's suppose that each node detects maximum 1 event per hour. An interesting event can be a crack in the rock, or a sudden rise in snow height. It can be recognized by superating a certain threshold or by differing significantly from a model of the monitored phenomena, executed on the MCU. Further on, let's suppose that a node receives in average 5 wake-up signals in an hour, like in Fig.1. Adding the AS3932 WURx to the TinyNode, and having 1 wake-up signal to send and 5 wake-up signals to receive each hour, causes 10% additional power consumption to the node with only Dozer protocol.

3.2.2. Synchronous communication: Another benefit of adding a WURx in low-power MAC protocols like Dozer is for synchronizing timeslots for TDMA communication. A similar solution was proposed for a single-hop star wireless body area network, where authors used their own WURx design and showed about 14 times lower communication consumption compared to their low power TDMA protocol [16]. Precise clock compensation is a complex and energy-consuming task in WSNs, especially in harsh conditions like glacial environment, due to large temperature variations causing clock drifts. For approximating the benefits of using AS3932 in Dozer, it would be necessary to implement the whole system. Namely, the Dozer protocol would have to be modified in a way that it doesn't perform the synchronization. Instead, the synchronization would be performed by WURx, and the Dozer would only be used for the communication handshake. In that way, the protocol would be simpler and less energy-consuming.

4. Conclusion

In this paper, we propose using a WURx to enhance the existing low-power TDMA MAC protocols, in two aspects, as showed in Fig.2: (i) for asynchronous communication upon detecting an interesting event or discrepancy between sensed and the modeled phenomenon; (ii) to

synchronize the start of TDMA communication. Those two challenges (event detection and synchronization) were also recognized as future work challenges in Dozer [9], but at that time WURxs were not that known technology as they are today. Comparison of characteristics of AS392 WURx and Dozer MAC protocol shows that there would be 10% of power consumption increment when adding the WURx, but it would reduce the latency of the system from 2 minutes to several milliseconds. Latency avoidance is important for detection of safety-related events in glacial environments, and timely reaction useful for avoiding catastrophes like rock falls or avalanches. In case of using WURx for synchronizing the TDMA communication, reliable and robust data gathering producing continuous data logs already implemented with Dozer would be preserved. In addition, there wouldn't be the necessity to compensate the nodes clock drift for synchronization, and the communication could also be event-triggered. It is expected that in the next few years there will be more WURxs available on the market, with even better characteristics than the AS3932, enabling a promising enhancement for power saving and delay reduction in wireless asynchronous systems.

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