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Deployment and evaluation of a wireless sensor network for methane leak detection

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ABSTRACT

Wireless sensor networks (WSN) have been adopted in various monitoring applications. However, due to the high power consumption of catalytic gas sensors, which enable reliable gas detection, there is a lack of real WSN deployments aimed at the monitoring of combustible gases. This work reports on the evaluation of a WSN deployed in a real operational boiler facility. The WSN consists of nine battery-powered wireless sensor nodes (with an onboard catalytic sensor) controlled by a network coordinator. In this safety critical environment our objective is twofold: (i) guarantee precise and fast sensor response, and (ii) deliver the sensed data from the sensor nodes to the network coordinator safely in case of methane leakage. We first describe the deployment of the WSN and then evaluate the catalytic sensor response under various conditions. Besides, we evaluate the wireless links using the received signal strength indicator (RSSI) and link quality indicator (LQI) metrics. Finally, the experimental results demonstrate that during 5 months of deployment the sensor nodes have been discharged for 22–27%.

1. Introduction

Wireless sensor networks (WSN) [1] are collections of resource constrained sensing and processing devices that have a variety of different successful applications, including environmental monitoring (monitoring of floods [2], an active volcano [3], monitoring of zebras migration [4]), safety and security (monitoring of radioactive materials [5], wildfire [6], and buildings [7]), assisted living (smart medication system [8]), control (light control in tunnels [9]). Among these, hazardous/combustible gas monitoring, e.g., ethylene [10] and methane [11], is particularly promising for WSNs, since it requires capillary sensing capabilities in often difficult or harsh environments, favoring the adoption of simple, low-maintenance units. Until recently, however, hazardous/combustible gas monitoring with WSNs has lacked real deployments and experimentations in real scenarios. The reasons are found in the many limiting factors of this kind of deployments: (i) the high power consumption of catalytic [12] and semiconductor [13] sensors which fails to meet the long-term operation requirement of WSNs; and (ii) the long response time of colorimetric sensors which consume low power, but do not meet safety standards [14]. Hence, today the monitoring of hazardous gases in industrial premises or living apartments is typically carried out by wired systems [15] which can employ accurate and power 'hungry' sensors, and fast and powerful processors.

There are many reasons why one would like to replace the available wired solutions for gas monitoring in favor of a WSN approach. The principal one is that the major drawbacks of wired monitoring systems are their maintenance cost and their large demand in terms of cables, which constrain the way the system can be deployed. The WSN paradigm, in contrast, enables easy deployment of sensor nodes *anywhere* they are required and provides high flexibility and ease of maintenance. The use of this technology is possible today thanks to semiconductor and catalytic sensors with low power consumption on board of a WSN node that are able to meet the standard [14] of gas monitoring and energy-aware sensing [16] requirements, in terms of accuracy and response time.

In this work we present a novel application where a WSN is used to monitor methane levels in an operational boiler facility in Moscow. In particular, we evaluate and characterize the response of the sensors with respect to environmental conditions. To avoid dangerous situations, we emulate the leakage of methane in lab conditions and evaluate the sensor performance at 0.26% and 2% of methane concentration in the environment. In such a safety-critical application, the system must ensure the highest control quality, which strongly depends on reliable measured data delivered in time by the wireless communication channel. For this reason, our results include an estimation of the wireless link quality between

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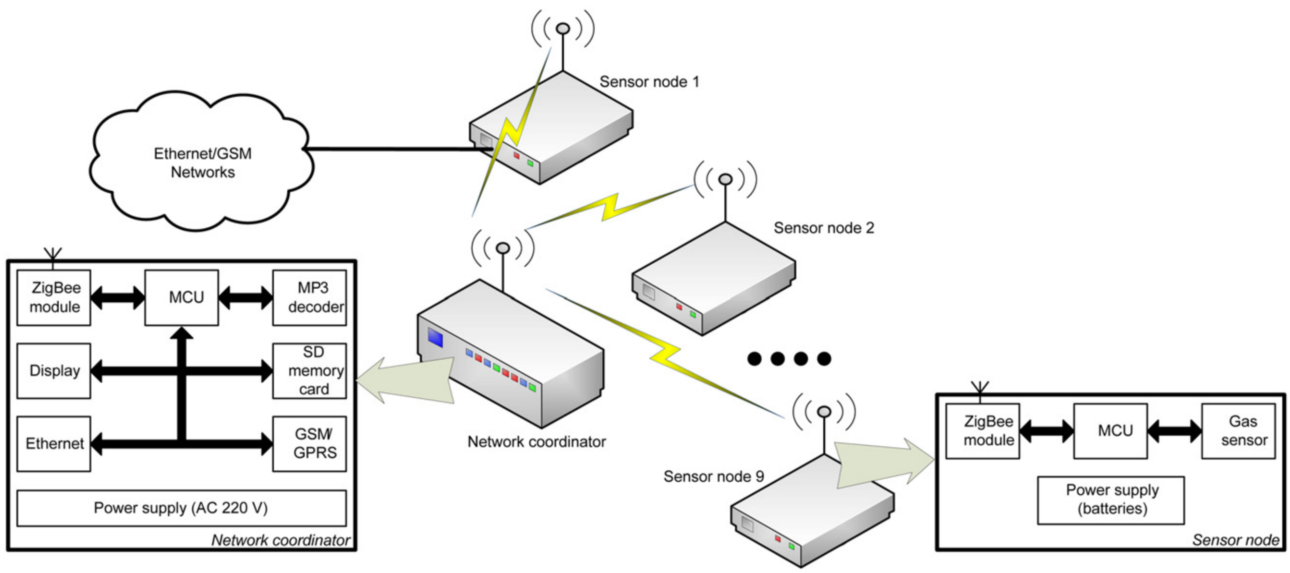

Fig. 1. Schematic diagram detailing the network operation and internal architecture of the sensor nodes and network coordinator.

the network coordinator and the sensor nodes in varying environmental conditions.

This paper is organized as follows: we introduce the reader to the used WSN in Section 2 where we describe the catalytic sensor, the battery-powered gas sensor nodes, and the network coordinator which enables remote sensor calibration. The details on the deployment scenario are shown in Section 3. The experimental results on the sensor response in a real boiler facility, the evaluation of wireless links and the sensor node long-term operation are demonstrated in Section 4. Finally, we discuss the related work and provide our concluding remarks in Section 5 and Section 6, respectively.

2. Wireless sensor network description

For this deployment, we have upgraded and improved the wireless gas sensor network (WGSN) research platform we introduced in our previous work [17]. For example, our current, commercially oriented platform supports remote sensor calibration (see Section 2.2) of sensor nodes and employs external antennas.

The WGSN consists of 9 battery-powered wireless sensor nodes and 1 network coordinator (see Fig. 1). The network topology is of star configuration. The network coordinator sets up the network parameters automatically. Communication within the network is implemented using the IEEE802.15.4 standard and the low-power wireless specification ZigBee. The network coordinator, however, has access to the Ethernet and GSM networks, so that, in case of alarm, it can notify a network operator or a boiler service team by sending a message through the Internet. All devices used in the deployment are customized, so we could easily adapt them to our needs.

2.1. Sensor nodes

The full block diagram of the sensor node is presented in Fig. 2. The sensor nodes are based on an AtXmega32A4 microcontroller and use an ETRX3 communication module (IEEE802.15.4, ZigBee, 2.4 GHz). The chosen communication module supports convenient self-configuration functions, at the expense of the power consumption which is slightly higher than other traditionally used solutions. Our choice does not degrade significantly the performance of the network, since the module power consumption is still very low compared to the rest of the system (especially the sensor heating) and considering also the duty cycle of the application. The nodes are supplied by two 2D-type batteries, wired in series. The input voltage from the batteries to the sensor node is regulated by a DC–DC converter. The sensor nodes can operate autonomously for more than 1 year [16]. To support the stable communication between the nodes and the coordinator, all wireless devices have an external antenna. The sensor node includes the gas sensor, which is described in Section 2.1.1. A picture of the sensor node is shown in Fig. 3.

The sensor node performs the catalytic sensor heating every 30 s. The heating voltage is adjusted by a built-in Digital-to-Analogue Converter (DAC) in the microcontroller and by an output amplifier. The measurement circuit is disabled by a MOSFET switch when it does not perform the sensing of the environment. Apart from the methane measurement, the wireless sensor nodes perform also self-diagnostics which includes the monitoring of the voltage level of the batteries and the sensor heater status.

2.1.1. Sensor

The sensing circuit, shown in Fig. 2, consists of an *active* (R4) and a *reference* (R5) catalytic sensor. In this work we use planar catalytic gas sensors by NTC-IGD, Russia. The sensor is manufactured on gamma alumina membranes with a thickness of 30 μm and has low power consumption [16]. The active sensor has a platinum micro-heater covered by porous gamma alumina oxide material that is used as catalyst support for catalytically active metals (mixture of Pd and Pt). In order to impregnate the catalyst support by the catalytic metal, salts of palladium chloride ($PdCl_2$) and platinum acid (H_2PtCl_6) are used. The noble metal clusters are formed on the catalyst support after annealing. The reference sensor has only a microhotplate covered by porous gamma alumina oxide material without catalytically active metals and is used to compensate for environmental factors such as temperature and humidity. The sensors are arranged in a Wheatstone bridge configuration, where the resistance of R1 and R2 is 1 kΩ each. The resistance of R3 is 1 Ω and is wired in series to the bridge to measure the heating current by measuring its voltage drop and applying Ohm's law. The resistance of the active and reference sensors is 12 Ω each under normal condition. During the heating process the resistance of the sensors changes, but does not do so equally for both sensors. This effect will be discussed in Section 4.1.

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