A Wireless Carbon Monoxide Sensor Node with Hybrid Power Supply

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***Abstract*—Gas monitoring is an important issue since the leakage associated with the penetration of gases in the surrounding environment can result in fatalities and harsh consequences. In this work, we propose a novel sensor node architecture for a wireless outdoor CO monitoring unit. To guarantee an autonomous operation, the sensor node is supported by a hybrid power supply, which takes advantage of both wind and solar ambient energy sources to power the node and to charge super capacitors that act as energy buffers. Also, the gas measurement logic is developed such that the energy consumption is minimized. An additional backup energy storage is based on a Li-ion battery. Using an electrochemical CO sensor, we secure the low power consumption of the node without degrading the sensing capabilities. Our solution can be applied for CO monitoring in urban areas and outdoor industrial facilities.**

Keywords—CO wireless gas sensor, gas monitoring, energy harvesting, power management

I. INTRODUCTION

Carbon monoxide (*CO*) is a colorless, odorless, and tasteless gas which is toxic to humans and animals in high concentrations. The natural sources of CO include volcanoes and forest fires. In industry, CO can be generated by operating stoves and combustion engines. Intense urbanization and the growing number of vehicles has resulted in the increase of CO concentration in the cities. The monitoring of CO, therefore, is of particular significance as this toxic gas is often present in industrial and living environments.

In the last decade, monitoring solutions have transitioned from wired to wireless, using the WSN paradigm, ensuring fast deployment and unmanned operation in difficult to access places. The application of WSNs is, however, restricted by the limited onboard energy resources [1], requiring careful design and power management.

Indeed, the problem of power management in WSN has been tackled from different perspectives such as energy-aware synchronization [2], protocols [3], sensing [4] and analysis [5]. In terms of power consumption, the microcontroller (MCU), sensor and wireless transceiver are the most power hungry components onboard. The total energy consumption of sensor nodes could exceed hundreds of milliwatts, requiring the use of wires to provide electric power to the sensor node [6]. At the same time, the WSN paradigm involves not only the wireless data transmission, but also the independence on power grid. As a matter of fact, the wired power supply limits the practical use of wireless sensor networks. The transition from electric power through wires to battery power requires a special focus on power consumption optimization [4][5] to ensure the WSN long lifetime.

A number of research works have been dedicated to this problem so far. For example, the intelligent approaches presented in [7] and [8] adjust the operation of a gas sensor by changing its duty cycle depending on the context, e.g., people presence in a building. A similar intelligent approach developed in [9] is based on a sensor fusion component which detects the presence of chemical species and estimates their concentration. Analyzing the measured data, the node infers whether the situation can be potentially dangerous and whether the data must be forwarded to a network operator. The research conducted in [10] and [11] reports on energy savings due to the optimized measurement procedure. In [10][28] the authors propose to change the duty cycle of the heating pulse of the sensor during the measurement by fast turning on and off the device. This approach may result in sensor damage. A more advanced "differential" heating profile is investigated in [11]: it is 65% more energy efficient while ensuring the sensor performance as in a typical measurement procedure. In contrast, designs shown in [12][13] demonstrate long lifetime of the sensor nodes by employing a light sensor in conjunction with a colorimetric chemical sensing film, but significantly suffer in performance in terms of long sensor response, which fails to meet safety requirements.

Another way to increase the lifetime of WSN is the application of energy scavenging technology [14][15][16]: different classes of generators can harvest and perform conversion to electricity from almost every form of ambient energy. The sensor nodes can use the ambient energy directly or keep it in storage elements such as a battery or super capacitor. During the last decade there have been plenty of architectures and power management [17] solutions proposing and implementing the energy scavenging paradigm in the scope of WSN. In the context of power hungry gas sensing, it should be noted that not all energy scavenging technologies generate sufficient amount of power [18][25]. Another crucial point is that some ambient energy sources are available only in particular weather conditions which do not guarantee the stable operation of wireless gas sensors.

In this work, we present a CO wireless sensor node with a hybrid power supply, which collects the ambient energy from

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sun and wind. In our approach, the dual harvester directly powers the sensor node at any time through the source with the most amount of available energy, while the remaining scavenged energy is stored in super capacitors or on a backup battery. When the ambient energy is not sufficient, the node is powered through the secondary storage elements, i.e., super capacitors. The CO sensor node can be assigned for individual use as well as being integrated into an IEEE 802.15.4. ZigBee network which is less power hungry than a WiFi one [27]. The novelty of this work lies in the energy efficient design of the platform with a particular focus on the hybrid power supply.

This paper is organized as follows: in Section II we perform an overview of the developed system, present the system architecture and design requirements. Section III describes the sensor node operation. We discuss energy scavenging and power consumption estimation in Section IV. Finally, we provide concluding remarks and discuss our future work in Section V.

II. SYSTEM OVERVIEW

In this section we first overview the relevant standards on admissible CO concentration, and then describe the system architecture. The following standards regarding the maximum permissible concentration of CO gases for the residential areas as well as industrial complexes are accepted in Russia:

- For residential areas, the maximum permissible concentration of CO for a long term stay is 3 mg/m³ (approximately 2.6 ppм at the temperature of 20 ^{0}C and pressure of 1 bar) and for a short duration of stay it corresponds to 5 mg/m³ (approximately 4.3 ppм at the temperature of 20 ^{0}C and pressure of 1 bar).
- The maximum permissible value of the CO concentration at industrial complexes is 20 mg/m³ (approximately 17 ppм at the temperature of 20 ^{0}C and pressure of 1 bar).

An autonomous wireless sensor node for CO monitoring is shown in Fig. 1. The core element of the node is the *processing unit,* based on the ATXMTGA32A4 MCU, which manages the operations of the *sensing* and the *wireless communication* blocks. The sensing circuit is built around a NAP-505 electrochemical sensor with three electrodes (working, reference, counter) by Nemoto. Wireless communication supports the ZigBee protocol and is implemented using an ETRX3 2.4 GHz wireless modem. The ZigBee transceiver is operated by the AT commands, which are transmitted through the UART interface of the MCU. The node is supplied by a hybrid power supply via a DC/DC converter which outputs 2.8 V. The hybrid power supply consists of wind and solar harvesters each wired in parallel with a super capacitor and one 3.7 V Li-ion battery. In thisdesign, the battery is a backup storage: our experimental results demonstrate that the node can successfully rely on the ambient energy and the energy stored in the supercapacitors.

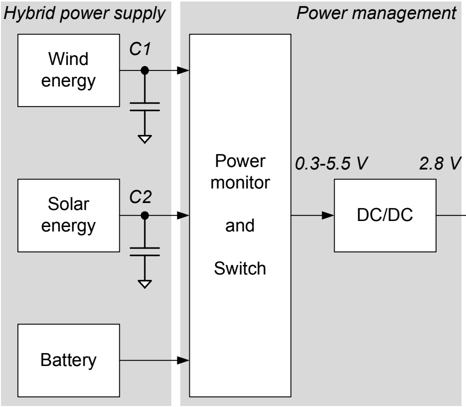

Fig. 1. The block diagram of the CO wireless gas sensor node with a hybrid power supply where *C1* and *C2* are super capacitors

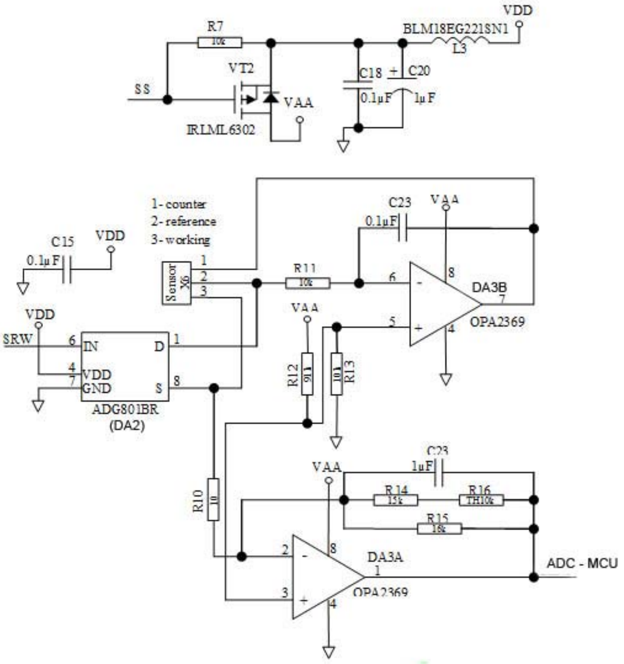

Fig. 2. Analog sensing circuit

The power management block operates as follows: the voltage across the battery and super capacitors *C1* and *C2* is controlled by the *power monitor* and relayed by the *switch*. If the voltage across the super capacitors exceeds 0.4 V, the one with the most charged unit is selected for powering the node. *C1* is supplied by wind energy and *C2* by solar energy. The supplied voltage level is then converted to a stable 2.8 V by the DC/DC unit (TPS61200).

As for the CO sensor, we used an NAP-505 (Nemoto) gas sensor operating in amperometric mode for this work. The CO wireless gas sensor node uses the Zigbee technology and transmits data via the BACnet protocol. An ETRX3 Zigbee modem was used for data transmission and the protocol was realized by the MCU program.

The wireless sensor is designed to operate in a wireless network in order to perform outdoor ecological monitoring of air in urban areas and industrial facilities. The data regarding the concentration of CO are sent to the network coordinator, which can be a computer with a Zigbee USB modem or device having a sound and light alarm. The range of data transmission depends on the antenna used and also the area in which the measurements are made. The range of transmission exceeds 300 m in open outdoor areas with an external antenna [26].

III. SENSOR NODE OPERATION

In order to increase the autonomous operation of the sensor node we implement a periodic CO gas measurement, i.e., there are three modes of operation which are *data measurement*, *data transfer* and *sleep*. We discuss them in this section.

A. Sensing Circuit

The sensing circuit of the node is shown in Fig. 2. It is a modified version of the sensing circuit recommended by Nemoto [19]. Our solution enables to carry out periodic measurements by switching the circuit on and off. When no measurement is conducted, the power supply is turned off by using MOSFET VT2 (IRLML6032). In order to connect the electrodes, we use an analogue switch DA2 (ADG801) instead of an FET transistor used in the Nemoto design.

The measuring parameter (voltage) is at *output 1* of amplifier DA3A (OPA 2369). This voltage is supplied to the MCU for detecting the concentration of the CO gas.

At normal conditions, a 1–2 minute time interval is required for the stabilization of the output voltage of the CO gas sensor after coming out of sleep mode. Therefore, the duration of the measurements shall be no less than 2 minutes. However, if the working and reference electrodes are connected during the sleep mode the stabilization period is reduced up to 10 seconds. During the remaining time, the MCU switches the sensor to sleep mode due to power saving reasons for a specified period. The management of the operation mode of the sensor is performed by the analogue switch DA2 and MOSFET VT2. The MOSFET is connected to the MCU input-output line (SS line) and the transition between active and sleep modes of the measuring circuit is provided. In sleep mode, this MOSFET is closed and there is no VAA voltage. In this case, the voltage at output 1 (ADC - MCU) is also zero. The analogue switch provides a stable voltage at output 1 (ADC–MCU) when the measuring circuit is shifted between active and sleep operation modes.

B. Measurement Procedure

The operation principle of the sensor is based on applying a certain amount of potential difference corresponding to oxidation or reduction of the substance to be detected. The amount of current in the cell is proportional to the concentration of the substance.

In order to carry out precise amperometric measurements, three electrodes are used in the electrochemical sensor: working, counter and reference ones. The reference voltage is necessary to support a stable voltage between working electrodes. The gas penetrates into a permeable membrane as well as a carbon filter, which removes all gases except carbon monoxide. The reaction takes place at the three phase boundary of electrolyte, gas and catalyst. As a result of the CO oxidation in the sensor, current flows. The results of this experiment conducted at normal conditions are shown in Fig. 3. The CO gas was injected into a measuring chamber in which the sensor was located. The CO concentration was varied as can be seen in Fig. 3.

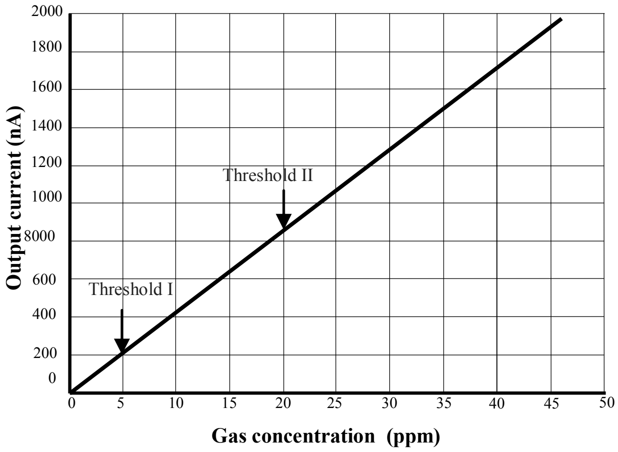

Fig. 3. Curve showing sensor response (output current) w.r.t. CO concentration

The sensor node is designed to detect CO using two thresholds (see Fig. 3), set to $T_1 = 5$ mg/m^3 and $T_2 = 20$ mg/m^3, respectively, and stored in MCU memory. The mentioned thresholds can also be changed within the program. If the detected concentration is less than T_1 – the sensor node goes to sleep mode; if the concentration is between T_1 and T_2 – a local sound alarm announces the increased CO concentration; finally, if the concentration is higher than T_2 – the node transmits an alarm message to an operator via the network coordinator. As a result, the operator can (de)activate an actuator, e.g., a gas valve, to avoid potentially dangerous situations.

The CO measurements are performed periodically according to the following algorithm. Most of the time, the sensor is in sleep mode, during which no measurements occur. During this time, the working and reference electrodes are connected. When a measurement is required, the MCU comes out of sleep mode and powers the sensor. At the same time, the working and reference electrodes are disconnected, and transient signals can be observed at the output. In this case, as specified earlier, the stabilization of the output voltage is carried out within 10 seconds after the power is on. In order to decrease energy consumption within this time, the MCU goes again into sleep mode. Then, the MCU wakes up and the measurements of the CO concentration is performed and, if thresholds are exceeded, the data is sent to the sensor network coordinator. The measurements of the CO concentration are performed every minute during which the microcontroller wakes up. In this process, the working and reference electrodes still remain disconnected. When the measurements are over, the MCU connects the working and reference electrodes and switches the sensor node to sleep mode. Actually, the MCU is in energy saving mode almost the entire time, except when the measurements are performed or during the transceiver activation. During the data transfer time, the main consumer of energy is the transceiver. It is necessary to note that if the concentration of the CO gas is less than the defined thresholds, there is no need to send data to the network coordinator and this in turn decreases the power consumption.

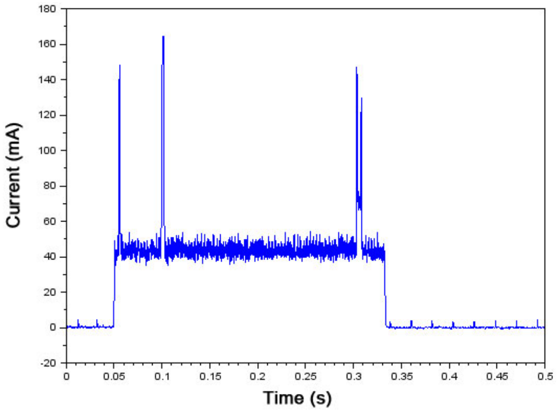

Fig. 4. Current consumption of sensor node (average current consumption is 43.49 mA within 0.28 s)

Fig. 4 illustrates the current consumption during the CO measurement and data transfer to the network coordinator. The peak of current consumption is observed when data is received or transmitted. The current peak associated with connecting or disconnecting working and reference electrodes is not visible at this time scale since the switching time takes place in milliseconds. It can be seen from Fig. 4 that the main power consumption periods are caused by the operation of the modem. The average current consumption during the data transfer time is 43.49 mA within 0.28 s (Fig. 4). Therefore, one measurement and consequent data transmission within one cycle, i.e., 1 minute, results in 0.2 mA of average current consumption. Using one 3.7 V 3200 mAh Li-ion AA-type battery, the node can operate 21 month. The sensor node for CO monitoring proposed in this work improves the power consumption of the state-of-the-art platforms [7][10][20] up to three times depending on the measurement procedure and the period of measurements.

IV. ENERGY SCAVENGING

Since green sources of energy have an intermittent nature, a robust model is needed in order to provide a more stable operation of the sensor node. One of the ideas to address this issue is the use of hybrid models which include more than one energy source for the sensor. As for the ambient energy sources, we use solar and wind energy harvesters due to their availability in most outdoor conditions and sufficient amount of power generated at their output.

A wireless sensor node with energy scavenging technology requires a buffer to store the harvested energy. The energy buffer allows the system to be supplied even if the ambient source is unavailable at the moment when the system is in operation. In our work, we use a battery and two super capacitors. Each super capacitor is wired in parallel with the harvesters. The super capacitors are manufactured by KEMET with a nominal capacity of 100 F and a voltage of 2.7 V. The solar cell power is approximately 2 W at 1.5 A (short circuit current I_{sc} = 0.9 A and open-circuit voltage U_{oc}= 2.2 V). A small wind turbine provides a maximum open circuit voltage and short circuit current of 2.2 V and 27 mA at a wind speed of 4.3 m/s respectively.

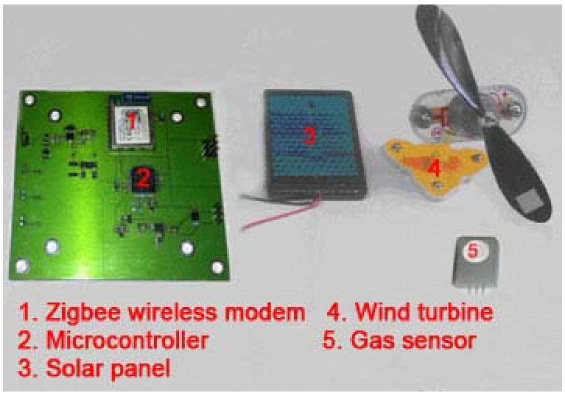

Fig.5. Prototype of the wireless sensor node for CO monitoring

The battery is used only as a backup energy storage. Changing from battery to energy harvesting sources takes place when the amount of voltage in the super capacitors is above 400 mV. The prototype of the sensor node is shown in Fig. 5.

Since the main task designated for the gas sensor node is to monitor the CO concentration, it is necessary to provide a continuous operation of the sensor node even in cases when the amount of energy provided by the harvesting sources is not enough to power the sensor node. Therefore, the battery can be used as a complementary system for powering the sensor node. Each super capacitor stores energy independently as a result of which it will be possible to store and use the energy from each source with maximum efficiency.

The energy stored in the super capacitor is given by the following equation:

$$W = C/2 \cdot \left(V_{\max}^2 - V_{\min}^2\right) \qquad (1)$$

where V_{max}, V_{min} are maximum (2.7 V) and minimum (0.4 V) voltage, respectively, and C is the capacity. The result is 358 J or 0.1 Wh.

Therefore, the energy of a super capacitor which is completely charged is enough for the operation of the wireless gas sensor for about 150 hours. Since we use two super capacitors, the operation time of the sensor node based on energy harvesting is around 300 hours when fully charged, without the need of further energy from the ambient sources.

Hybrid energy scavenging is indeed considered as a technology which can potentially ensure the ‘perpetual’ operation of WSN and has become popular recently [21][22]. The prototypes have evolved from lab ones [23] to real deployments [24], e.g., for structural health monitoring. However, more research efforts are still required in this field to study hybrid structures in more detail, analyze their pros and cons, potential applications and real world deployments.

V. CONCLUSION

In this work, we have presented a CO wireless gas sensor with a hybrid power supply which takes its energy from solar and wind ambient sources. The sensor node can be applied for outdoor monitoring in urban areas and industrial facilities. The combination of the alternative energy sources and a backup battery can significantly extend the sensor lifetime.

Switching from battery to the alternative energy sources takes place when the amount of voltage at the super capacitors is 0.4 V; i.e., even when they are not fully charged. This mechanism saves more energy for the battery. The choice of using wind or solar energy is based on the amount of voltage available on the corresponding super capacitors, i.e., that alternative source powers the sensor node whose super capacitor has the highest voltage. Moreover, the circuit design makes it possible to charge the super capacitors and extract energy from them simultaneously.

The CO sensor has two gas concentration thresholds, which are at 5 and 20 mg/cm^3. The sensor is designed to operate in the IEEE 802.15.4. ZigBee networks. The electrical circuit of the CO sensor and the measurement algorithms are optimized so that efficient energy consumption can be achieved.

We plan to apply the developed power supply circuit to other devices of the WSNs as well. These devices can be coordinators, actuators, relays and other gas sensors.

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