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Investigation of heating profiles and optimization of power consumption of gas sensors for wireless sensor networks

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ABSTRACT

Monitoring of hazardous and combustible gases at industrial premises and in the living apartments has been a topic of top priority for a number of decades. Within the last decade a great many of solutions have been proposed including the one relying on the Wireless Sensor Network (WSN) paradigm. Being an autonomous monitoring system, it is essential to guarantee a long lifetime of gas WSN. In this work, we are investigating and implementing a number of heating profiles for catalytic and semiconductor sensors used on board of the wireless sensor nodes to reduce their power consumption. After analyzing the pros and cons of these profiles, we propose the heating profile based on the Pulse Width Modulation (PWM) and the multi stage heating profile. Experimental results demonstrate that the average current consumption of the gas sensor node can be reduced up to 0.76 mA and its power consumption up to 2.54 mW thereby ensuring the autonomous operation of the sensing device for more than one year.

1. Introduction

A Wireless Sensor Network (WSN) is a collection of tiny sensing devices, sensor nodes, with the wireless communication capability. Most of the time sensor nodes spend in sleep mode to ensure long-term operation of WSN. Depending on duty cycle the sensor nodes wake up from time to time, measure physical phenomena and send the data to a user over the WSN. Due to the WSN flexibility they have been employed in a high number of monitoring and control applications, e.g. environmental [1] and wild life monitoring [2], road tunnel [3] and building structural health monitoring [4], gas leak [5] and fire detection [6].

Most of the monitoring applications require low power sensors, e.g. temperature, light, accelerometer, on board of sensor nodes. The applications aiming at the detection of hazardous or combustible gases in the environment rely on inherently power hungry catalytic or semiconductor gas sensors which meet the industrial standards requirements in terms of sensor response time [7,8]. Safety standards require annual calibration of gas sensors which implies one year of autonomous operation of gas WSN.

A high number of power consumption optimization techniques for gas WSN have been proposed recently [9,24]. For example, context aware sensing [10] adjusts the gas sensor node duty cycle with respect to people presence in the area, a design space exploration framework [11] ensures energy efficient WSN nodes design, improved thermal insulation packaging [12] prevents heat dissipation during the measurement procedure and energy harvesting technology which helps to replenish the energy storage of gas sensor nodes [13]. Even though these approaches contribute towards the power consumption reduction of gas sensor nodes, they are not truly helpful: a lion share of power during the operation of sensor nodes is consumed by catalytic/semiconductor gas sensors in contrast with typical monitoring applications where a wireless transceiver is the most power hungry component of the sensor node [14].

Novelty and contribution of this work is implementation and investigation of sensing circuits and associated heating profiles for gas sensors nodes as well as proposing a heating profile based on Pulse Width Modulation (PWM) and multistage heating profile. The goal of this work is to estimate the power consumption of various heating solutions and discuss their pros and cons.

This paper is organized as follows: Section 2 introduces gas sensing platform for investigation of various heating profiles, in Section 3 we implement and discuss these heating profiles with a special focus on their power consumption, in Section 4 we present the heating profile based on PWM and multistage heating. Finally, we provide conclusions in Section 5.

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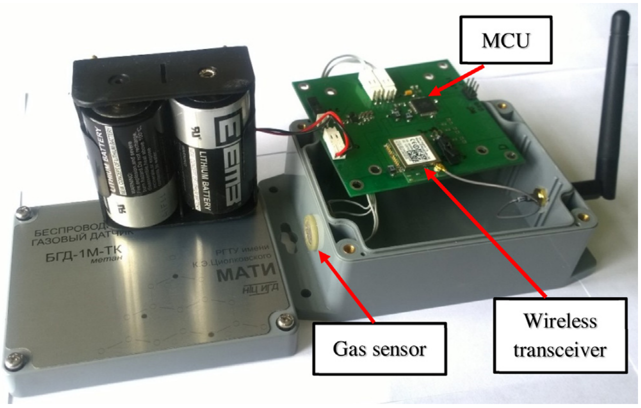

Fig. 1. Wireless combustible gas sensor node prototype.

2. Gas sensing platform

Power consumption of catalytic and semiconductor gas sensors was reduced from hundreds of mW to tens of mW [9,15,16] within a couple of decades. At the same time, commercially available sensors [17–19] are still power hungry electronic components that prevents their application on board of autonomous sensing devices.

In this work, we use the catalytic sensor DTK fabricated by NTC IGD, Russia. DTK sensor height is 9.5 mm, diameter is 9 mm and power consumption is around 190 mW in continuous measurement mode. Its power consumption is much lower comparing to other commercial samples [17–19] and is achieved by applying a heater implemented as 10 μm platinum micro wire in glass insulation (2 μm). The sensor package includes two sensing elements: an active and reference (or passive) one. The active sensing element has a platinum micro wire 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. After annealing at 500 °C, noble metal clusters are formed in the catalyst support. To conduct the measurements with the Wheatstone sensing circuit both sensing elements are involved in sensing. For the sensing circuits based on one sensor (see Sections 3.2 and 3.3) only active sensing element performs sensing.

Circuits for gases detection with catalytic sensors are commonly based on the Wheatstone bridge, which includes two resistors and two sensing elements, as specified earlier. Most of the power goes into the sensor heating process (about 450 °C for methane detection), required to perform the measurement. The power consumption of the Wheatstone circuit (around 150 mW) is high enough that makes its application in the WSNs unlikely. However, by optimizing the gas sensor and sensor node operation the total power consumption can be significantly reduced.

The active sensing element is used to conduct the measurement. The reference sensing element, which is identical to the active one but not covered with the catalyst and therefore insensitive to the gas concentration, is used to compensate for environmental factors such as temperature and humidity. The resistance of the active and reference sensing elements is about 12 ohm each under normal condition. This measurement approach is highly reliable in terms of quality of measurements. As noticed earlier, the optimization of its power consumption is required.

In this work, we investigate a number of options on decreasing the power consumption of wireless gas sensor node for methane detection.

Fig. 2a presents a block diagram of the wireless gas sensor node. The sensor node is built around the AtXmega32A4 Microcontroller

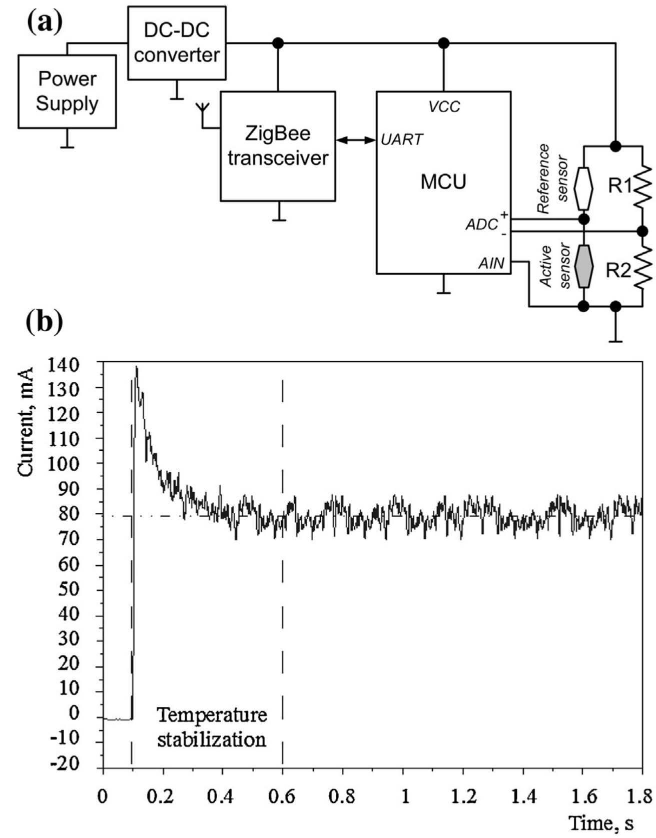

Fig. 2. (a) Block diagram of the wireless combustible gas sensor node in continuous mode of operation and (b) its current consumption.

Unit (MCU) and use an ETRX3 wireless modem. The selection of the MCU was mainly driven by the following requirements: low power consumption, on-chip temperature sensor, and precise Analogue-to Digital Converters (ADC) and Digital-to-Analogue Converters (DAC) integrated in MCU.

The wireless modem supports IEEE 802.15.4 standard (ZigBee specification) and transmits in unlicensed 2.4 GHz ISM band. The modem has an integrated chip antenna used in this design (transmitting distance is up to 25 m) and a connector for an external antenna to enable a boost mode allowing data transmission for up to 350 m. Besides that, the modem has a number of self-x features enabling, for instance, WSN self-configuration and self-diagnostics which significantly reduce WSN debugging and deployment time.

Two batteries of D type with voltage 3.6 V are used in the wireless sensor node. Capacity of a single cell lithium battery of D type is typically 15000 mAh. Its voltage is 3.6 V. Since there are 8760 h a year, the average discharge current for one year sensor node lifetime is no more than 2 mA. Power management is performed by a DC-DC converter TPS63060 which generates stable output voltage from 2.5 V to 12 (the maximum value is 7.2 V for two D-type batteries) on its input. The sensor node prototype is shown in Fig. 1.

Comparative study on power consumption of electronic components used in the gas wireless sensor node design is shown in Table 1. The data for sensor is obtained experimentally other ones are taken from the technical specification of the components.

3. Investigation of heating profiles

In this section we investigate the heating profiles for catalytic sensors. This study is carried out by implementing the sensing circuits and associated heating profiles using the sensor node platform presented in Section 2. The platform experienced some

Table 1
Average power consumption of electronic components used on board of gas sensor node.

Device	Power or current consumption
DTK sensor, continuous heating	150 mW (for both active and reference sensing elements)
Wireless transceiver ETRX3	Tx: 31 mA
	Rx: 25 mA@ 3.6 V
	Sleep mode: 1.3 μA
MCU ATxmega32A4	Active mode: 11.4 mA @ 3 V/32 MHz
	Power-save mode: 0.7 μA @ 3 V/32 kHz
DC-DC TPS63060	Quiescent current: 30 μA

minor changes required for implementation and evaluation of each approach. The goal of this investigation is the estimation of power consumption of each solution as well as the discussion of their pros and cons.

3.1. Continuous heating

Continuous heating profile is typically used in wired monitoring systems which are either wired in a network or are standalone gas detection devices connected to the grid. These devices are not limited in energy resources and may rely on power hungry gas sensors and apply to them continuous heating profile [22].

Fig. 2a and b present the block diagram of the wireless gas sensor node and its current consumption in continuous measurement mode, respectively. The sensor node employs the Wheatstone circuit to perform the measurements and is supplied by 2.8 V. This voltage is generated by DC-DC converter from 7.2 V and works well for the sensing circuit, as well as for other units of the sensor node, i.e. the transceiver and MCU. The noise presented in Fig. 2b is related to the measurement procedure where the DC-DC converter is a device operating on the pulse principle. In order to define the real power consumption of wireless sensor node and, in particular, the DC-DC consumption, the current consumption is measured on the input circuit of the DC-DC converter in the circuit. We note that there is no noise in the output circuit of DC-DC converter.

As it is shown in Fig. 2b, it takes around 0.5 s to heat up the sensor and stabilize its temperature. This time depends on different conditions, e.g. ambient temperature, humidity and sensor parameters. During the measurement procedure the temperature is maintained at a certain level. Gas detection is realized as follows: if a combustible gas presents in the environment it starts burning on the pre-heated active sensing element. Its temperature and resistance increase. The actual measurement is a voltage difference between the response from the active and reference sensing elements embedded in the Wheatstone circuit.

Overall average current consumption of the wireless sensor node in continuous measurement mode is about 81 mA. This value includes the current consumption of the sensor, MCU and DC/DC (without the power consumption for data transmission). Since the power supply voltage is 2.8 V the average power consumption is about 225 mW. This value is higher than the one expected from the numbers shown in Table 1. It happens due to 'efficient' operation of DC-DC converter which is about 83% in our case. The power consumption 225 mW is still high enough and does not guarantee one year of autonomous operation of the sensor node.

3.2. Pulse heating

To reduce the value of power consumption obtained in the continuous measurement mode, pulse heating profile can be applied to the sensor [25,27].

To realize this idea into practice a *power switch* is added in the sensor node block diagram (see Fig. 3a). The switch controls the sensor heating by generating the heating pulses of required time period. According to the gas detection safety standards [7,8], sensor

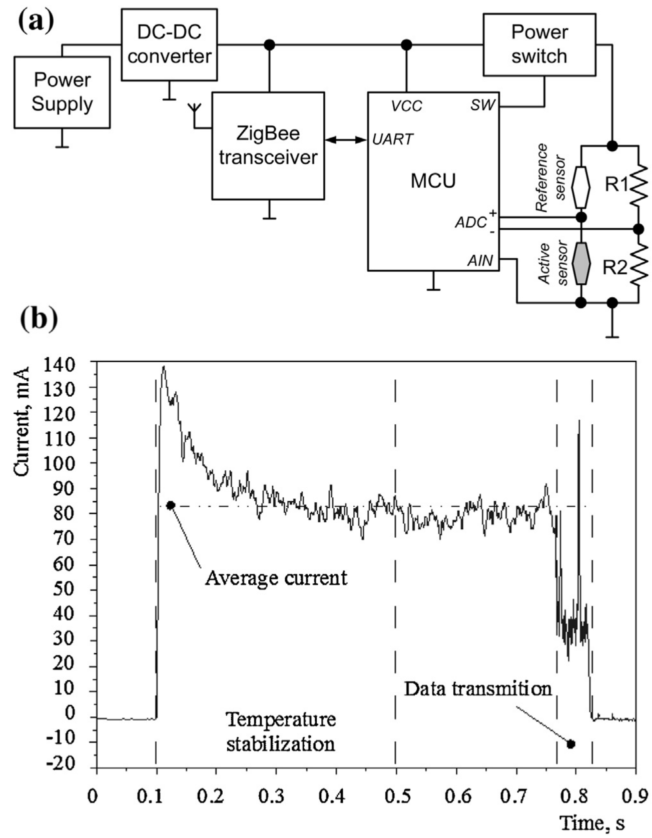

Fig. 3. (a) Block diagram of the wireless combustible gas sensor node in periodical mode of operation and (b) its current consumption.

node response time should be less than 20 s. Therefore, all calculations in this work are done for one measurement per 20 s.

Fig. 3b shows how the current consumption depends on the measurement time during one cycle. The total measurement time is around 0.72 s.

The average current consumption (it is the square under the curve representing the current consumption in Fig. 3b) is about 81 mA. The average power consumption at 2.8 V is about 225 mW. Since the measurements are conducted periodically one time every 20 s the average current and power consumption for the overall period are 2.91 mA and 8.1 mW (2.91 mA* 2.8 V), respectively. The obtained power consumption is still high enough to ensure at least one year of the autonomous operation of the sensor node.

3.3. Multi stage heating profile

Multi stage heating profile is proposed and discussed in details in [20,21]. Feature of this approach is in abandoned Wheatstone sensing circuit with two gas sensors. Multistage heating is based on a voltage divider circuit with a single active sensor and a resistor (see Fig. 4a). This sensing circuit helps to drastically reduce the

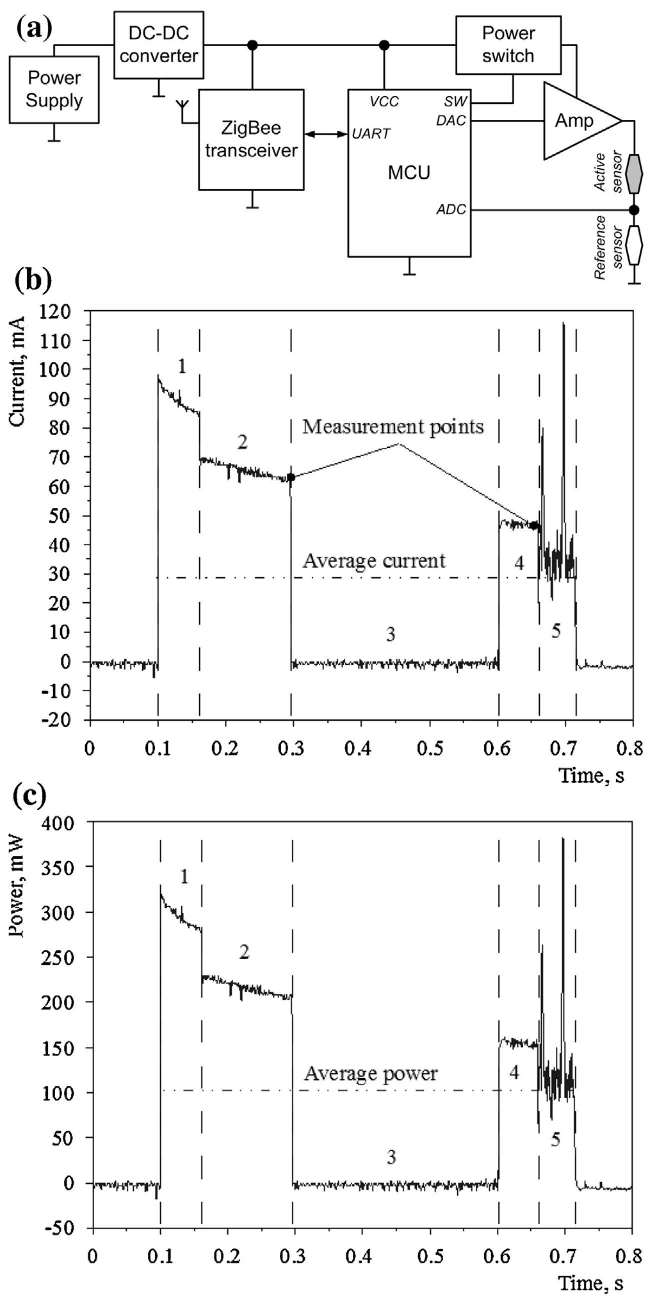

Fig. 4. (a) Block diagram of the wireless gas sensor node in periodical mode of operation with multistage heating profile, (b) its current consumption and (c) power consumption.

power consumption. The compensation of environmental conditions is realized by adapting a four-stage heating profile. Apart from the power consumption reduction this solution can be useful in extending of sensing capability of the circuit [23], i.e. the sensing circuit can be adjusted for detecting the combustible gases in the range from 100 ppm up to 100% vol.

Four-stage heating profile can be formed by applying different heating voltage to the sensing circuit. The heating voltage is generated by DAC. Due to high heating current requirement an extra operational amplifier is used together with DAC which can not ensure sufficient amount of heating current.

Fig. 4 shows the block diagram of the wireless gas sensor node and the current consumption during the measurement procedure which applies the multi stage heating profile.

The multistage heating profile includes four stage. We introduce each stage as follows:

- 1st stage (3.3 V) ensures sensor heating up to a certain temperature, e.g. 450 °C in the case of methane detection.
- 2nd stage (2.4 V) maintains the temperature of the sensor. The first and second stages provide the sensor heating to the external diffusion region of catalysis and the partial evaporation of surface water (∼450 °C).
- The first two stages are followed by the 3rd stage during which the sensor is not heated at all.
- During the 4th stage (1.5 V) the sensor is heated till the beginning of the kinetic region of catalysis (∼200 °C). After this pulse, the element cools down to ambient temperature.

Heating voltages for the stages are 3.3 V, 2.4 V, 0 V and 1.5 V, respectively. Supply voltage generated by the DC-DC converter is 3.3 V. Upon the measurement completion the data transmission is performed (5th stage in Fig. 4b).

The measurement result is the voltage difference between the voltage response measured after stage 2 and voltage response measured after stage 4 (see Fig. 4b).

The total heating time is about 0.62 s. The average current consumption including the data transmission is about 31 mA (dashed line in Fig. 4b). Since the supply voltage is 3.3 V the average power consumption is 101 mW in continuous mode.

The measurement is performed one time per 20 s. The average current and power consumption for the total period, i.e. 20 s, is about 0.96 mA and 3.15 mW (0.96 mA × 3.3 V), respectively.

Since the average current consumption is around 0.96 mA which is in line with the requirements discussed in Section 2 the autonomous lifetime of the sensor node is more than one year. Since the DC-DC converter provides 3.3 V, part of the voltage necessary to ensure multi stage heating at 2.4 V and 1.5 V is dissipated. These energy losses can be reduced by employing the pulse-width modulation technique at the time of the sensor heating.

The multi stage heating profile is helpful in reducing the power consumption of the measurement procedure, but its application results in sensitivity degradation comparing to the Wheatstone sensing circuit. For avoiding this problem during the measurement procedure, extra hardware components and devices, i.e. DAC and buffer amplifier (see Fig. 4a), are involved in the sensing circuit based on the single sensor with respect to the Wheatstone circuit.

4. PWM heating

Pulse-Width Modulation (PWM) is a frequently used technique for heating the sensors up to a working temperature [26]. PWM allows for changing of the average heating voltage by changing periods of the heating pulses.

Using multistage heating pulse for catalytic gas sensors it is possible to decrease drastically average current and power consumption of measurement circuit. It is enough to obtain autonomous lifetime of the sensor node more than one year.

The main parameters of PWM are its period (*T*) or frequency, pulse width (*t*), supply voltage (*Us*) and average voltage (*Ua*) on the load. These parameters are illustrated in Fig. 5.

Sensor heating based on the PWM does not require extra electronic devices such as DAC and operational amplifier used in previous section. This is possible due to the PWM which regulates the average voltage on the load by controlling heating pulse duty cycle and helps avoiding extra power consumption (see Fig. 6).

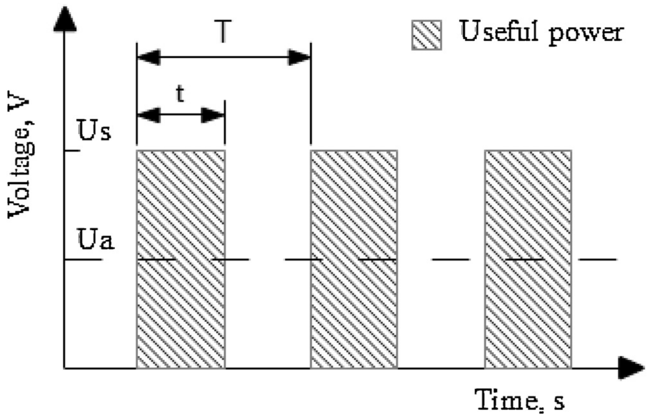

Fig. 5. Pulse-width modulation parameters.

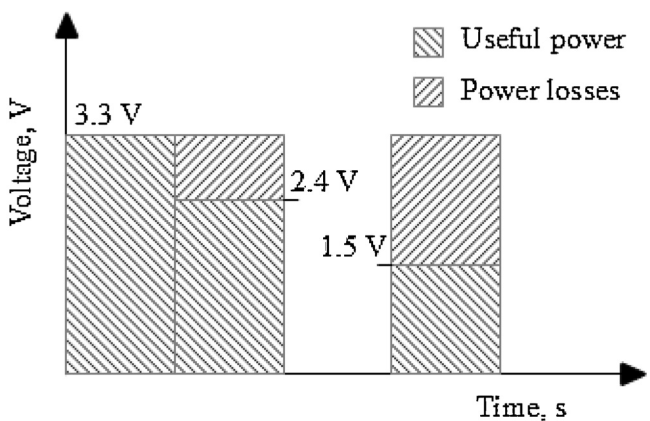

Fig. 6. Multistage heating profile power losses.

The average voltage of PWM heating profile can be defined as follows:

$$Ua = \frac{t}{T}Us. \quad (1)$$

With the PWM technique it is fairly straightforward to directly adjust heating voltage required to guarantee heating pulses of various voltage amplitude. It helps avoiding waste of heating power comparing to the case of 'classical' multistage heating profile [20,21].

Fig. 7a and b shows the block diagram of the wireless gas sensor node and its power consumption in multi stage heating profile where every stage adopts the PWM technique, respectively. Since voltage regulation is performed on the sensing circuit by the DAC, the current consumption for both circuits except for the DAC and buffer amplifier is the same.

Fig. 7 demonstrates the advantages of PWM application in addition to the multi stage heating profile: the power consumption of the 2nd stage is decreased from 200 to 230 mW to 150–160 mW and of the 4th stage from 150 mW to up to 80 mW. PWM frequency is 1 kHz and it is not used for the 1st heating stage since the required

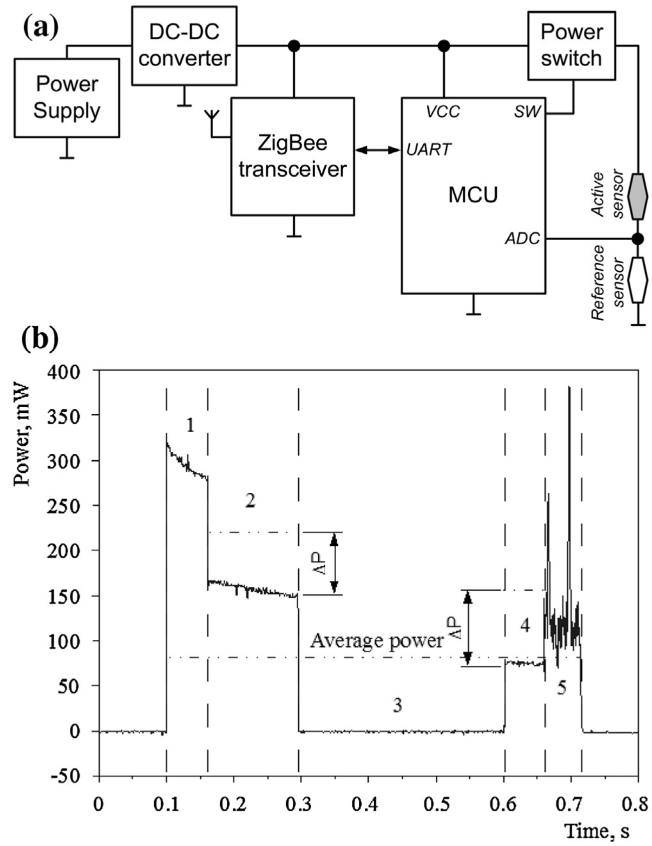

Fig. 7. (a) Block diagram of the wireless combustible gas sensor node in periodical mode of operation with PWM regulated multistage pulses and (b) its power consumption.

3.3 V for the 1st heating stage is provided on the output of DC-DC converter.

The average power consumption is decreased from 10 1 mW up to 82 mW. It is 20% less than the multi stage heating profile with the DAC.

The average power consumption for the overall period is about 2.5 mW (0.76 mA at 3.3 V). We summarize the power consumption of the sensor node and single electronic components with respect to heating profiles applied in Table 2.

5. Summary and conclusions

In this work, we have addressed the problem of high power consumption of catalytic gas sensors employed on the wireless sensor nodes which are used for hazardous and combustible gases detection. In particular, we have investigated popular heating profiles used to drive the catalytic sensors and demonstrated how to decrease the power consumption of a gas sensor node by sequential optimization of the measurement procedure.

To meet the safety standards' requirements we set up the sensor node to conduct the gas measurement in the environment once every 20 s. Also, to ensure at least one year of autonomous opera-

Table 2
Real power consumption for different operation modes.

	Continuous, mW	Pulse, mW	Multistage, mW	Multistage with PWM, mW
Sensor	193	6.6	1.75	1.15
MCU	31.9	1.1	0.95	0.94
Transceiver	0.3	0.3	0.35	0.35
DC-DC Converter	0.1	0.1	0.1	0.1
Total	225	8.1	3.15	2.54

tion of the device we aimed at achieving 2 mA of average current consumption.

First, we have investigated the Wheatstone sensing circuit (includes two sensing elements: active and reference) with continuous and pulse heating profiles. Our results demonstrated that the sensing circuit consumes about 225 mW in continuous mode and 8.1 mW in pulse heating mode where the length of heating pulse is 0.72 s and the measurement period is 20 s, as specified earlier.

To further reduce the power consumption, we adopted the sensing circuit with one sensing element and multistage heating profile. This approach helped reducing the power consumption up to 3.15 mW where the average heating current is 0.96 mA at 3.3 V of power supply consumed within 0.62 s. However, this measurement procedure requires extra hardware components (DAC and buffer amplifier) with respect to the Wheatstone circuit. We note that to improve the energy budget of the sensor nodes our future work includes the application of energy harvesting technologies, as well as, development and investigation of hybrid power supply for the wireless gas sensor nodes.

For excluding the power losses on these components we have proposed and implemented the multistage heating profile with PWM on the single sensor based sensing circuit. Our approach has resulted in 2.54 mW of power consumption. This result is 20% better than the approach based on a single sensor sensing circuit and using the DAC and buffer amplifier to effectuate the multistage heating profile.

Further reduction of power consumption is possible if the DC-DC converter is excluded from the device. Instead of it, the PWM technique can fully substitute it and ensure the sensor heating according to the multistage heating profile as it is described in Section 4. This approach works well for powering the MCU and wireless transceiver which can operate in a wide voltage range, i.e. 2.1-3.6 V. That is why one 3.6 V Li-ion battery could potentially supply the sensor node. This option will be considered in our future work.

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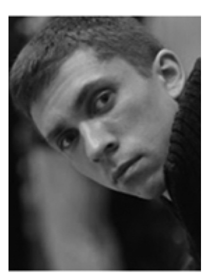
Biographies



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