



Development of wireless sensor network for combustible gas monitoring

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ABSTRACT

This paper describes the development and the characterization of a wireless gas sensor network (WGSN) for the detection of combustible or explosive gases. The WGSN consists of a sensor node, a relay node, a network coordinator, and a wireless actuator. The sensor node attains early gas detection using an on board 2D semiconductor sensor. Because the sensor consumes a substantial amount of power, which negatively affects the node lifetime, we employ a pulse heating profile to achieve significant energy savings. The relay node receives and forwards traffic from sensor nodes towards the network coordinator and vice versa. When an emergency is detected, the network coordinator alarms an operator through the GSM/GPRS or Ethernet network, and may autonomously control the source of gas emission through the wireless actuator. Our experimental results demonstrate how to determine the optimal temperature of the sensor's sensitive layer for methane detection, show the response time of the sensor to various gases, and evaluate the power consumption of the sensor node. The demonstrated WGSN could be used for a wide range of gas monitoring applications.

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1. Introduction

Efficient monitoring of the gas composition of the environment with sensor networks which cover large territories and provide continuous monitoring of combustible and toxic gases can be regarded as a problem of special significance [1]. The primary aim of a gas detection system is to warn about potential danger associated with life hazard and material injury. There are a number of relatively simple to highly sophisticated gas monitoring systems which ensure early detection and warnings [2]. In this paper, we focus our attention on gas sensors assembled and/or integrated in a network.

Prior to the introduction of Wireless Sensor Network (WSN) technology [3], sensor arrays were arranged in a network through wires [4], which included the power supply. Being power independent, wired monitoring systems may use powerful hardware, such as powerful gas sensors [5] or digital signal processors (DSP) for real-time data processing [6]. Wired sensors and monitoring systems, however, come with many shortcomings: a long deployment time, high maintenance cost, dependence on cable telemetry systems, the inability of cables to resist to various damages, as well as large demand in cable supplies. Moreover, in many cases there may

be no power supply available to implement monitoring where it is needed. Our first goal is therefore to remove the wires and develop an autonomous gas monitoring system.

In order to resolve the issues related to wired systems, the paradigm of WSN has been recently adopted. Hazardous gases may be detected with small, inexpensive wireless sensor devices which are located throughout the territory and operate autonomously on a co-operative basis [3]. There are two main strategies for detecting target gases by a sensor node. The first strategy is 'power efficient' and uses a light sensor in conjunction with a colorimetric chemical sensing film [7] or a silicon bridge-type micro-gas sensing film [8]. These kinds of sensors, however, do not have sufficient sensitivity and accuracy, resulting in long response times in the order of 300 s [7] which fail to meet the requirements of safety standards [9]. The second 'power hungry' strategy is based mainly on a laser spectroscopic sensor [10] or catalytic and semiconductor sensors [11–13]. The laser spectroscopic sensor has high sensitivity but may consume current up to 800 mA [10], which is a limiting factor for deploying the nodes. Catalytic and semiconductor sensors exploit chemical reactions on their surface to provide good sensitivity and selectivity along with short response time. Besides, they have lower power consumption (see Table 1) than the laser spectroscopic sensor. Table 1 presents the power consumption of some off-the-shelf sensors with typical functions applied in WSNs. In this work we use the 2D semiconductor gas sensor [13] numbered 4-th in Table 1, discussed in more details in Section 3.1. This sensor ensures early gas

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Table 1
Power consumption for some off-the-shelf sensors with typical functions.

No.	Sensor	Manufacturer	Purpose	Power consumption, mW
1	STDS75	STM	Temperature	0.5
2	HIH-4000-001	Honeywell	Humidity	10
3	2200/2600 series	Gems	Pressure	50
4	2D (semiconductor)	Experimental series KI	Methane	260
5	TG S2610 (semiconductor)	FIGARO	LP gas	280
6	NAP-66A (catalytic)	Nemoto	Flammable gases	360
7	MC series (catalytic)	Hanwei Electronics	Combustible gases	420, 450, 600
8	KGS 601 (catalytic)	Korea New Ceramics	Combustible gases	440
9	AD81 (semiconductor)	GE	Gasoline & diesel exhaust gas	620
10	MQ-4 (semiconductor)	Hanwei Electronics	Methane, natural gas, smoke	750
11	NLK series (laser spectroscopic)	NTT Electronics	Combustible gases, hydrogen cyanide	800 mA

leak detection, has low response time and supports a pulse heating mode which results in even lower power consumption. So, our second goal is to prolong the long-term operation of the wireless nodes with the use of an on board semiconductor gas sensor.

In this paper we present a wireless gas sensor network (WGSN) for early gas leak detection and fast operator alarm. The network consists of four units: a sensor node, a relay node, a network coordinator, and a wireless actuator. The sensor node is equipped with a microcontroller, a wireless modem, a battery power supply, and a 2D semiconductor gas sensor. Since the sensor is the most power 'hungry' component on board, we apply pulse width modulation (PWM) for the heating of the sensor sensitive layer that significantly reduces its energy consumption. In addition, to support continuous monitoring of the environment, we have carefully chosen low power consumption components and energy saving modes during the sensor node development. The range of wireless transmission is extended using the relay nodes, which support communication between the sensor node and the network coordinator. Whenever a hazardous gas is detected in the atmosphere, the network coordinator alarms an operator by the GSM/GPRS or Ethernet network and/or controls a gas emission source by the wireless actuator.

The paper is organized as follows: Section 2 presents the system overview, while Section 3 introduces the reader to the hardware implementation of the system. Section 4 describes the algorithm of network routine and emergency operation in an apartment house. Experimental results are presented in Section 5. Finally, we conclude in Section 6.

2. System overview

The block diagram of the WGSN for the monitoring of combustible gas concentration is presented in Fig. 1. The system consists of a number of sensor and relay nodes, a network coordinator, and possibly one or more wireless actuators.

The sensor node monitors the combustible gas concentration in the environment. It is set up for several ranges of gas concentration, as we discuss below. Wireless communication between the sensor node and the network coordinator is implemented via the relay node.

The network coordinator is responsible for creating and controlling the network, indicating the current situation and alerting the external and emergency services. Alerting the emergency services may be implemented through the GSM cellular network by sending an SMS or with the TCP/IP protocol over Ethernet or GSM/GPRS. Apart from alerting of the potential emergency, the coordinator is able to carry out preventive actions by seating the valve controlling the gas delivery and deactivating electrical devices. These emergency preventive measures are the responsibility of the wireless actuators, which are part of the network and communicate with the coordinator over the wireless link.

Communication within the network is implemented using the IEEE 802.15.4 standard [14], while data are transmitted over the ZigBee protocol stack [15]. Among the known data wireless transmission standards, such as Bluetooth, WiFi, etc., we have found ZigBee the most acceptable in terms of the trade-off between bandwidth and power consumption, to ensure long autonomous battery operation of the device. In addition, the modems which use the ZigBee standard have the option to self-organize the whole sensor network.

3. System and component architecture

In this section we will analyze the individual components of the gas detection system in more details, focusing on the design choices.

3.1. Sensor and relay nodes

The hazardous gas concentration can be measured using optical, catalytic and semiconducting gas sensors [16]. The major problem associated with the measurement of combustible gas concentration in autonomous devices is the high power consumption associated with the sensors. In this work, we have used a 2D semiconductor gas sensor produced on an aluminum membrane [13]. This type of sensor is characterized by high sensitivity, long lifetime and relatively low energy consumption (see Table 1 '2D semiconductor sensor'). Besides, the sensor has an ExsIU/ExdIIB+H2U degree of implosion protection (see the protection requirements in [17]), which makes it safe to use in a hazardous environment. The system works by heating the sensitive layer of the sensor to a temperature of around 500 °C, and then measuring the conductivity of the semiconductor, which is affected by the gas concentration. Typical applications [11] use a continuous measurement mode in which the semiconductor is kept at a constant temperature. In our system, instead, to further decrease the energy consumption [18], the sensitive layer is only heated when measurements are required, which occurs at regular intervals, i.e., we replaced the continuous measurement mode with the pulse of a PWM signal implementing a duty-cycle mode [19].

In addition to the gas sensor, the node shown in Fig. 2 includes a microcontroller, a ZigBee module, and a battery power supply. All components of the sensor node, as well as its operation modes, were chosen with respect to minimal energy consumption. The full block diagram of the sensor node is presented in Fig. 3. Note, that the relay node is technologically identical to the sensor node except that it does not include the on-board sensor for sensing capability.

The measurement and data processing is controlled by the 8-bit ATmega168p RISC microcontroller [20]. The sensitive layer conductivity and the heater temperature are measured with the AD converter (ADC) built into the controller. The heater is driven by a PWM signal with a switching frequency of 1 kHz. Using PWM it is possible to change the heating profile depending on the envi-

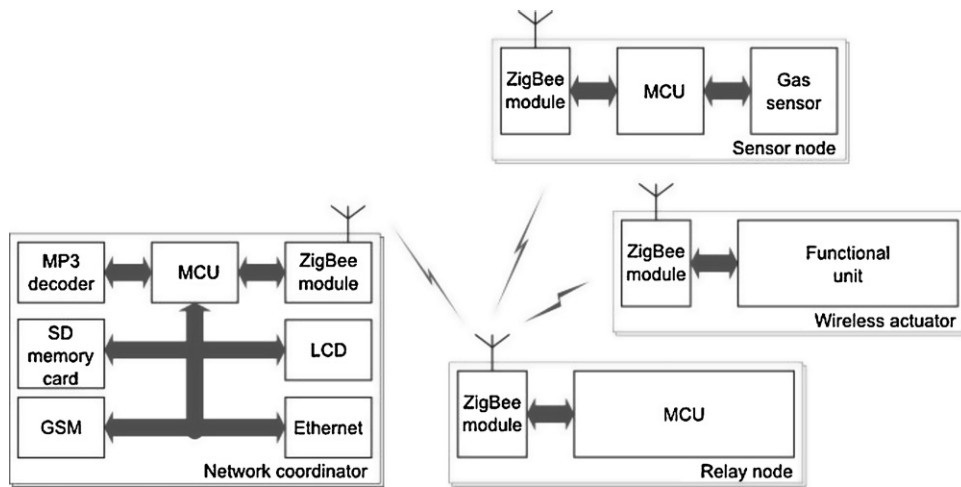


Fig. 1. Block diagram of the wireless system for combustible gases monitoring (sensor node, relay node, network coordinator, and wireless actuator). Data transmission within the network is supported by the ZigBee protocol (IEEE 802.15.4 standard).

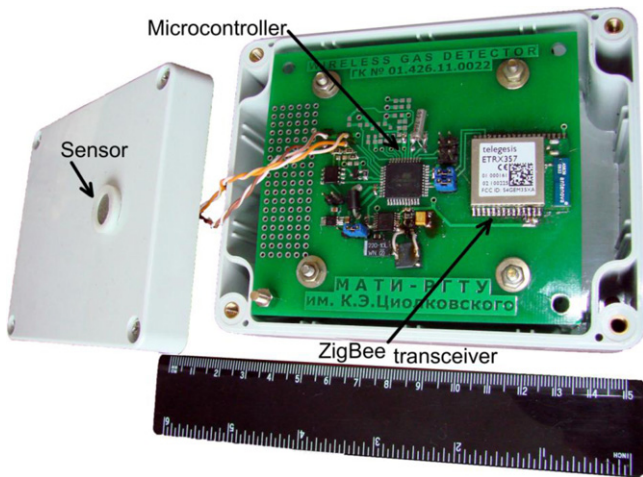


Fig. 2. Physical implementation of the sensor node (top view), showing the sensor, the microcontroller, and the ZigBee transceiver.

ronmental conditions and, at the same time, to avoid extra energy consumption to supply an additional DAC chip, since the PWM signal is software controlled. In order to let the heating current pass through, the PWM signal is used to control a transistor switch. As measurements are taken at regular intervals, functioning of the measuring section of the circuit is not required in between the measurements. In this case, the supply voltage of the measuring section and the microcontroller ADC module are switched off to reduce power consumption.

The microcontroller is characterized by low energy consumption and yet fast response during concentration measurements and data transmission (4 mA in operating mode and 0.1 μA in stand-by/sleep mode) [20]. The low energy consumption of the microcontroller is further improved through additional circuit and software measures. For instance, during program execution, only the microcontroller modules used at that time are on. The microcontroller timing in the stand-by/sleep mode is implemented using an ultra-low-power crystal-controlled oscillator running at a 32 kHz frequency.

Data transmission with the ZigBee protocol is implemented using the Telegesis ETRX2 module. The module is controlled by AT-commands [21] and is characterized by low energy consumption in operating and stand-by/sleep modes [22].

The sensor node is supplied by three 1.5 V (3000 mAh) AA batteries. The supply voltage of the circuit components is 3.3 V. This voltage is obtained using the ADP3335 voltage regulator with low intrinsic consumption current. The current consumption of the sensor node for different operating modes is shown in Table 2.

3.2. Network coordinator

The WGSN coordinator (see Fig. 4) is a fixed node of the network equipped with a 5 V, 550 mA power adapter.

The coordinator is based on the LPC2478 microprocessor connected to the TG-ETRX2 ZigBee module and to the MTSMC-G-F4-IP GSM/GPRS modem (a block diagram is shown in Fig. 1). This

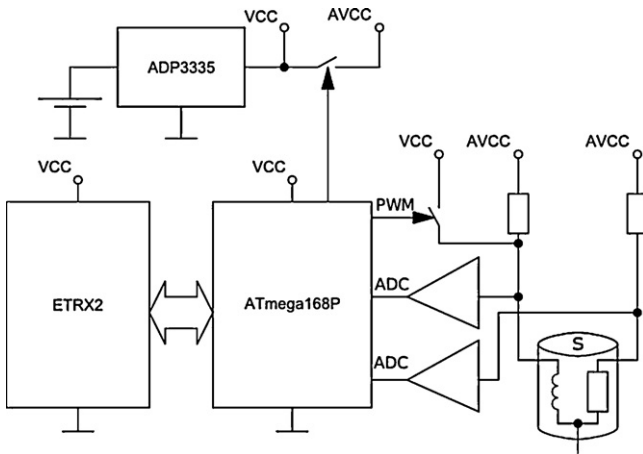


Fig. 3. Schematic diagram of the sensor node. ADP3335, voltage regulator; ETRX2, ZigBee transceiver; ATmega168P, microcontroller; S, circuit schematic of semiconductor sensor.

Table 2

The current consumption of the sensor node for different modes.

Mode	Maximal current, mA			
	ATmega168p	TG-ETRX2	ADP3335	Sensor
Measurement mode	4	0.01	1	250–120
Transmission mode	4	42	0.5	0
Sleep mode	0.0009	0.01	0.08	0



Fig. 4. The implementation of the network coordinator, based on the LPC2478 microprocessor, in casing. The LCD display on top is used to show the operational status of the network.

configuration is the required minimum for the network coordinator implementation. Other modules provide additional functional capabilities, e.g., indicating the network current status with a color TFT LCD or converting the data protocol using other widely applied data interfaces, such as Ethernet or CAN. Being a 'sink node' (data aggregation) device, the network coordinator can be easily adapted to various tasks depending on the needed functional capabilities.

As some of the additional modules that extend the functional capabilities require large memory, an SDRAM memory chip has been connected to the microprocessor via an external memory interface. A 32 Mb chip memory is sufficient for storing both the LCD image buffer frames and sounds and data on the previous status of the system. The color LCD is used to show the current status of the sensor network and actuating modules. As the microprocessor built-in peripheral devices include an LCD controller, the LCD can be directly connected to it without additional chips, which makes the design cheaper. The coordinator implements a simple user interface for the wireless sensors and wireless actuators. The status changes of the network components are additionally alerted with voice messages, which are decoded and replayed using an MP3-decoder connected to the microprocessor over the SPI interface. Besides, the microprocessor's MCI interface has a connector for SD cards, which is used to store data and configuration files of the coordinator. This makes it possible to adjust the coordinator without additional re-programming. On top of that, the SD card can be used to store and track the changing status of the sensors and other network components.

3.3. Wireless actuator

The wireless actuator (see Fig. 5) consists of a ZigBee TG-ETRX2 transceiver, a power supply circuit, and a valve. As the ZigBee transceiver software allows the node to control the signal level on the transceiver outputs that control the actuator, the only features needed to carry out the above functions are the components to bring the switch voltage to the required level. Applying a voltage results in seating the valve, which prevents further gas leakage. For the wireless actuator, a stationary power supply is used. The power required by the actuator module depends mainly on the power needed for the valve, which typically varies between 24 and 36 V and 1–2 A.



Fig. 5. Wireless actuator contains the valve for gas emission source control and the casing with the ZigBee transceiver and power supply inside.

4. Network operation

In this section we describe the WGSN normal, or routine, operation and the sequence of actions that are performed if some anomaly occurs (emergency situation). Since one of the potential applications for the proposed network is the detection of a fire in an apartment house, we have chosen a cluster topology for the WGSN (Fig. 6) which provides secure and reliable operation. The data routing in the network is performed by the ZigBee protocol. The sensor nodes are deployed inside the apartments and are battery operated devices. Conversely, the relay nodes are deployed on a landing (one device per floor) in the electrical control unit of the house and, therefore, have a stable power supply. However, these nodes are also equipped with on-board batteries as a backup power supply. The network coordinator is on the ground floor and collects information from the relay nodes and the wireless actuators.

In the day-to-day routine, the sensor nodes (marked with the letter 'S' in Fig. 6) periodically measure the methane concentration in the environment, alternating with the ultra low-power sleep mode: measurement mode–sleep mode–measurement mode. In the measurement mode, all components of the sensor node are functioning except for the ZigBee transceiver. Gas measurement occurs as follows: in the measurement mode the voltage on the sensor sensitive layer, which depends on the gas concentration, is measured using the built-in ADC of the microcontroller. The obtained value is compared with two preset thresholds specified for the sensor node. For methane, the lower specified threshold is set to 0.15–0.5% vol.; if the concentration rises above this threshold, the WGSN will send an alert about the presence of methane in the environment. The second limit is set to 0.5–1%, vol. In fact, the lower limit of methane explosion is 5% vol. [9]. If the second threshold is crossed, an appropriate alarm is transmitted over the data channel. These specified limits could be changed by reprogramming.

4.1. Network routine operation

In the case of routine operation, when hazardous gas concentration is not detected or is below 0.15% the sensor node goes to sleep mode. The measured values of gas concentration are not transmitted to the network coordinator (marked with the letter 'C' in Fig. 6), but can be saved in a memory chip onboard. However, while the

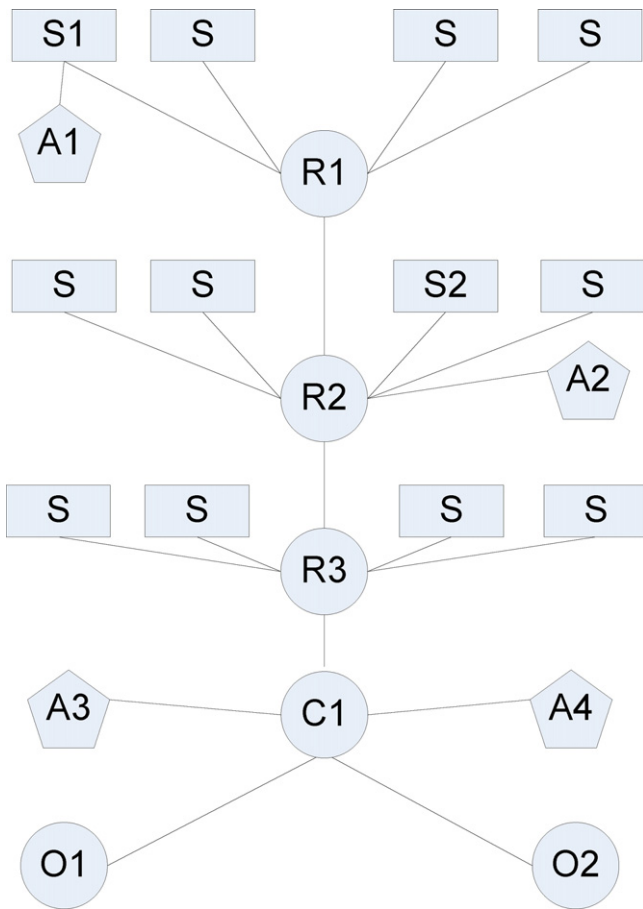


Fig. 6. Network topology showing the organization of sensor (S) and relay (R) nodes, wireless actuators (A), and network coordinator (C) in WGSN. The network coordinator notifies a network operator (O_1) and/or apartment owner (O_2) about the emergency situation.

sensor node performs the measurements, the relay nodes (marked with the letter 'R' in Fig. 6), the network coordinator and the wireless actuator (marked with the letter 'A' in Fig. 6) must be operated in receive mode all the time. In accordance with the ZigBee protocol, the sensor node acts as a remote terminal. As data transmission is only performed when the preset events occur, most of the time the ZigBee ETRX2 module is in sleep mode and its energy consumption is insignificant [23].

4.2. Network operation in emergency situation

In the event of an excess concentration of hazardous gases, the system (in line with the pre-settings) may perform actions aimed at preventing the emergency by deactivating the gas source. If a sensor node has detected a hazardous gas concentration in the range of 0.15–0.5%, the microcontroller changes the ZigBee module over to transmission mode, generates an alert message and transmits it to the network coordinator via the relay node. This message includes the identification data about the sensor node which generated the alert message. Upon receiving the acknowledgement, the ZigBee module goes back to sleep mode. If the acknowledgement does not contain the request to repeat the gas measurement, the sensor node goes to sleep mode as well.

If the hazardous gas concentration measured by the sensor node, e.g., S1, is in the range of 0.5–1%, the microcontroller again changes the ZigBee module over to transmission mode, generates an alert message and transmits it directly to the wireless actuator A1, to close the gas valve. Upon receiving the acknowledgement from the

actuator, it generates an alert message and transmits it to the network coordinator C1 via relay nodes R1–R3. In a similar way, the sensor node S2 transmits an alert message to the wireless actuator A2 and then notifies the network coordinator C1 about the emergency situation. The network coordinator notifies a network operator O_1 and/or apartment owner O_2 about the danger. Upon completing all the activities involved in the emergency situation, the sensor node goes to sleep mode.

5. Experimental results

We have conducted several experiments to characterize the performance of our monitoring system. Our first set of measurements is oriented towards calibrating the sensor readings. We have then focused on finding a trade off between sensitivity and power consumption, by analyzing the changes with the sensor temperature. We then have estimated our system response time and average power consumption. The next section provides full details for these experiments.

5.1. Sensor node calibration

In order to measure the gas concentration, we need to characterize the response of the sensor to different values of the concentration as a function of the sensor temperature. The process of measuring the combustible gas concentration with the use of a semiconductor gas sensor is implemented at the sensitive layer temperatures in the range from 450 to 550 °C [13]. At this temperature range, the sensor provides high stability and selectivity. The sensitive layer is heated by the heater built into the sensor. The sensor resistance, R , depends on the temperature and can be estimated by the formula:

$$R = R_0 \cdot (1 + a \cdot (T - 20 \text{ } ^\circ\text{C})) \quad (1)$$

where R_0 is the resistance of the heating layer of the semiconductor sensor (12 Ω) under normal conditions, a is the temperature coefficient of resistance (0.0027 1/°C in our case) indicating the relative change of R when the temperature is changed by 1 °C, and T is the temperature (in °C). This formula can be used to estimate the sensor heater temperature by measuring the resistance.

The principle of the semiconductor gas sensor operation is based on the change of the sensor sensitive layer conductivity due to gas absorption (the conductivity increases with the increase of the gas concentration). The heating of the sensitive layer activates physical and chemical processes on its surface, thereby increasing sensitivity to certain gases. The measurement circuit provides a voltage divider circuit (whose ratio depends on the sensitive layer conductivity) with a voltage in the range from 0 to 3.3 V. Fig. 7a indirectly shows how the conductivity of the sensor increases with the increase of methane concentration in the atmosphere by plotting the voltage across the sensor, which is inversely proportional to its conductivity. In practice, the increase in conductivity results in the voltage measured across the sensor to drop from 3 V to 1.2 V (at 500 °C). Hence, for any given temperature, the concentration level corresponds to a certain voltage on the sensitive layer. This data is collected experimentally and stored in the microcontroller memory to be used later for the determination of the gas concentration in the atmosphere.

5.2. Optimal temperature for methane measurements

Throughout the operating cycle, the measuring module changes between the active operation mode and the stand-by/sleep mode. Heating the sensitive layer, measuring its conductivity and, if necessary, transmitting data to the coordinator are performed in the active mode.

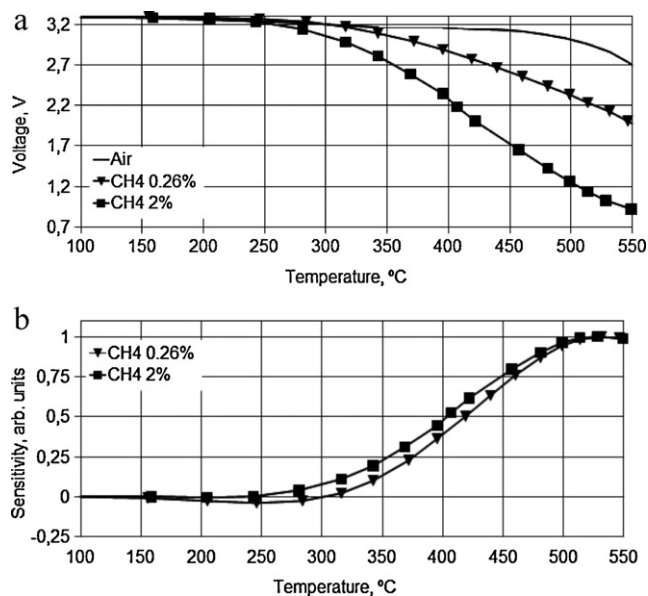


Fig. 7. (a) Voltage on the gas sensor. The curve indirectly shows how the sensor conductivity depends on methane concentration in the atmosphere. (b) The relationship between the sensor relative sensitivity and the temperature at various methane concentrations.

The energy consumed by the sensor node for heating the sensitive layer is quite substantial. It is therefore important to minimize this component of the sensor node energy consumption. To find the best trade-off between sensitivity and power consumption, we have performed experiments to find the minimum temperature of the measurements for which the maximum sensor node sensitivity is not significantly affected.

The relationship between the sensor sensitivity and temperature can be assessed again by looking at the magnitude of the voltage across the sensitive layer. In this case, we are interested in measuring relative data, which may be obtained by subtracting the magnitude of the voltage on the sensitive layer in the presence of methane from the magnitude of voltage in the air. Fig. 7b shows how the sensor relative response (or sensitivity) depends on the temperature of the sensor sensitive layer. One can see that the two curves for different methane concentrations in the air are close to each other, but do not coincide. This is due to the variation of the sensor sensitivity as a function of the gas concentrations. From the diagram, it follows that the relative voltage on the sensitive layer in the presence of methane rapidly increases as the temperature changes from 100 °C to 500 °C and reaches its maximum between 500 and 550 °C. We have chosen 500 °C for our measurements.

Obviously, the response of the semiconductor sensor differs depending on the kind of gas present in the air. We can take advantage of this fact to increase the sensor sensitivity and selectivity to a specified gas along with the capability to discern the gases in a mixture by measuring the sensor response over a wide range of temperatures. These measurements are performed by our system both during heating as well as during the cooling of the sensor sensitive layer.

Fig. 8 shows the response of the sensor in the presence and absence of wood pyrolysis, alcohol fume, and methane during one such temperature scanning mode. One can see, for instance, that the conductivity curve corresponding to the presence of methane differs substantially from that of wood pyrolysis or alcohol fume. Thus, the analysis of the shape of the response curve may lead to an improvement of the sensor selectivity to methane, and hence to an increase of the precision of the measurements. In contrast, if the temperature of the sensor is kept constant, one may detect the

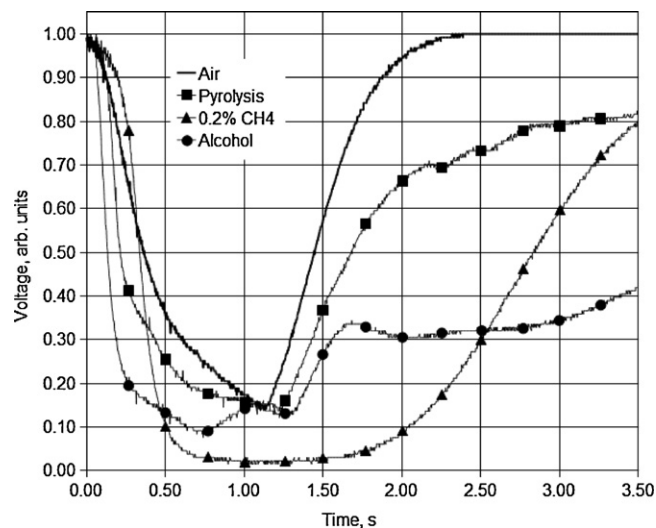


Fig. 8. Sensor response to air, pyrolysis, 0.2% methane, and alcohol fume at $T=500^{\circ}\text{C}$.

presence of a dangerous gas by the analysis of the minimum of its respective curve. Operating the sensor in constant mode (always heated) obviously disables the sensor selectivity and drastically decreases its sensitivity. Experiments on cross sensitivity to other gases can be found in the literature [13].

5.3. Determining the system response to sudden gas emission

One of the most important parameters for a system that monitors combustible gases concentrations is the time required for its reaction to the abrupt change of gas concentration in the environment. For some of the devices, this time is prescribed by the available standards for gas indicators. In the case of a distributed wireless system, this parameter should obviously be estimated for the system as a whole. For gas alarms which combine optical and acoustic alarm along with the option to activate a tripping device (in our case it is the wireless actuator) an alarm signal delay of up to 120 s is allowed [9].

The reaction time of the system, denoted by t_r , depends on the measurement time (t_m) and the time required for data transmission over the wireless channel (t_t):

$$t_r = t_m + t_t \quad (2)$$

At the same time, we can change the sensor node reaction time by varying the measurement interval which, with the aim of minimizing power consumption, should be maximized.

The time of data transmission over the wireless network depends on both the time for housekeeping operations (network services) (t_s), the time for communicating over one hop (t_h) and the total number of hops needed to transmit data to the coordinator. We should note that t_h also includes the time for storing the data in the memory before it is retransmitted to the following hop. In order to get maximally objective data, and to estimate the worst case scenario, the sensor node reaction time should be measured at the maximum possible number of hops which, for the TG-ETRX2 module, is equal to 30 [22]:

$$t_t = t_s + 30t_h \quad (3)$$

The resulting time of data transmission (along with acknowledge receipt) over the wireless network is around 347 ms (empirically determined). As will be shown below, the data transmission time is much lower than the measurement time and the interval between measurements, so that if transmission is impacted by packet loss,

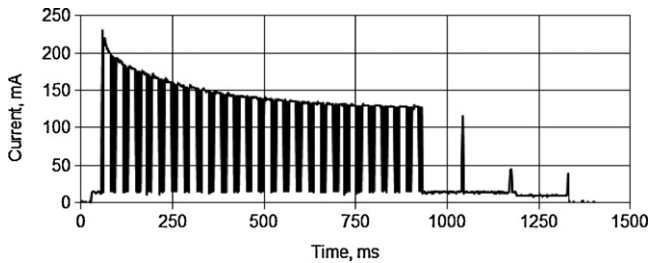


Fig. 9. Current consumption of the sensor node in active mode. Prior to the ~1000 ms mark the sensor node is in heating mode, after the ~1000 ms mark in data transmission mode. The heating is implemented using the PWM pulses with 60% duty cycle. Data transmission and management is supported by the ZigBee module.

which requires retransmission, the total time will not be significantly affected. Because the data transmission component t_t is small compared to the requirements on the overall response time, in practice the reaction time t_r is dominated by the measurement time t_m , which we can control by adjusting the measurement duty-cycle to trade off reaction time and power consumption, as shown in the next section.

5.4. Average power consumption of the sensor node

Throughout the operating cycle the node changes between several operational conditions: the heating and gas concentration measurement mode, the data transmission mode to alert about the occurrence of an event, and the stand-by/sleep mode. In order to assess the sensor node average current consumption, one needs to estimate the current absorbed in each of the above modes. The results of the current consumption measurements are presented in Fig. 9. Most of the time the node is in the stand-by/sleep mode and its current consumption is 0.08 mA. Once every period, the node wakes up, heats the sensor and measures the sensitive layer conductivity. The heating and measurement time is of the order of one second (Fig. 9). For this experiment, a PWM signal with a 60% duty cycle is used for pulse heating. Fig. 9 shows the current consumption profile, which decreases in the range from 0 to 900 ms (760 ms) as the sensor is heated up. Because of the duty cycle, the average heating current for the sensitive layer is only about 80 mA. If an emergency event occurred, the message is transmitted to the network coordinator. The average current consumption in data transmission mode, shown in the graph in the range from 1000 to 1500 ms (347 ms), is 40 mA. Fig. 9 shows that the pulses of data transmission do not affect the average current consumption much. Besides, the data transmission occurs only in the case of an alert. Therefore, we may neglect the current consumption in data transmission mode for the purpose of computing the average current consumption. The average current consumption, \bar{I} , may be determined with the formula:

$$\bar{I} = \frac{\sum I_n \cdot t_n}{\sum t_n} \quad (4)$$

where I_n is the current consumption of the sensor node for different modes and t_n is the time of duration of each mode.

Since we use three AA batteries which have a capacity of 3000 mAh (1.5 V) and knowing the current consumption of the sensor node, which equals 80 mA for one measurement cycle, we can evaluate the lifetime of the sensor node. With these parameters the sensor node can support $3000/80 = 37.5$ h of continuous operation. However, the demands on response time require that we take a measurement for every 120 s [9], given that we can essentially neglect the transmission time. Because one measurement cycle lasts for about 1 s (excluding transmission, which takes place only

in the event of an emergency), the total estimated lifetime of the sensor node is $3000/(80 \times 1/120) = 4500$ h (187.5 days).

It is possible to further increase the node lifetime by reducing the sensor energy consumption by using a semiconductor sensors realized on a membrane (some experimental samples with average power consumption <1 mW exist [24]) and by increasing the battery capacity. Three batteries of type C or D can provide a total of 8000 mAh and 15,000 mAh respectively, increasing lifetime up to 5 times our baseline, and with limited impact on the size of the node. Besides, depending on the WGSN deployment scenario, various forms of energy scavenging technologies could be employed [18].

6. Conclusion

In this work we have proposed a wireless gas sensor network (WGSN) that employs an autonomous semiconductor gas sensors node. To increase the sensor sensitivity and selectivity, we have used a temperature scanning analysis mode for gas measurement, as well as the sensor sensitive layer heating in pulse mode. Experiments made with methane have shown that the system is able to accurately detect and measure the methane concentration in the atmosphere. In addition, we have found out that the maximal sensor's sensitivity to methane is achieved when the sensor is heated up to 525 °C.

We have also demonstrated that the optimization of gas measurement, data processing and data transmission may significantly decrease the power consumption of the sensor. Besides, the ZigBee standard provides additional power savings for the on board transmitter.

Due to its reasonable simplicity, wireless connectivity, and low power consumption, the WGSN can be deployed in a short time without entailing considerable maintenance cost. In addition, the use of Ethernet and GSM technologies makes it easy to manage the network in real-time. The demonstrated WGSN could be used for a wide range of gas monitoring applications.

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