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Design, Characterization and Management of a Wireless Sensor Network for Smart Gas Monitoring

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Abstract

Air quality monitoring in indoor environments is of great significance for comfort and health, especially nowadays that people spend more than 80% of the day indoor. We propose flexible wireless system able to detect polluted air and dangerous situations in a complex and large environment. It is important for ambient intelligent systems to be unobtrusive and to optimize the power consumption of the platforms in order to be able to live on batteries for several years. We present a system with aggressive energy management that involves three levels: sensor level, node level and network level. The sensor board we designed is a wireless sensor network (WSN) node, with very low sleep current consumption (only 8 _A). It contains two modalities — a gas sensor and a Pyro electric Infrared (PIR)sensor. The network is multimodal: it uses information from the PIR sensor and neighbor nodes to detect the presence of people and to modulate the duty cycle of the node and the Metal Oxide Semiconductor (MOX) gas sensor. In this way we reduce the nodes' activity and energy requirements, providing reliable service at the same time. We simulate the benefits of the context-aware adaptive duty-cycling of the gas sensor activity and we demonstrate a significant lifetime extension compared to the continuously driven gas sensor (several years vs. several days).

Keywords—Wireless sensor network, gas sensor, metal oxide semiconductor technology, energy management, people detection.

I. Introduction

Monitoring Indoor Air Quality (IAQ) is very important for people's comfort, health and safety. Nowadays we spend most of our time indoor, thus the lack of ventilation causes the Sick Building Syndrome (SBS), with symptoms like headaches, nausea, dizziness, eye and throat irritation [1]. Earlier, ventilation has been controlled only by the information from the CO_2 sensors. In the recent several years Volatile Organic Compounds (VOCs)have been proven to show better results about persons' comfort(being able also to sense the smell in the room). Important sources of VOCs in a building are people (bio effluents), furniture, building materials, paints, etc. [2]. Besides comfort, detection of dangerous situations, like gas leakage (e.g. CH_4 or CO) is very important. CH_4 (methane) is a principal constituent of the natural gas, used in almost every household for cooking or heating. When it reaches a certain concentration in air (5–15%),it is flammable and explosive [3]. CO (carbon monoxide) sources are tobacco smoke, gas heaters and stoves, leaking chimneys, etc. It is colorless, odorless and tasteless, hence impossible to notice without a sensing device. In smaller quantities (e.g. 100 ppm) it causes a headache and dizziness after a couple of hours of exposure. Higher concentrations (e.g. 3200 ppm) cause headaches and dizziness after 5–10 min, and death within 30 min. Very high concentrations (e.g. 12800 ppm) cause unconsciousness after a couple of breaths, followed by death in less than 3 min [4].

Implementation of Wireless Sensor Networks (WSNs) in IA monitoring avoids installation costs due to wire depositions, introducing at the same time power efficiency as a main challenge. In fact, wireless sensor nodes are mainly battery-powered. Even if they are equipped with power harvesting units [5],energy is a limited resource and should be managed wisely. A WSN should be autonomous and self-sustainable, able to function for several years with battery power supply. To fulfill this goal, power consumption should be minimized. In general, wireless transceivers consume a major amount of energy and many power management policies have been investigated and applied to reduce their activity. However, even sensors can be power-hungry, and gas sensors do consume significant power. Their power consumption is in the same order of magnitude of transceivers' power consumption (typically 60–70 mow) and they should be active most of the time to sense the gas concentration and ensure a good quality of service. Thus, we need power management techniques that schedule both energy-consuming sensors and the transceiver [6].

There are several examples in literature of sensor systems for monitoring IAQ. In [7], an automated decentralized indoor climate control system is presented, including stationary wiredmulti-gas sensor modules and wearable wireless devices. Energy consumption of the system is not mentioned. Postulate teal. [8] present a Wi-Fi network for indoor and outdoor air quality monitoring with MOX sensor arrays from Figaro [9]. They are focused on advanced onboard processing and data publishing on the Web. Power consumption of the nodes is quite high(8 W). Choi et al. [10] present design and implementation of sensor board for air pollutant monitoring applications, based on an Mote, with IEEE 802.15.4/Sigsbee communication protocol. They developed an automated sensor-specific power management system and use pulse mode of the gas sensors, but the current consumption of their solution is still quite high (about 100 mA).

We focus on the power consumption reduction of the gas monitoring WSN through design of an ultra-low-power node. The power consumption of our node in sleep state is only24 _W. Information about presence of people and the messages received from the other nodes in the network enable contextawareadaptation of the gas sensor duty cycle. That features essential for achieving average power consumption of the network low enough to survive at least for one year on a battery power supply, without losing important information from the environment at the same time.

Most convenient gas detectors for WSN applications are those fabricated in Metal Oxide Semiconductor (MOX) technology, due to the small form factor and power efficiency. In [11], it is shown how the sensitivity, selectivity and response time of Moggs sensors strongly depend on the sensing layer temperature. Substantial study of the pulse mode for three different fabricated MOX gas sensors is presented in [12]. From these two papers it is important to emphasize power savings of an order of a magnitude compared with typical commercial off-the-shelf (COTS) Moggs sensors (the fabricated sensors consume only about 9 mow).In [13], authors study the dynamic behavior of low-power COMOX sensors (COTS sensors from Figaro) operated with pulsed temperature profiles and conclude that sensor thermal dynamics changes as a function of the CO concentration. They propose two parameters describing the sensor response shape, to provide an indication of the gas concentration, regardless of any calibration. These papers show the intensive effort to reduce the power consumption of the MOX gas sensors with pulse operational mode. Upon the state-of-the-art and expectations of further COTS gas sensors power consumption reduction, we decided to develop our system with MOX technology gas sensors. We base our simulations of node duty cycle on the research results of the gas sensor pulse mode.

From the literature we notice the lack of cooperation between the research field of MOX gas sensors fabrication and the network cooperation research field. Our main contribution is to merge knowledge from both of these fields, which would enable more energy-efficient and flexible system design. In this paper we present a preliminary study of a flexible, context-aware Westford smart gas monitoring. The energy consumption reduction, that enables several years long battery lifetime, is performed on three levels:

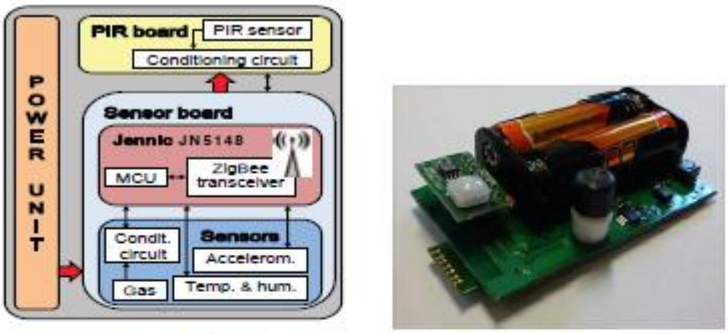
·sensor level: pulse mode operation of the MOX gas sensor;

·node level: ultra-low sleep power consumption, dutycycling,activity modification based on people presence detection;

· network level: activity modification based on the messages received from the neighbor nodes.

To enhance the ambient intelligence of our system, we merge the information from gas sensors and Pyro electric Infrared sensors(PIRs) that detect people presence. From our experience [14, 15],PIR sensors, although very low-resolution, are able to give useful information when densely deployed and cooperating. Another advantage is that they have almost no impact on people’s privacy.

This paper is organized as follows. Section II gives an overview of the network we designed and Section III the characterization of the network in terms of energy consumption reduction. Section IV presents several case studies with simulations that show the benefits of the proposed system. The conclusions, together with future work plans, are brought in Section V.



(a) Block architecture (b) Node with sensors

Figure 1. Sensor node

II. Network architecture

The network we propose consists of several sensor nodes organized in an IEEE 802.15.4/Sigsbee network. For this preliminary work intended for gas monitoring in smaller apartments/buildings, the nodes are organized in a star configuration. One of the nodes is the Sigsbee coordinator, and the others are end devices. The coordinator is always on and it is mains powered, thus its energy consumption is not an issue. On the other hand, end devices are battery-powered and reducing their energy consumption is a crucial task for the longevity of the network. The hardware architecture of the nodes is the same, they differ only in the software application. In order to reduce the power consumption of the hardware as much as possible, we decided to design our own wireless sensor node, with the possibility of controlling activities of its components.

A. Sensor node

The architecture block-scheme and the photo of the sensor node we designed are shown in Fig. 1. The node is built around Jennic JN5148 module, placed on the sensor board, together with several sensors connected to it. A PIR board is connected to the sensor board over GPIO pins to provide the information about the people presence. The power unit contains two AA batteries, but can be also augmented with a power harvesting unit.

1) Jennie module: Jennie JN5148 module [16] is an ultralow-power, high performance wireless microcontroller targeted at Sigsbee PRO networking applications. The device features an enhanced 32-bit RISC processor, a 2.4 GHz IEEE 802.15.4compliant transceiver, 128 dB of ROM, 128 dB of RAM and arch mix of analogue and digital peripherals. Compared to the other similar solutions in the field of WSNs, it introduces about35% power savings — its power consumption is 15 mA for TX and 18 mA for RX. Using Sigsbee PRO protocol stack enables us to form a standardized and easy-expandable network.

2) Sensors: The sensor board comprises several sensors —an accelerometer, a temperature and humidity sensor and a gas sensor with its conditioning circuit — useful for various ambient monitoring applications. Here we focus on the gas sensor and its conditioning circuit.

There are several different technologies used for gas sensor manufacturing: Metal Oxide Semiconductor (MOX), pellistor,electrochemical, quartz microbalance [9, 17, 18]. Due to advantages over other technologies, like the small form factor, fast response time and lower energy consumption, we chose them OX technology. A MOX sensor is composed of a metal oxide(most often SO2) that should be heated to induce the reaction of absorbing the gases on its surface. Electrons, which are released during the reaction of the gas molecules and the sensor surface, lead to a higher conductivity of the semiconducting material. As soon as the induced lattice vacancies are filled again with oxygen from ambient air, conductivity returns to its initial value. Disadvantages of this type of sensors (sensitivity to temperature, humidity and airflow) have to be taken into account while designing and deploying the nodes.

We used a commercially available sensor MiCS-5121 frome2v technologies [19]. It is a sensor for VOC (including CH4)and CO. We built an abundant conditioning circuit for the gas sensor that enables us to control the heater voltage by a Dacron the MCU and monitor the sensor resistance and current consumption on the ADCs. By modifying the heater voltage, we can control the temperature of the heater, which is responsible for the chemical reaction progress. The temperature has a significant effect on sensor sensitive (e.g. at a lower temperature the sensors more sensitive to CO). However, calibration and accuracy of the gas sensor have not been tackled in this stage of work.

B. PIR board

The Pyro electric Infrared (PIR) sensor is a low-power, low cost sensor that detects person presence by detecting variations of incident infrared radiation of a body that is not in thermal equilibrium with the environment. It is often used in alarm systems providing a simple digital presence/absence signal. Being passive and very low-power, but still reliable, it is very convenient for usage in battery-powered systems, often as a trigger for energy consuming video cameras [20]. We designed a separate board with Murata IRA E710 PIR sensor and a conditioning circuit able to create two outputs: a digital and an analog output. From the analog output we can recognize the direction of the movement of the person [21]. For one direction the first peak is positive, for the other direction the first peak is negative. The board has also the capability to modify the sensitivity (range) of the PIR sensor. For the preliminary work presented in this paper we used only the digital output, to wake the node up from the inactive state on a detection of a person movement in the monitored area.

III. Energy consumption

To detect the gas, the MOX sensor has to be heated (76 required to reach the 340 _C operating temperature [19]). If the sensor is used in a continuous mode, energy consumption would be too high and the node, battery-powered, would run out of energy quite soon. By keeping the node in sleep state and waking it up periodically or on an event, we can reduce the energy consumption. With putting the JN5148 in sleep state and turning off all other components on the sensor board, we accomplished an ultra-low current consumption of 8 _A at 3 V, which is apostolate for designing a long-living WSN.

A. Duty-cycling the gas sensor activity

Duty cycle (D) of the node's activity is defined as the fraction of time when the node is on:

$$D = \frac{t_{on}}{T}, \tag{1}$$

$$T = t_{on} + t_{off}. \tag{2}$$

Power consumption of the node depends on the duty cycle:

$$P_{avg} = \frac{P_{on} \cdot t_{on} + P_{off} \cdot t_{off}}{T}. \tag{3}$$

Furthermore, power in inactive state (Puff) is usually several orders of magnitude lower than the power in active state, so we can approximate the average power consumption as:

$$P_{avg} = P_{on} \cdot D. \tag{4}$$

Hence, in order to decrease the node's power consumption, were trying to reduce its duty cycle (D). To reduce the duty cycle, we should decrease the ton time as much as possible and increase the period (T) as much as possible, taking into account some limitations. ton minimum value is limited by the gas sensor technology. The critical issue is to find the minimal time the gas sensor has to be heated in order to read a reliable gas concentration value. That time is called the wake-up latency. If the sensor reading is performed before the wake-up latency has elapsed, the acquired data is not valid [6, 10]. Hence, the sensor node has to be active long enough for the sensor to wakeup (wakeup) and to acquire the measured data (tacquire).

$$t_{on} \geq t_{wakeup} + t_{acquire}. \tag{5}$$

For MOX gas sensors that should be the time necessary for the temperature (reaction) to reach the steady state. That usually takes at least several seconds, but technical documentation of the MiCS-5121 indicates that the gas concentration can be determined also from the transient signal. The optimum duration of the pulses can vary from 20 MS to several minutes, depending on the application and the response time and accuracy required[22]. Next step in our research is to perform calibration and measurements with this gas sensor in a professional chamber to confirm these statements and determine more precisely the minimal required pulse duration (ton). T maximal value is limited by the application in terms of system reaction time. It directly influences the tuff time. The worst case for the application is that the tuff is longer than the time necessary to react before the dangerous/explosive/lethal concentration is reached. Also, to ensure the appropriate fast reaction to the alarm messages from the adjacent nodes, we need to have a certain duty cycle of the radio activity. A simplified graphics of the node's power consumption with duty-cycled activity is shown in Fig. 2.

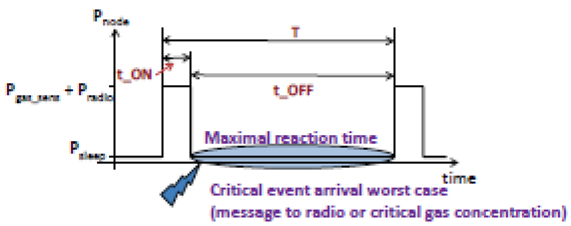


Figure 2. Duty-cycling of the gas sensor and transceiver activity

Table I. Sensor node's current consumption @ 3 V

State			Current consumption [mA]
MCU	radio	gas sensor	
sleep	off	off	$8 \cdot 10^{-3}$
on	on, idle	on	55,80
on	on, TX	on	58,02
on	off	on	38,06
on	off	off	8,08
on	on, idle	off	21,80
on	on, RX	off	9,62

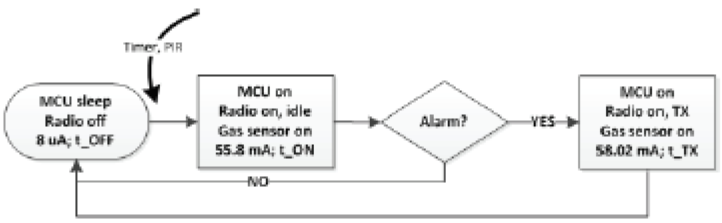


Figure 3. Behavioral flowchart of a periodically awaken sensor node, with gas sensor in pulse mode

B. Energy modeling

Table I shows the sensor node's current consumptions for different states of its components, with 3 V power supply. Their board introduces another 0.35 mA when an event is detected and 0.105 mA otherwise. The energy consumption of a node can be modeled with a behavioral flowchart. A behavioral flowchart consists of all power states that a node is going through its lifetime and the transitions between them. For each state and each transition we need to know the power consumption (Pstate,Ptrans) and time (tstate, ttrans) the node spends in [23]. The energy consumption of the node can then be calculated as the sum of energies in all states and energies of all transitions between states:

$$E_{node} = \sum_{state} P_{state} \cdot t_{state} + \sum_{trans} P_{trans} \cdot t_{trans}. \qquad (6)$$

Behavioral flowchart of the designed node for smart gas monitoring is shown in Fig. 3. We measured the power and times for every power state and transitions between them. For the sake of visual clarity, not all information is depicted. The information from the PIR sensor (about the presence of people) and from the transceiver (about the reception of an alarm message from another node in the network) can be used to modify the duty cycle and adjust the sensor to the situation, with effort of minimizing the node's activity without decreasing the quality of service.

IV. Experimental setup

Our goal is to design a system that can perform a reliable gas monitoring and operate on batteries at least for a year. Design of the node enables ultra-low power consumption in sleep state(Table I). To reduce the overall (average) power consumption of the node, we need to keep it as much time as possible in sleep state. At the same time, it is of crucial significance to obtain sufficient node activity to detect critical gas concentration, in order to ensure a comfortable and safe indoor environment. Network management is very application dependent. Pre-deployment modeling of the monitored area (building), taking into account air flows, window and door position, etc., is useful to define the initial values of the system variables, and critical times and concentration values. Based on the information extracted from the sensors (the PIR sensor and the gas sensor itself), the system should be able to predict the behavior, adapt the duty cycle and send the alarm message if necessary. Also, actuators in a form of ventilation control can be included in the system. To show the advantages of our proposed approach in terms of network longevity and reliability, we perform simulations for two typical application scenarios — monitoring gas concentration due to contamination produced by a person during a longer period and contamination during a dangerous event like a pipe failure.

A. Application scenario

We propose a flexible, autonomous system able to monitorial in various situations. We can divide those situations into two groups: quasi-stationary detection and event detection.

1) Quasi-stationary detection: VOC concentration highly depends on the person presence (not only by physiology, but also busing cleaning products, cooking, smoking, etc.) and during time in a room (without proper ventilation) we can notice continuous gas increment. Thus, it is useful to merge data extracted from the people presence detector (PIR sensor) to develop a flexible, energy-efficient system. As mentioned before in subsection II-B,PIR sensor can also give the information about the direction of movement. Deploying it by the door, we can keep track of the number of people in the room and dynamically modify the frequency of gas concentration sensing (duty cycle).

2) Event detection: Detecting dangerous events like high gas concentrations is important for people’s (and infrastructure’s)health and safety. Pipe failure is the most common source of dangerous gas concentrations indoor. Before deploying the network, it is necessary to obtain information about the pipe placements in the building, to know which rooms are connected with pipes and which nodes have to be woken up first in case of leakage in a certain room. Also, history of previous failures and state of the pipe infrastructure have to be investigated in order to designate each room a leakage risk factor. Modeling the pipe failures before network deployment can help us decide about

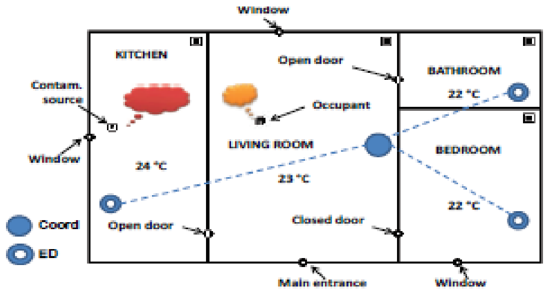


Figure 4. An example of the smart gas sensor network deployment

Figure 5. CO concentration in a house after an hour long pipe failure

nodes' placement in the room and their duty cycles (including activity of the radio and activity of the gas sensor). The inactive(sleep) state is critical in terms of reaction time. Modeled gas flow rate is important for determining the maximal reaction time of the node, that has to be shorter than the time of a gas to reach the dangerous (flammable/explosive/lethal) concentration. Also, for the rooms where initial field tests and models show low risk of dangerous gas concentration, we can capture the gas sensor value only on a detection of a person presence by the PIR sensor. After detecting dangerous gas concentration values, safety becomes more important than the network's lifetime. Hence, we wake the node up to continuously sample the gas sensor and inform all the nodes in the network (building) to do the something, which enables tracking of the gas flow, that is useful for post-leakage analysis and reparation of the building.

B. Simulation

For creating some everyday life case studies of air pollution, we use CONTAM, one of most popular free multimode simulation tools [24]. To show the benefits of our approach based on adaptive duty cycle, we simulate a simple tested, a typical house, with a dangerous contamination source in one room and one person living in the house. The house and the example of the smart gas detection WSN deployment is depicted in Fig. 4. The gas flow rate simulated in CONTAM help us estimate the network's lifetime in Matlab, using measured power consumptions of the node (Table I) and expression (6).

Table II. Activity period (T) for different t_{on} and duty cycles

T [s]		Duty cycle [%]						
		10	5	2	1	0.5	0.1	0.01
t_{on} [s]	0.5	5	10	25	50	100	500	5000
	1	10	20	50	100	200	1000	10000
	2	20	40	100	200	400	2000	20000
	5	50	100	125	500	1000	5000	50000

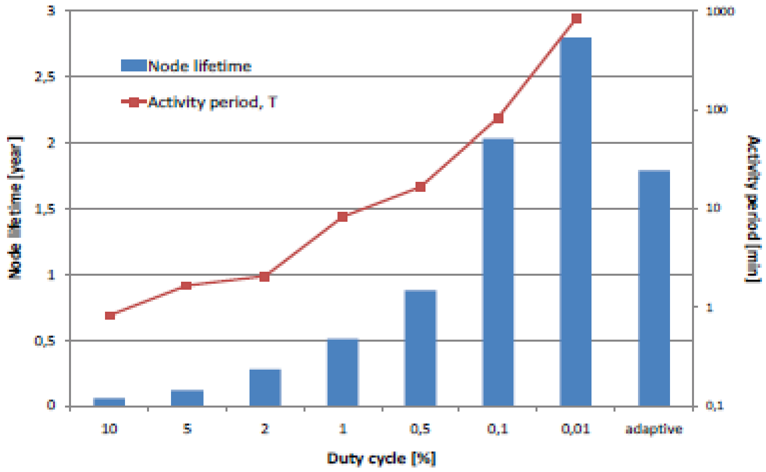


Figure 6. Node's lifetime and the activity period (T) for different duty cycles, in worst case, with $t_{on} = 5\ s$

1) Everyday life: Fig. 5 is an example of a hazardous event, an hour long pipe failure in the kitchen (from 13 h to 14 h). It produces a constant leakage of CO with 500 mg/s rate.

When a node detects a gas concentration higher than a predefined threshold, it sends an alarm message to other nodes, triggers the control system to start a proper reaction to the situation and increases its duty cycle to ensure more precise monitoring of the gas concentration. Also, when the gas concentration is low and there are no other warnings of a possible enhanced contamination, the node decreases the duty cycle. In that case we still need to ensure that the WSN detects the concentration changes.

2) General case: We simulated several modes of monitoring air quality with our designed network:

a) Gas sensor in continuous mode (duty cycle 100%)

b) Fixed duty-cycling (10%, 5%, 2%, 1%, 0.5%, 0.1%, 0.01%)

c) Adaptive duty-cycling (combination of 2%, 1%, 0.5% and0.1% duty cycles) with occasionally waking up the node and the transceiver during the node's (and gas sensor's) inactive time — information about the environment both from PIR sensor and transceiver.

In this stage we are not able to determine the wake-up latency of the gas sensor, but, from the literature, we can suppose several possible node's active times (ton). For each of them (0.5 s, 1 s,2 s and 5 s) we calculate the activity periods (T) for the set of simulated duty cycles and show it in Table II. Since the active time is much smaller than the activity period, the inactive time, thus the worst case reaction time, can be approximated as the activity period. Fig. 6 depicts the activity period and the node's lifetime for different duty cycles in the worst scenario, with ton =5 s. The node is equipped with two AA batteries providing 3 Vend 3000 math It is obvious that we are facing an inactive time– node lifetime trade-off. The benefits of duty-cycling the node's activity in terms of lifetime prolongation are evident. A node with a continuous gas sensing would survive only for 2 days and6 hours. A 0.01% duty cycle, on the other hand, provides very good node's lifetime (2.8 years). But, it is unacceptable in terms of a very long reaction time with the risk of missing important events. Since we are trying to accomplish at least one year of system's autonomy (a typical demand for a real-life application),duty cycles of 0.5% and lower are most appropriate.

To test an example of adaptive duty-cycling, we suppose a situation of a typical room where for 2 h in a day we have2% duty cycle (very often gas sampling — lots of people present), for 10 h in a day 1% duty cycle, for another 10 him a day 0.5% duty cycle and for 2 h in a day 0.1% duty cycle. The worst case inactive times (Fig. 6) are still acceptable for practical system implementation, like the one depicted in Fig. 5.In order to additionally decrease the reaction times, we include more frequent activity of the radio while the gas sensor is in inactive state. In other words, while in sleep state, the node is periodically waking up, turning on only its transceiver to check if there is an alarm message from another node in the network. In this example, we chose the duty cycle of a transceiver tube 0.1%, increasing the sleep current consumption of the node from 8 _A to 29.8 _A. The lifetime of the node in this cases 1.79 years, as showed in Fig. 6 (adaptive duty cycle). It is lifetime prolongation compared to the continuous gas monitoring of 99.66%. The most important thing is that it is appropriate for safe monitoring of the situations we simulated in CONTAM.Although this is a preliminary study, with only some typical real-life situations predicted, we clearly see enormous potential of prolonging the network's lifetime by using the designed low power nodes in a pulse mode. Bibliography doesn't show any example of a WSN for IAQ that could be autonomous for several years on batteries'.

V. Conclusions

In this paper we present a preliminary study of a smart Winnable to detect polluted air. We designed a system with energy consumption reduction on three levels: sensor level, node level and network level. The node level power management results with a very low sleep current consumption (only 8 _A). By duty cycling the node and the MOX gas sensor, together with using the information about people presence from the PIR sensor and alarm messages from the other nodes in the network, we are reducing the nodes' activity (thus also the energy consumption), but still providing a reliable service. Simulations show our system is able to live for almost two years on 2 AA batteries with adaptive duty cycle. For future work we find most important to define the minimal time the sensor should be heated in order to give reliable information about the monitored gas concentration (ton).With that information, we can approach the issue of choosing proper duty cycle set for the gas sensor and the transceiver that satisfies the long network lifetime and a low reaction time. By implementing power harvested from the environment on the node, we can design a perpetually autonomous WSN.

Acknowledgment

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基于无线传感器网络的智能气体检测系统的研究和管理

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摘要

室内环境中的空气质量监测对舒适度和健康状况具有重要意义，特别是现在人们在室内每天花费超过 80%的时间。我们提出一种灵活的无线系统，能够在复杂的大环境中检测污染的空气和危险情况。对于环境智能系统来说，不重要的是要优化平台的功耗，以便能够在电池上使用数年。我们提出一个积极的能源管理系统，涉及三个级别：传感器级别，节点级别和网络级别。我们设计的传感器板是一个无线传感器网络（WSN）节点，具有非常低的睡眠电流消耗（仅 8μA）。它包含两种模式 - 气体传感器和热释电红外(PIR)传感器。该网络是多模式的：它使用来自 PIR 传感器和邻居节点的信息来检测人员的存在并调节节点和金属氧化物半导体（MOX）气体传感器的占空比。通过这种方式，我们减少了节点的活动和能量需求，同时提供可靠的服务。我们模拟了气体传感器活动的环境感知自适应责任循环的益处，并且与持续驱动的气体传感器（几年与几天）相比，我们展现出显着的寿命延长。

关键词 无线传感器网络，气体传感器，金属氧化物半导体技术，能源管理，人员检测。

I. 介绍

监测室内空气质量（IAQ）对人们的健康和安全非常重要。 现在我们大部分时间都是在室内度过的，因此空气不流通会导致病态建筑综合症（SBS），出现头痛，恶心，头晕，眼睛和咽喉刺激等症状[1]。 此前，通风只能通过 CO2 传感器的信息进行控制。 在最近几年中，挥发性有机化合物（VOC）已被证明可显示出更好的人体舒适度(也能感知房间中的气味)。建筑物中 VOC 的重要来源是人(生物污水)，家具，建筑材料，涂料等[2]。 除了舒适性之外，检测危险情况，例如气体泄漏（例如 CH4 或 CO）也非常重要。CH4（甲烷）是天然气的主要成分，几乎在每个家庭都用于烹饪或烹饪加热。 当它在空气中达到一定浓度时（5-15%），它是易燃和易爆的[3]。 CO（一氧化碳）来源是烟草烟雾，燃气加热器和炉灶，烟囱泄漏等，它是无色无味无味的，因此不通过传感装置就无法察觉。 如果 CO 数量较少（如 100 ppm），暴露几小时后会引起头痛和头晕。 较高的浓度（如 3200 ppm）会在 5-10 分钟后引起头痛和头晕，并在 30 分钟内死亡。

非常高浓度（例如 12800 ppm）在几次呼吸后导致昏迷，然后在不到 3 分钟内死亡[4]。

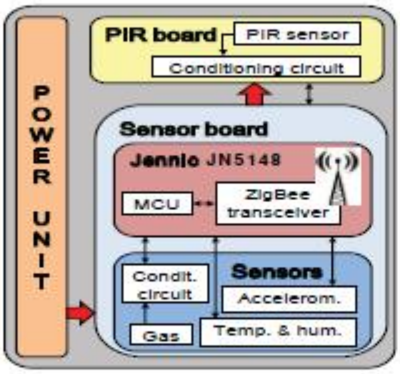
在室内空气质量监测中采用无线传感器网络（WSNs）可降低安装成本。 事实上，无线传感器节点主要由电池供电，虽然它们配备了能量收集单元[5]，但是能源也是一种有限的资源，应该进行一定的资源分配。 无线传感器网络应该具有自主性和自我可持续性，能够在电池供电的情况下运行数年，为了达到这个目标，功耗应该降到最低。 一般来说，无线收发器消耗大量的能量，许多电源管理策略已经对该部分进行资源的限制，以减少它们的活动。 但是，即使传感器可能耗电大，但是气体传感器的功耗也很大，它的功耗与收发器的功耗（通常为 60-70 mW）处于同一数量级，并且大部分时间应该处于活动状态，以检测气体浓度并确保良好的服务质量。 因此，我们需要能耗管理技术来调度耗能传感器和收发器[6]。在传感器系统的文献中有几个例子用于监测 IAQ。 在[7]中，提出了一种自动化的分散式室内气候控制系统，包括固定有线多气体传感器模块和可穿戴无线设备，但是他们都没有提到系统的能耗。 Postolache 等人[8]提出了一个基于 WiFi 网络用于室内和室外空气质量监测的装置，使用了来自 Figaro 的 MOX 传感器阵列[9],MOX 专注于网络上的先进板载处理和数据发布， 传感器节点的功耗相当高（8 W）。Choi 等人 [10]介绍了基于 Hmote 和 IEEE 802.15.4 / ZigBee 通信协议的空气污染物监测应用传感器板的设计和实现。他们开发了一种自动化的传感器专用电源管理系统，并使用气体传感器的脉冲模式，但目前他们的解决方案能量消耗仍然非常高（约 100 毫安）。 我们通过设计超低功耗节点，专注于瓦斯监测 WSN 的功耗降低。 我们使节点处于睡眠状态的功耗仅为 24μW。 信息与人的存在以及从网络中的其他节点接收到的消息，使得气体传感器占空比的调整适应。 该功能对于实现网络的平均功耗低到足以在电池电源上保存至少一年而不丢失重要信息由于体积小和功率效率高，用于无线传感器网络应用的方便的气体探测器是用金属氧化物半导体（MOX）技术制造在[11]中，它展示了 MOX 气体传感器的灵敏度，选择性和响应时间如何强烈依赖于传感层温度。 [12]中介绍了三种不同的 MOX 气体传感器的脉冲模式的实质性研究。 从这篇论文中，重点强调与典型的商用现成（COTS）MOX 气体传感器（制造的传感器仅消耗约 9mW）相比数量级的功率节省。在[13]中，作者研究了低功率 CO MOX 传感器（来自费加罗的 COTS 传感器）在脉冲温度曲线下运行的动态行为，并得出结论：传感器热动力学随着 CO 浓度的变化而变化。 他们建议描述传感器响应形状的两个参数，以提供气体浓度的指示而不管任何校准。 这些论文展示了在脉冲操作模式下努力降低 MOX 气体传感器的功耗的努力。随着最新 COTS 气体传感器的功耗降低，我们决定用 MOX 技术气体传感器开发我们的系统。 我们基于对气体传感器脉冲模式的研究结果进行节点占空比模拟。

从文献中我们注意到 MOX 气体传感器制造的研究领域与网络合作研究领域

之间缺乏合作。我们的主要贡献是合并来自这两个领域的知识，从而实现更高能效和灵活的系统设计。在本文中，我们提出了一个灵活的，用于智能天然气监测的环境感知 WSN 的初步研究。 能耗降低能够使电池寿命延长几年，分三个级别进行：

- 传感器水平：MOX 气体传感器的脉冲模式操作；
- 节点级别：超低睡眠功耗，工作循环，基于人员存在检测的活动修改；
- 网络级别：基于从邻居节点收到的消息进行活动修改。

为了提高我们系统的环境智能，我们合并来自气体传感器和热电红外传感器（PIR）的信息，以检测人员的存在。 根据我们的经验[14,15]，PIR 传感器虽然分辨率很低，但能够在密集部署和协作时提供有用的信息。 另一个好处是它们几乎不会影响人们的隐私。 本文组织如下。 第二部分概述了我们设计的网络，第三部分描述了网络在能耗减少方面的特点。 第四部分介绍了几个案例研究和仿真，连同未来的工作计划，都列入第五部分。



(a) Block architecture


(b) Node with sensors

图 1.传感器节点

II. 网络架构

我们提出的网络由几个传感器节点组成，这些节点组织在建筑物中的气体监测的初步工作，节点以星形配置进行组织其中一个节点是 ZigBee 协调器，其他节点是终端设备，调员始终打开，并且由市电供电，因此其能耗不是问题。另一方面，终端设备采用电池供电，降低能耗是网络使用寿命的关键。 节点的硬件体系结构是相同的，它们仅在软件应用程序中有所不同。 为了尽可能降低硬件的功耗，我们决定设计我们自己的无线传感器节点，并有可能控制其组件的活动。

A. 传感器节点

我们设计的传感器节点的体系结构模块和照片如图 1 所示。该节点是围绕 Jennic JN5148 模块构建的，放置在传感器板上，并连接了几个传感器。 PIR 板通过 GPIO 引脚连接到传感器板，以提供关于人员存在的信息。 功率单元包含

两节 AA 电池，但也可以增加一个功率收集单元。

1） Jennic 模块： Jennic JN5148 模块 [16] 是一款针对 ZigBee PRO 网络应用的超低功耗高性能无线微控制器。 该器件具有增强型 32 位 RISC 处理器，2.4 GHz IEEE 802.15.4 兼容收发器，128 kB ROM，128 kB RAM 以及丰富的模拟和数字外设。 与无线传感器网络领域的其他类似解决方案相比，它节省大约 35%的功率 - 其功耗为 15 毫安（TX）和 18 毫安（RX）。 使用 ZigBee PRO 协议栈使我们能够形成标准化且易于扩展的网络。

2） 传感器：传感器板包含多个传感器 - 加速计，温度和湿度传感器以及带有调节电路的气体传感器 - 可用于各种环境监测应用。 在这里，我们专注于气体传感器及其调节电路。

气体传感器制造有几种不同的技术：金属氧化物半导体（MOX），热敏电阻，电化学，石英微量天平[9,17,18]。由于具有体积小，响应速度快，能耗低等优点，我们选择了 MOX 技术。 MOX 传感器由金属氧化物（最常见的是 SO2）组成，该金属氧化物应被加热以引起表面吸收气体的反应。 在气体分子和传感器表面反应期间释放的电子导致半导体材料的较高电导率。 一旦诱导的晶格空位再次填满来自环境空气的氧气，电导率返回到其初始值。 如果传感器以连续模式使用，则会消耗能量太高，节点，电池供电，很快就会耗尽能源。 通过保持节点处于睡眠状态并定期唤醒或事件唤醒，我们可以降低能耗。通过将 JN5148 置于睡眠状态并关闭传感器板上的所有其他组件，我们在 3 V 电压下实现了 8μA 的超低电流消耗，这是设计长寿命无线传感器网络的设想。

A 气体传感器活动的工作循环

节点活动的占空比（D）定义为节点开启时的比例：

$$D = \frac{t_{on}}{T}, \tag{1}$$

$$T = t_{on} + t_{off}. \tag{2}$$

节点的功耗取决于占空比：

$$P_{avg} = \frac{P_{on} \cdot t_{on} + P_{off} \cdot t_{off}}{T}. \tag{3}$$

我们使用了 e2v technologies [19]的商用传感器 MiCS-5121。它是用于 VOC（包括 CH4）和 CO 的传感器。我们为气体传感器建立了丰富的调理电路，使我们能够通过来自 MCU 的 DAC 控制加热器电压，并监测传感器电阻和电流消耗 ADC 的。通过修改加热器电压，我们可以控制加热器的温度，这是造成化学反应进程的原因。 温度对传感器敏感（例如，在较低温度下传感器对 CO 更敏感）具有显着影响。 然而，在这个阶段的工作中，气体传感器的校准和准确性还没有得到解决。

B.　PIR 板

热释电红外（PIR）传感器是一种低功耗，低成本的传感器，通过检测与环境热平衡的物体的入射红外辐射变化来检测人员存在。 它经常用于提供简单数字存在/不存在信号的报警系统。 被动，功耗非常低，但仍然可靠，在电池供电系统中使用非常方便，通常作为耗能摄像机的触发器[20]。我们设计了一个带 Murata IRA E710 PIR 传感器的独立电路板和一个能够创建两个输出的调理电路：数字和模拟输出。从模拟输出中，我们可以识别出人员移动的方向[21]。 对于一个方向，第一个峰是正的，而另一个方向的第一个峰是负的。 该板还具有修改 PIR 传感器灵敏度（范围）的功能。对于本文介绍的前期工作，我们只使用数字输出，在检测到监控区域内的人员移动时将节点从非活动状态唤醒。

III. 能源消耗

为了检测气体，必须加热 MOX 传感器（达到 340℃工作温度所需的 76 mW [19]）。如果传感器以连续模式使用，则会消耗能量。

$$P_{avg} = P_{on} \cdot D. \tag{4}$$

因此，为了减少节点的功耗，我们试图减少它的占空比（D）。 为了减少占空比，我们应该尽可能地减少 t 上时间并尽可能增加周期（T），同时考虑到一些限制。

数值受气体传感器技术的限制。关键问题是要找到气体传感器必须加热的最短时间，以便读取可靠的气体浓度值。 这段时间被称为唤醒延迟。 如果传感器读数在唤醒等待时间过后才执行，则采集的数据无效[6,10]。 因此，传感器节点必须足够长才能唤醒传感器（t_{wakeup}）并获取测量数据（$t_{acquire}$）。

$$t_{on} \geq t_{wakeup} + t_{acquire}. \tag{5}$$

对于 MOX 气体传感器来说，这应该是温度（反应）达到稳定状态所需的时间。这通常需要至少几秒钟，但 MiCS-5121 的技术文档表明，气体浓度也可以从瞬态信号确定。 脉冲的最佳持续时间可以从 20ms 变化到几分钟，这取决于应用和所需的响应时间和精度[22]。 我们研究的下一步是使用专业工作室中的气体传感器进行校准和测量，以确认这些陈述并更精确地确定最小所需脉冲持续时间（t *上*）。 T 最大值受系统响应时间的限制。 它直接影响 t *离*时间。 应用程序的最坏情况是 t *离*比在危险/爆炸/致命浓度达到之前作出反应所需的时间更长。 另外，为了确保对来自相邻节点的警报消息作出适当的快速反应，我们需要有一定的责任用来修改占空比并根据情况调整传感器，尽量减少节点的活动而不降低服务质量。

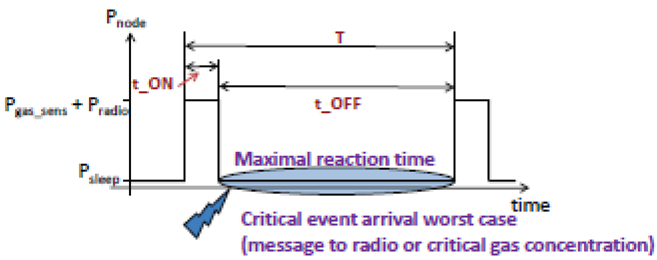


图 2.气体传感器和收发器活动的占空比

表 I.传感器节点的电流消耗@ 3 V.

State			Current consumption [mA]
MCU	radio	gas sensor	
sleep	off	off	$8 \cdot 10^{-3}$
on	on, idle	on	55,80
on	on, TX	on	58,02
on	off	on	38,06
on	off	off	8,08
on	on, idle	off	21,80
on	on, RX	off	9,62

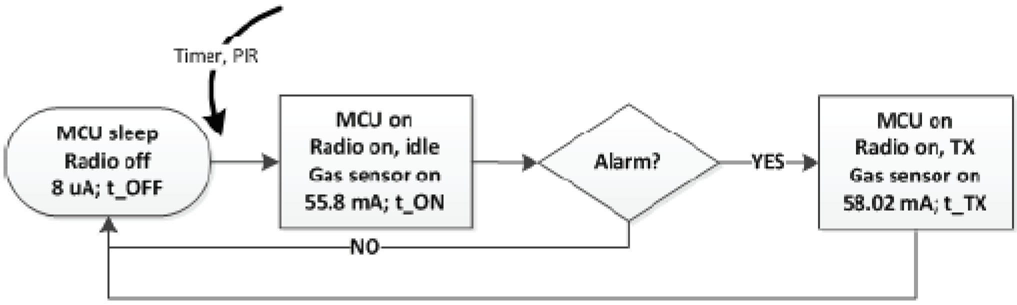


图 3.周期性唤醒传感器节点的行为流程图，气体传感器处于脉冲模式

我们的目标是设计一个系统，可以执行可靠的气体监测并使用电池至少一年。该节点的设计实现了睡眠状态下的超低功耗（表 I）。 为了降低节点的整体（平均）功耗，我们需要尽可能在睡眠状态下保持尽可能多的时间。 同时，为了保证舒适安全的室内环境，获得足够的节点活动来检测临界气体浓度具有至关重要的意义。网络管理非常依赖于应用程序。监测区域（建筑物）的预先部署建模，考虑到空气流量，窗户和门的位置等，可用于定义系统变量的初始值以及临界时间和浓度值。 根据从传感器（PIR 传感器和气体传感器本身）提取的信息，系统应能够预测行为，调整占空比并在必要时发送警报消息。 此外，系统还可以包含通风控制形式的执行器。 为了展示我们提出的方法在网络寿命和可靠性方面的优势，我们针对两种典型应用场景进行模拟 – 监测由于人员在较长时间段

内产生的污染而导致的气体浓度以及管道故障等危险事件期间的污染。

A. 应用场景

我们提出了一个灵活的，自主的系统，能够在各种情况下监测 IAQ。 我们可以将这些情况分为两类：准平稳检测和事件检测。

1）准静态检测：VOC 浓度在很大程度上取决于人员的存在（不仅仅是生理情况，还有使用清洁产品，烹饪，吸烟等），以及在室内（没有适当的通风），我们可以注意到持续的气体增量。 因此，合并从人员存在检测器（PIR 传感器）提取的数据以开发灵活的节能系统是有用的。如前面在第 II-B 小节中所述，PIR 传感器也可以提供有关运动方向的信息。通过门部署，我们可以跟踪房间中的人数，并动态修改气体浓度感测（占空比）的频率。

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网络中，需要获取有关管道的信息在建筑物中的位置，知道哪些房间与管道连接，以及哪些节点必须首先被唤醒，以防某些房间泄漏。 另外，为了指定每个房间的泄漏风险因素，必须调查以前故障的历史和管道基础设施的状态。 在网络部署之前对管道故障进行建模可帮助我们做出决定。

B.能源建模

表 I 显示了使用 3 V 电源时，传感器节点对其组件不同状态的电流消耗。PIR 板在检测到事件时引入另一个 0.35 mA，否则引入 0.105 mA。 节点的能量消耗可以用行为流程图来建模。行为流程图包含节点正在经历其所有生命周期以及它们之间转换的所有电源状态。 对于每个状态和每个转换，我们需要知道节点在[23]中花费的功耗（P 州，P 反式）和时间（t 州，t 反式）。 然后可以将节点的能量消耗计算为所有状态下的能量总和以及状态之间的所有转换的能量：

$$E_{node} = \sum_{state} P_{state} \cdot t_{state} + \sum_{trans} P_{trans} \cdot t_{trans}. \quad (6)$$

智能气体监测设计节点的行为流程图如图 3 所示。我们测量了每个功率状态的功率和时间以及它们之间的转换。为了视觉清晰起见，并非描绘所有信息。来自 PIR 传感器的信息（关于人的存在）和来自收发器的信息（关于来自 PIR 的报警信息的接收）可以用来修改占空比并根据情况调整传感器，尽量减少节点的活动而不降低服务质量。

IV. 实验装置

我们的目标是设计一个系统，可以执行可靠的气体监测并使用电池至少一年。该节点的设计实现了睡眠状态下的超低功耗（表I）。 为了降低节点的整体（平均）功耗，我们需要尽可能在睡眠状态下保持尽可能多的时间。 同时，为了保

证舒适安全的室内环境，获得足够的节点活动来检测临界气体浓度具有至关重要的意义。 网络管理非常依赖于应用程序。 监测区域（建筑物）的预先部署建模，考虑到空气流量，窗户和门的位置等，可用于定义系统变量的初始值以及临界时间和浓度值。 根据从传感器（PIR传感器和气体传感器本身）提取的信息，系统应能够预测行为，调整占空比并在必要时发送警报消息。 此外，系统还可以包含通风控制形式的执行器。 为了展示我们提出的方法在网络寿命和可靠性方面的优势，我们针对两种典型应用场景进行模拟 - 监测由于人员在较长时间段内产生的污染而导致的气体浓度以及管道故障等危险事件期间的污染。

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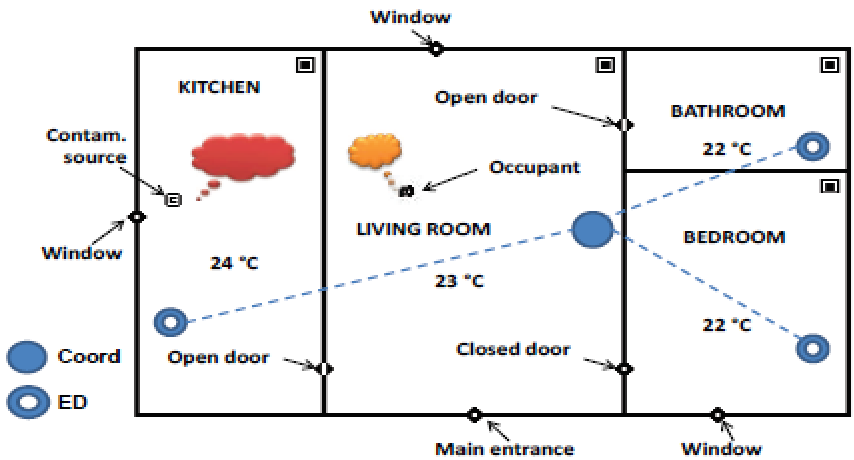

图4. 智能气体传感器网络部署示例

图5.管道失效一小时后，房屋内的CO浓度

节点在房间中的位置以及它们的工作周期(包括无线电活动和气体传感器的活动)。 无效（睡眠）状态在反应时间方面非常重要。 模拟气体流量对于确定节点的最大反应时间非常重要，它必须比气体达到危险（易燃/爆炸/致命）浓度的时间短。此外，对于初始现场测试和模型显示危险气体浓度风险较低的房间，我们只能在 PIR 传感器检测到人员存在时捕获气体传感器值。 在检测到危险气体浓度值后，安全性变得比网络寿命更重要。 因此，我们将节点唤醒以连续采样气体传感器，并通知网络（建筑物）中的所有节点做同样的事情，从而跟踪气体流量，这对于泄漏后分析和修复建造。

B. 模拟

为了创建一些关于空气污染的日常生活案例研究，我们使用 CONTAM，这是最受欢迎的免费多区域模拟工具之一[24]。为了展示基于适应性工作循环的方法的好处，我们模拟了一个简单的试验床，一个典型的房屋，在一个房间里有一个危险的污染源，一个人住在房子里。 房屋和智能气体检测 WSN 的部署示例如图 4 所示。在 CONTAM 中模拟的气体流量帮助我们在 Matlab 中估计网络的使用寿命，使用测量的节点功耗（表 I）和表达式（6 ）。

表二。 不同吨数和工作周期的活动期（T）

T [s]		Duty cycle [%]						
		10	5	2	1	0.5	0.1	0.01
t_{on} [s]	0.5	5	10	25	50	100	500	5000
	1	10	20	50	100	200	1000	10000
	2	20	40	100	200	400	2000	20000
	5	50	100	125	500	1000	5000	50000

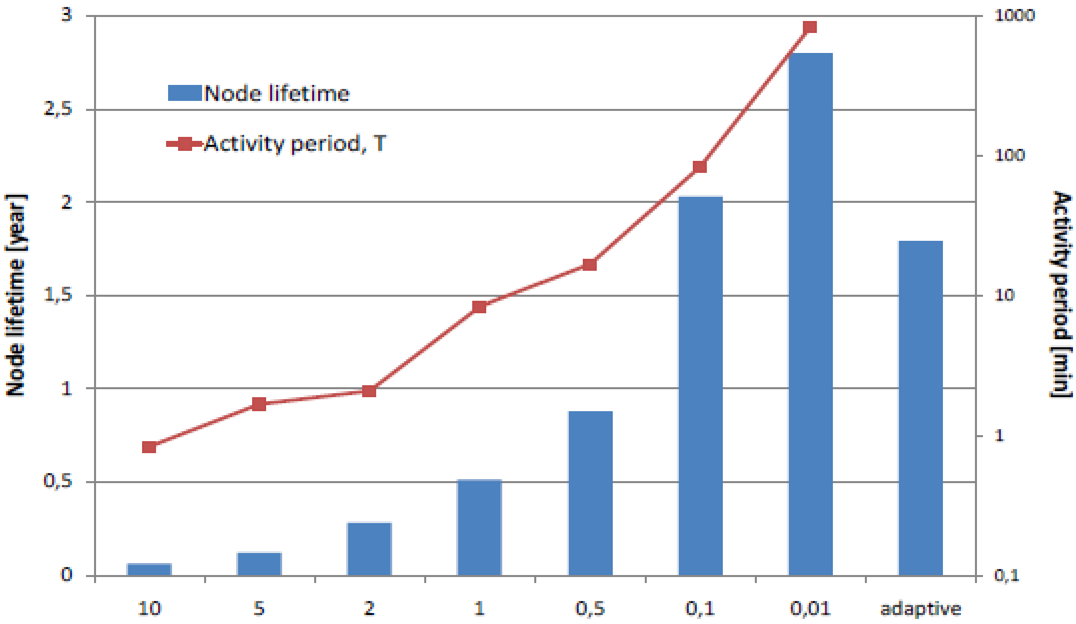

图 6. 节点的寿命和不同占空比的活动周期（T），最坏情况下，ton = 5 s

日常生活：图 5 是一个危险事件的例子，厨房里一小时长的管道故障（从 13 小时到 14 小时）。它会以 500 毫克/秒的速率产生一个不断泄漏的一氧化碳。当节点检测到的气体浓度高于预定义的阈值时，它会向其他节点发送警报消息，触发控制系统开始对情况做出适当反应并增加其占空比，以确保更精确地监测气体浓度。 另外，当气体浓度较低并且没有其他警告可能会增强污染时，节点会减少占空比。 在这种情况下，我们仍然需要确保 WSN 检测浓度变化。

一般情况：我们用我们设计的网络模拟了几种监测空气质量的模式：

a) 气体传感器处于连续模式（占空比 100%）

b）固定的工作循环（10%，5%，2%，1%，0.5%，0.1%，0.01%）

c）在节点（和气体传感器）非活动时间期间偶尔唤醒节点和收发器的自适应工作循环（2%，1%，0.5%和 0.1%占空比的组合） - 关于来自 PIR 传感器和收发器。

在这个阶段，我们无法确定气体传感器的唤醒延迟，但是，从文献中，我们可以假设几个可能的节点的活动时间（t 上）。对于它们中的每一个（0.5s，1s，2s 和 5s），我们计算一组模拟占空比的活动周期（T），并将其示于表 II 中。 由

于活动时间远小于活动时间段，所以非活动时间（即最坏情况下的反应时间）可近似为活动时间段。 图 6 描述了最坏情况下不同工作周期的活动周期和节点的寿命，其中 t 上=5 秒。 该节点配备两节 AA 电池，提供 3 V 和 3000 mAh。 很明显，我们正面临一个不活跃的时间节点寿命折衷。 在终身延长方面责任循环节点活动的好处是显而易见的。 持续气敏的节点只能存活 2 天 6 小时。 但是，在很长的反应时间和遗漏重要事件的风险方面，对于实际的系统实施来说，最坏情况的无效时间（图 6）仍然可以接受，如图 5 所示。为了额外减少反应时间，当气体传感器进入时，我们包括更频繁的无线电活动无效状态。

V. 结论

在本文中，我们介绍了一种能够检测污染空气的智能 WSN 的初步研究。 我们设计了一个能耗降低系统，分为三个级别：传感器级别，节点级别和网络级别。节点级电源管理结果的睡眠电流消耗非常低（仅为 8μA）。 通过对节点和 MOX 气体传感器进行工作循环，并使用来自 PIR 传感器的人员存在信息和来自网络中其他节点的警报消息，我们正在减少节点的活动（因此也是能源消耗），但仍然提供可靠的服务。仿真表明，我们的系统能够在具有自适应占空比的 2 节 AA 电池上存活近两年。 对于未来的工作，我们发现最重要的是定义传感器应该加热的最短时间，以便提供关于监测的气体，为气体传感器和收发器选择合适的占空比集合的问题，该传感器和收发器可以满足较长的网络寿命和较低的响应时间。通过在节点上实施从环境中收集的能量，我们可以设计一个永久自治的 WSN。

声明

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