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Robotic Gas-Analyzer Complex for Atmosphere Monitoring by WSN Technology in City Moscow

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Abstract
Hydrogen content in the urban atmosphere is a new sensitive indicator of the environmental ecology. The complexity of determining this element due to low absolute concentrations and high volatility of this gas requires the development of specialized autonomous complexes for H_2 monitoring and challenge. We have developed a robotic complex based on a wireless data transmission network - wireless sensor network (WSN) technology and specialized hydrogen sensors developed by metal-insulator-semiconductor (MIS) structures.
The article presents the first data on monitoring in the Moscow region at two stations with high and low levels of atmospheric pollution. It is shown that the course of hydrogen is complementary and is determined by atmospheric parameters, but the difference in concentration levels in the center of Moscow and on its border is almost an order of magnitude. These data are compared with information on monitoring in other cities of the world - Paris, Helsinki, etc.

Keywords: hydrogen monitoring; semiconductor gas sensor; WSN network; MIS sensor

Abbreviations: MIS: metal-insulator-semiconductor; WSN: wireless sensor network

1. Introduction

The aim of our work is the organization of long-term ecological monitoring of the modern composition of the atmosphere in big cities. The environmental atmosphere safety and control of hazardous conditions in industries requires prompt trace components in atmosphere monitoring. A major breakthrough in this technology of creating such systems occurred with the emergence of wireless sensor network (WSN) technology - wireless data transmission systems. WSNs are spatially distributed autonomous sensors to monitor physical or environmental conditions, such as gas, temperature, pressure, etc., and to cooperatively pass their data through the network to a main location. The WSN is built of "nodes" - from a few to several hundreds or even thousands, where each node is connected to one (or sometimes several) sensors. Each such sensor network node has a radio transceiver with an internal antenna or connection to an external antenna, a microcontroller, an electronic circuit for interfacing with the sensors, and an energy source, usually a battery or an embedded form of energy harvesting.

Our project includes the development of an informational and analytical system, which includes a network of gas sensors and GIS technologies. The advantages of this technology are autonomous work (to several months and more), high-frequency programmable measurement of gas sensors, low cost (on one node of the network), and the possibility to connect to one node of supervision several types of sensors.

The works describe the technology for constructing WSNs in sufficient detail [1–3]. There are also many specialized monographs [4] and periodic journals ("Wireless Sensor Network", "International Journal of Sensor Networks (IJSNet)", "Ad Hoc Networks", "IEEE Sensors", "EURASIP Journal on Wireless Communications and Networking"). Here we briefly list the main technical advantages of WSN data transmission technology:

1. The possibility of wide scaling the system.
2. Low power consumption, and, as a result, the possibility of long-term operation in autonomous mode.
3. Reliability of data transmission due to duplication of transmission channels.
4. Convenient protocols for connecting external devices, including various sensors, and several peripheral devices can be connected to one node.
5. Small size of transmitting equipment.

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There are certain disadvantages that also need to be mentioned:

1. Small working distance for signal transmission. This is the downside of the low power consumption of WSN networks.

2. Lack of conventional equipment for creating a network and the need to develop specialized sensor devices compatible with WSN technologies.

We are currently at the stage of developing experimental WSN systems coupled with various environmental monitoring equipment. Just now, the development of applied methodological and theoretical solutions for monitoring various gases under various conditions is underway.

Without pretending to provide a complete description of the projects that exist today, we will note recent work. Some overview projects related to the monitoring of gas emanations carried out on the basis of WSN technology are presented [5–7]. Several monographs on this topic have been published [8, 9].

Several interesting works concern the results of implemented projects in the field of mining safety in the coal industry [10–12]. The authors measure the contents of CO_2, CH_4, and O_2 in the mines. First of all, the problem of predicting underground gas explosions and fires through early warning of emergency situations (monitoring H_2, CH_4) is considered.

Data transmission was carried out via a GSM radio channel when monitoring gas emanations from a number of Japanese volcanoes [13] and Etna [14, 15]. The autonomy of the equipment was ensured by solar panels.

Gas emanations from the organic layer of soils have been actively studied using WSN technology. A large number (about 100 nodes) of CH_4, CO_2, and H_2S sensors were deployed at pilot sites in Finland [16]. This program is part of the large international project STRIVE [17].

Analysis of the results of these works shows that in addition to technical problems, there are also serious methodological problems in the use of WSN technology associated with the development of measurement techniques adapted for WSN node technology and the development of appropriate measuring equipment.

We started the project at the beginning of 2015 in two Moscow academic organizations - Vernadsky Institute of Geochemistry and Analytical Chemistry and Moscow State Geological Museum. One locality for the monitoring station is in the center of Moscow, near the Kremlin and the other one is in the most pure zone of Moscow - near Moscow State University, Vorobyovy Mountains (high point of Moscow). We plan to compare these regions by the concentration of H_2 and other gases (CH_4, SO_2) for gas pollution.

When starting this project, we were not yet familiar with WSN technology, and moreover, we did not have a gas sensor suitable for this technology. However, thanks to close cooperation with the MeshLogic company and the laboratory "Development and making of sensors based on MIS-structures" from the National Research Nuclear University, we were able to successfully implement this project.

2. Methodology and Equipment

The basis of the network is Wireless OEM modules ML-Module-Z **(Figure 1)** representing a complete integrated solution. The modules have a built-in special version of the MeshLogic network stack, optimized for building distributed information collection systems in which many devices transmit data to one or more collection points (base stations, gateways, etc.).

FIGURE 1: Modules ML-Module-Z.

The main feature of the ML-Module-Z modules is that they are all equivalent and are routers, that is, they are capable of relaying packets if necessary, but at the same time automatically switch to “sleep” mode, significantly reducing average power consumption and increasing battery life. To switch routers to standby mode, you do not need to configure synchronized access to the medium or set any other parameters since the modules independently determine the optimal operating mode depending on the network load. Wireless OEM modules ML-Module-Z represent a complete integrated solution **(Table 1)**.

The application network of monitoring is composed of gas sensors (H_2, CH_4), complex autonomous equipment for measurement of temperature, pressure, and humidity, and a network of telecommunications (used MeshLogic proprietary protocol).

The hardware of the robotic complex provides a wireless radio frequency network that ensures automatic data collection from spatially distributed sensors and the processing of telemetric information. The MeshLogic standard is distinct from other products in its network protocol stack that provides the following key benefits:

- Fully homogenous network topology and algorithm of calculation position nodes in spatial;
- All nodes are equal and are routers;
- Self-organization and automatic search routers. The signal transmission between nodes and router used radio channel 2.4 GHz;
- Resistance to conflicts between nodes with simultaneously inter transmit data;
- High scalability and reliability of data delivery;
- Ability of all the nodes to work on independent power supply. Accumulation of collected information in non-volatile memory (archive);
- Special software for service monitor radio equipment and sensor tools. Reading information from the archive upon request from a server or higher-level system for its display, processing, and analysis.

The hardware and software complex include **(Figure 2)**:

- wireless nodes;
- interface modules;
- sensors;
- wireless gateway;
- server;
- specialized software.

TABLE 1: Main technical parameters of the radio-module node.

Characteristic	**Value**
Type of radio protocol	IEEE 802.15.4
Radiofrequency range	2400...2483, 5 MHz
Transmitter output power	up 1 mVT (0 dbm)
Receiver sensitivity	-95 dbm
Supply voltage	from 2,7 to 3,6 V
Electric current consumption in transmission mode	21 mkA/24 mkA/3,7 mkA/9 mkA
Control interface	UART (LVCMOS)
Interface speed UART	from 9600 to 921600 bit/sec
Size device	25,4X19, 05X2,7 mm
Work temperature interval	-40...85°C

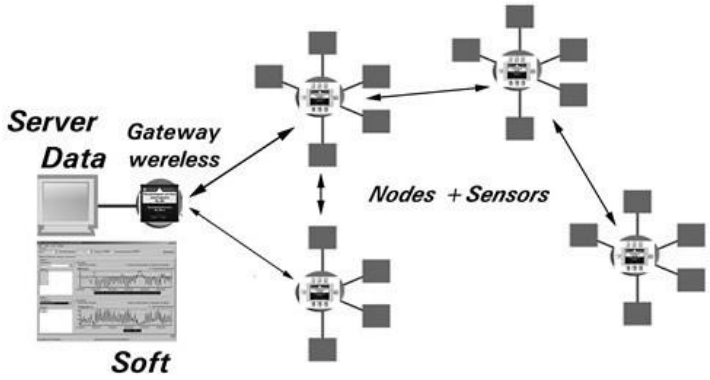
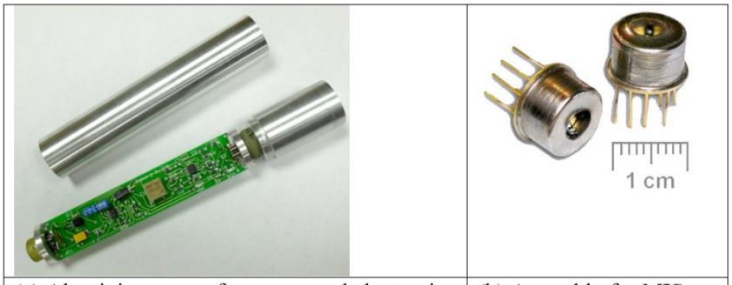


FIGURE 2: Total schema of WSN network collection data (IEEE 802.15.4 protocol). Node includes radio modem with peripheries gas sensors. There are several (about 5) devices that can be included in this point with a common power supply 12 V battery. The nodes include two groups - with gas sensors and without them which are used only for translating data to the gateway server (USB protocol). Gateway can be connected directly with the computer (USB-port) which collects information or connect with a GPRS modem to send data with cellular protocol.

With the help of a gateway, information collected by the wireless network is transmitted to a server or higher-level software system for further processing and storage. Information transfer from the gateway can be carried out via wired or wireless communication channels. In some cases, the infrastructure of cellular operators can be used to organize a wireless communication channel.

Interface modules are designed to connect external sensors to a wireless node and supply power to the sensors, as well as coordinate their output signals with the measuring system of the wireless node. In our case, these are high-precision hydrogen and methane sensors, as well as climate sensors: temperature, humidity, and pressure (gas emissions are highly dependent on climatic conditions). The gas sensors used in our monitoring system are a unique development of the Department of Solid State Physics and Nanosystems at Nuclear Center Moscow **(Figure 3)**.

Gas sensors for the monitoring system were developed on the basis of metal-insulator-semiconductor (MIS) structures. MIS sensors are suitable for measuring the concentrations of the following gases: hydrogen, hydrogen sulfide, nitrogen dioxide, ethyl mercaptan, chlorine, and ammonia. The basis of the sensor is MIS - structure Pd-Ta_2O_5-SiO_2-Si, whose capacitance changes when a reaction with gases occurs.



(a) Aluminium cover for sensor and electronic plate for connection with WSN node module

(b) Assembly for MIS sensor

FIGURE 3: Construction of the gas sensor. (a) general view of the assembled gas device; (b) sensitive part with MIS gas sensor. In the upper part of the device, a round recess is a window for the flow of gas mixture input.

The sensor fabrication technology is based on the microelectronics device fabrication technologies and the thin film laser deposition technique. The sensor can be used for measuring the concentration of any gas noted before, in the ambient temperature range of -30..+40°C and RH 30–90% (30°C) **(Table 2)**.

TABLE 2: Characteristics of the family of gas sensors with MIS construction.

Gas	Measurable concentration range, ppm	Response times, $\tau_{0.9}$, min	Relaxation times, $\tau_{0.1}$, min	Working* temperatures, °C	Guaranteed operation time, years
Cl_2	0,001–10	10	10	100–190	2
H_2S	0,005–0,3	5	15	120	1
NO_2	0,01–10	10	20	100–190	2
C_2H_5SH	0,01–0,3	5	15	120	1
H_2, D_2	10^{-1}–10^4	0,1–5	0,1–5	100	5
NH_3	0,02–10	8	20	100–190	2

*That is the temperature at which the working part of the sensor (sandwich) must be heated.

Three gas sensors with an analog interface were made for our experimental monitoring system. The original calibration was made using calibration of a special standard mixture of H_2 and atmosphere. There are 10–15 points on each calibration graphic with different H_2 concentrations in standard gas mixtures.

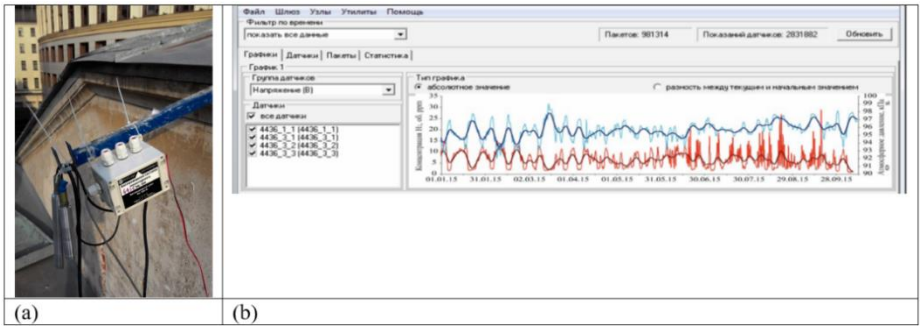
The accuracy of the approximating functions is 3–18%. At low concentrations (H_2 < 3 ppm), the error is rather high (about 20%). So, we think that 1 ppm is the low limit of measurement. The essential factor is temperature drift. We estimate this drift as 20 mV per 1 degree and make corrections because measurements were made in a wide temperature range (+29 - -20°C). To take this factor, we added it to our network by meteorological sensors.

3. Results

Our project offers technical solutions for monitoring the atmosphere network based on WSN technology and the high-sensitive sensors of hydrogen and methane, software, and electronic equipment with a transmitter network. This work is the first project in Russia.

One place is in the center of Moscow, near the Kremlin and the other one is in the clearest zone of Moscow - near Moscow State University, Vorobyovy Mountains (high point of Moscow). We plan to compare these regions by the concentration of H_2 and other gases (CH_4,) for green gas pollution. **Figure 4a** shows the localization of two of our gas detectors (H_2 and CH_4) connected with the WSN node in station 1 (center of Moscow on the roof of a building).

Also, in **Figure 4**, we can see a red cable that connects the sensors to a 12 V rechargeable battery in the attic at home. When two sensors operate with a measurement frequency of 15–30 minutes, its capacity is enough for about 1–2 months of operation. The attic is also equipped with a network server node connected to a GPRS modem for transmitting data to a common server by cellular protocol.



(a) (b)

FIGURE 4: Software interactive interface of the wireless gateway. The graphs of H_2 and atmosphere pressure-inverse correlation. (a) WSN node with gas detectors on the roof of a building; (b) sample of screen software working.

Station 2 is located in a green zone with connections to nodes located at different distances from the nearest highway. This was done to assess the impact of transport on the hydrogen content in the atmosphere and the need to evaluate hydrogen as a sensitive detector of atmospheric pollution.

Our observations show a strong negative dependence of hydrogen content on atmospheric pressure. Apparently, this is due to the high volatility of this impurity. At low pressure, the rate of hydrogen dissipation is low and the measured concentration is high. And the opposite is true for high pressure. Of course, this is only a working hypothesis and further research is needed.

A very clear picture was revealed when comparing sensors located at different distances from the road at station 2 **(Figure 5)**. The level of pollution decreases by an order of magnitude as you approach the road. There is also a correlation between the level of hydrogen concentration and the hours of transport loading.

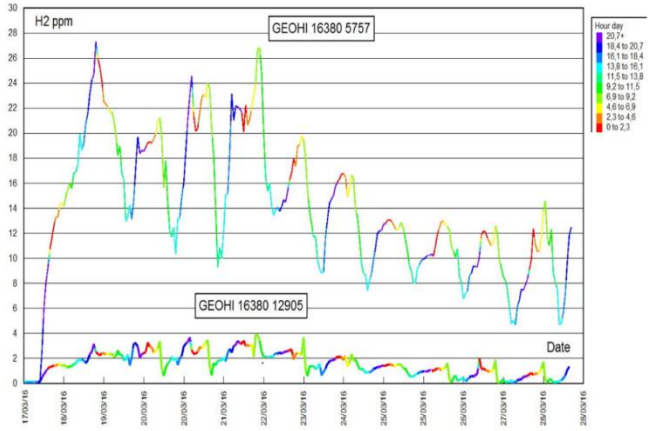


FIGURE 5: The data from station 2 situated at different node distances from the road. The pollution in a green zone is about one order less than near the automobile road.

Communication between the router and IT server used two methods: cable RS485 and GSM modem. GSM connection is unstable and influences operating stability. There are some problems in using of directional antenna because of the high level of the city's radio noises and radio interferences. Nevertheless, a number of experiments with the use of different technical solutions allowed us to perform continuous monitoring for 2 months. As a result, about 3 million data records were obtained during experimental works. This information provided an opportunity to develop the structure of database management systems to store data and the technology of online data collection from remote sensors. Using the abilities of program software, a periodical (12 hours) automatic export/import was realized. Access to files on remote computers is opened using FTP protocol. Database forms derived tables for each sensor. We use triggers to modify data, for example, to modify signals from gas sensors to gas concentration, depending on the unique sensor name.

Also, we revealed the periodicity of gas concentration with different harmonics.

We could not find in the literature similar works of H_2 monitoring in cities. Exclusion is the work of Nęcki et al. [18] to organize continued monitoring in Krakow and its neighborhood and Paris [19]. The authors also note periodicity in gas concentration affected by the seasons (increase in wintertime) and daytime (auto traffic).

In general, the hydrogen level in Krakow is 1–2 orders of magnitude lower than in Moscow, although over a long-term observation period (2008 January) maximums with similar contents of 2.5 ppm were recorded [18]. The observation station in Paris [19] recorded the same absolute H_2 contents of 0.35–1.4 ppm, with an average of about 0.55. Significant periodicity was noted for the winter-summer period. Maximum concentration in summer. Daily periodicity variation was also noted. In the Helsinki atmospheric observing network [20], unique data on hydrogen concentration of 0.5 ppm was established.

4. Conclusion

We consider that our work is one of the first experiments in the organization of long-time monitoring of cities atmosphere, using new technologies (WSN). Hydrogen concentration has proven to be an effective indicator of atmospheric pollution. A large difference in hydrogen content was found in the city center and ecologically clean areas. A sharp increase in the concentration of hydrogen in the atmosphere when approaching a highway and a daily periodicity apparently associated with automobile traffic has been established.

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