Mobile multisensor node for monitoring environmental parameters in urban areas

Marin Berov Marinov

Air quality is a matter of considerable concern as it affects public health, the environment and the economy of developed countries. Recent research has shown that air pollution can increase the incidence of diseases and impair the quality of life. It is therefore necessary to develop systems for real-time multi-parameter environment monitoring so that timely decisions can be taken. The use of such systems allows us to make a detailed study of the levels of major pollutants and their sources. Conventional monitoring systems have significant limitations, especially with respect to the cost of their installation and maintenance. Methods based on mobile handheld devices also have limitations and measurements usually are not fully automated. Advances in gas sensoric and in smart systems development have made it possible to have new low-cost, precise and accessible air quality monitoring tools. The paper presents an approach for cost effective measurement of basic environment parameters in real-time. A sensor array with integrated amperometric and NDIR gas sensors is used. Preliminary prototypes and implementation challenges are also discussed.

Мултисензорен модул за мониторинг на параметри на околната среда (Марин Беров Маринов). *Качеството на въздуха е основен проблем за общественото здраве, околната среда и икономиката на развитите страни. Последните проучвания показват, че замърсеният въздух може значително да увеличи честотата на заболявания и да влоши качеството на живот. Ето защо е необходимо разработването на системи за многопараметрично наблюдение на околната среда в реално време, които да подпомагат вземането на своевременни решения. Използването на системи за мултипараметричен мониторинг на околната среда позволява детайлно проучване на нивата на основните замърсители и на техните източници. Конвенционалните системи за мониторинг имат значителни ограничения, особено по отношение на разходите за тяхната инсталация и поддръжка. Реализациите, базирани на мобилни преносими устройства също имат ограничения и измервателните процеси обикновено не са напълно автоматизирани. Напредъкът в газовата сензорика и в развитието на интелигентните системи дават възможност на нови, достатъчно точни и достъпни инструменти за мониторинг на качеството на въздуха. В настоящата статия е представен подход за икономически ефективно измерване на основни параметри на околната среда в реално време. Реализиран е сензорен масив чрез използване на амперометрични и недисперсивни инфрачервени газови сензори. Представени са резултати от измервания с прототипи и предизвикателства при реализацията им.*

1. Introduction

Loss of environmental quality is one of the greatest threats of our century. Air pollution has been defined as the presence of particulates, biological molecules, or other harmful materials in the Earth's atmosphere; it causes diseases, death to humans, and damage to other living organisms, to food crops, or the natural or built environment. Air pollution may come from anthropogenic or natural sources [1].

Poor air quality is a growing global health problem which affects millions of people worldwide, especially in large cities. Large-scale industry, which is increasingly positioned outside of metropolitan regions and urban areas, is no longer considered the primary cause of air quality problems. Recent studies indicate that road traffic is the main source of air pollution. Road transport is responsible for an average of 25% of all harmful emissions in Europe. In many EU countries this value is higher than 30%. Thus, poor environmental quality, especially in urban areas, is one of the greatest environmental concerns of this century as it affects both health and welfare [2, 3]. Many studies show that today's increase in respiratory diseases, as compared to other related diseases and allergies, is primarily due to air pollution. According to official figures of the EU more than 225 000 people die every year from diseases caused by car emissions in Europe. To combat this threat, the European Union has introduced stricter laws and regulations and intends to reduce car emissions by 20% by 2020 [4].

Excessive noise is a further major environmental complaint in residential areas. Noise in cities has increased in the past decades, due to growing urban development and has also become an important parameter in environment quality assessment [5].

The use of real-time multi-parameter environment monitoring systems allows us to do a detailed study of the levels of major pollutants and their sources. Conventional environment parameter monitoring systems have significant limitations, especially with respect to costs of installation and maintenance [6]. Air quality is usually monitored through large and expensive sensing stations, installed at a limited number of locations. Environmental data is often provided to the public by government agencies that collect it for public health purposes. But for the citizens it is often difficult to obtain real-time pollution data. There is often a significant gap between how agencies report the data and the people who can benefit from access to that knowledge [7].

Low cost air quality sensors are indicative of emerging technologies gaining wide appeal. They exist in numerous configurations and are often available with a wide range of sensor configurations. Many of these configurations include the ability to measure gas phase air pollutants. While the commercial availability of such devices has increased dramatically in the last years, there is still uncertainty about the quality of the data that such devices provide. A number of recent studies show that low-cost sensors are a good alternative for the implementation of environment monitoring solutions [8, 9]. Select findings from these trials are as follows:

- In spite of their low commercial values (<200 Euro), many of these sensors have performance characteristics that often rival those of expensive instrumentation.
- They can be used for continuous or near-continuous environmental monitoring as they often demonstrare very fast response times.
- Many of them had a high degree of linearity over their full response range at concentrations.
- They often achieved levels of detection near those of the expensive precise instrumentation,.
- Extremes of temperature, RH and pressure often brought about undesirable response characteristics. Thus, it is necessary to measure these physical parameters and adjust the results [8, 10].

The present research is aimed primarily at the design and implementation of multi-sensor nodes with scalable architecture for mobile environmental sensing. They are based on off-the-shelf integrated sensors and can measure multiple environmental parameters and record or transmit them for further processing to other applications. The main goal is to find out if low-cost mobile monitoring sensor nodes can provide reliable data about air quality and can be used in practice. The obtained pollution measurements were compared with the official measurements made available by the local control authority [11].

The rest of this text has been organized in the following manner: Section 2 presents related work in the field of environmental monitoring; Section 3 reviews the main air pollutants, their sources and their effects on the human body. Section 4 presents the selection of sensors for measuring the concentration of the main air pollutants and additional physical parameters (temperature, humidity and atmospheric pressure). Section 5 discussess the implementation details of the mobile multisensor node for logging and monitoring of environmental parameters. Preliminary results are presented in Section 6. The paper finishes with Section 7, which summarizes the main points and outlines suggestions for further work.

2. Related Work

2.1. Indoor monitoring

Monitoring indoor air quality is important because we spend an average of 90% of modern life indoors, as reported by Jiang et al. [12], the InAir [13] and MAQS systems have been developed to address this issue.

In the InAir study the participants were provided with a stationary indoor air quality sensor for particulate matter and had access to real-time visualizations of daily graphs of the observed particulate readings at that location.

The MAQS [12] air quality system also examined the possibility of improving indoor air tracking by using mobile sensors that sampled CO_2 and interpolated VOCs (volatile organic compounds). The aim of the research was to give the people who were using the system personalized, room-level data.

A simple air quality monitoring module based on

CAN (Controller Area Network) protocol is presented by Pillai et al. [14]. CAN controller and CAN transceiver are the building elements of the sensor nodes. Each node is connected with VOC (Volatile Organic Compound) sensors, which continuously monitor environment and put sensor data into CAN bus. De Vito et al. developed an array of polymer based chemiresistors connected to TelosB motes from Crossbow Inc. Thus, a wireless e-nose for distributed air quality monitoring applications was implemented [15].

By using a wireless sensor network based on ZigBee technology Chengbo Yu et al. [16] measure temperature, soil temperature, dew point, humidity and light intensity in real time. Data to the sink node is sent by sensor nodes deployed in a greenhouse. Remote control and data download services can be provided by a sink node connected with GPRS/CDMA.

Ching-Biau Tzeng et al. [17] have described an indoor air quality (IAQ) monitoring system based on ZigBee wireless sensor network implemented with the TI CC2430 chip. In the system they propose, each sensor node measures temperature, relative humidity and carbon dioxide (CO_2). The data was acquired by running a data logger program. The test results show that the proposed system can be used for detecting harmful gases too.

2.2. Outdoor monitoring

However, our main interest is outdoor sensing. Wearable sensors have also been used to monitor air quality in this case, for instance in the *Common Sense* [18] and *CitiSense* [19] solutions. Both rely on small, battery-powered sensor nodes that measure the concentrations of polluting gases and send the data to users' smartphones via Bluetooth. This data and the GPS coordinates are then shared with other users through a dedicated website.

The CommonSense system explored outdoor sensors in a number of contexts including sensors attached to street sweeper vehicles, and hand held sensors that could be used to sample interesting outdoor locations. The utilization of street sweeper mounted sensors aimed to enlarge the existing sensor infrastructure in the city.

The CitiSense system provides desktop based, reflection supporting visualizations and "in-the-moment" visualizations that support real-time analysis [19].

In [20] a solution is proposed for generating high-resolution air pollution maps of urban areas, using nodes with sensors for particulate matter, CO, O_3, and NO_2. The nodes acquire location information through the GPS receiver, and transmit the gathered pollution measurements via a network to the back-end server.

3. Air and pollution

3.1. Main air pollutant

Certain air pollutants are widely used in estimating the level of air pollution in a lot of countries. The U.S. Environmental Protection Agency (EPA) has set the national air quality standards for six common air pollutants (also called the criteria pollutants): carbon monoxide (CO), ozone (O_3), lead (Pb), nitrogen dioxide (NO_2), sulfur dioxide (SO_2) and particulate matter (PM). These pollutants can injure health, harm the environment and cause property damage. On the basis of the measured pollutant concentrations the so called Air Quality Index (AQI) can be calculated. AQI is used by government agencies to characterize the quality of the air at a given location. Computing AQI usually requires real-time data about the air pollutant concentrations from the monitoring equipment. The function used to convert an air pollutant concentration to AQI varies from pollutant to pollutant, and is different for different countries [21, 22]. A brief summary of the main air pollutants and their sources is given in Table 1.

Table 1

Main air pollutant and their sources [2, 23].

Pollutant	Sources
CO	gas heaters, leaking chimneys, woodstoves, fireplaces, gas stoves
NO_2	kerosene heaters, unvented gas stoves, heaters, tobacco smoke
SO_2	fuel combustion (high-sulphur coal); electric utilities and industrial processes; natural sources such as volcanoes.
CO_2	gas heaters, tobacco smoke, woodstoves, fireplaces, gas stoves, automotive products

The choice of the sensors to be integrated into the monitoring system is made on the basis of these criteria pollutants. The choice of specific sensors with respective measurement ranges depends basically on the examined objects and whether the measurements will be made indoors or outdoors.

4. Sensors

There are different technologies for measuring the concentrations of the gases enlisted in the previous chapter as main pollutants. Amperometric gas sensors have been selected for this particular implementation.

The basic advantages of this type of sensors are their high accuracy and selectivity, low power consumption and low cost.

The combination of amperometric gas sensors for pollutant and oxygen measurement with sensors for precise measurement of basic physical parameters, such as atmospheric pressure, temperature and humidity make it possible to perform higher precision measurements of gas concentrations.

4.1. Gas sensors for pollutants and oxygen

A reaction in the amperometric gas sensors can be triggered by voltage supplied by an external voltage source. Implementations are also possible, where the reaction on the counter electrode is selected so as to provide the needed polarization potential for the working electrode. In this case the sensor works as a galvanic cell and needs no external voltage supply as is the case with the two-electrode oxygen sensors. Amperometric gas sensors from Alphasense were chosen for this particular implementation [24]. The sensing range, the typical sensitivity and the full scale output of the main air pollutant sensors are given in Table 2.

Table 2

Amperometric sensors for the main air pollutant [24].

Pollutant	Sensor	Full scale, ppm	Sensitivity, nA/ppm (typ)	Full scale output, μA
CO	CO-AF	1000	70	70
NO_2	NO2-A1	20	-350	7-8
SO_2	SO2-AF	20	500	10

4.2. CO_2 Sensor

There are only a few sensor technologies which are capable of detecting CO_2 at ppm concentrations with relatively high precision. Sensors have been developed on the basis of the electrochemical principle and intensive research is being done for the development of metal oxide based sensors for CO_2. Unfortunately, both technologies have significant cross-respond to other gas species and water vapour.

In recent years there has been considerable progress in the development of non-dispersive infrared (NDIR) detectors for CO_2 concentration monitoring. Nowadays the most common technology on the market for measuring CO_2 is the non-dispersive infrared technology. For atmospheric and especially for indoor concentration measurements, NDIR sensors are widely used since they are robust and stable against interference from other air components and pollutants. A commercially available model of diffusion type NDIR sensors K30 has been chosen for the present study [25]. This sensor is produced by SenseAir and has an operating range of up to $5000\ ppm$.

4.3. Sensor for particulate matter

One of the major city pollutants in the main EU cities is particulate matter and for that parameter the Sharp's PM2.5 Sensor Module DN7C3CA006 is used. The sensor is with analog output $(1 - 3.4\ V)$ and measures the concentration of fine particles with a diameter of $2.5\ \mu m$ or less in the range from 25 to $500\ \mu g/m^3$.

4.4. Sensors for basic physical parameters

As indicated above extremes of temperature, RH and pressure often resulted in undesirable response characteristics. And it is this that necessitates the measurement of these parameters in order to have effective dynamic adjustment of the readings and so increase the accuracy of the environmental sensors. The choice of sensors for the basic physical parameters is based primarily on considerations concerning the necessary accuracy levels so that sufficient compensation of the disturbing effects can be ensured.

In order to measure the basic physical parameters the following integrated sensors are selected: for relative humidity and temperature we have chosen a solution from Texas Instruments HDC1050, which has a relative humidity accuracy of $\pm 3\%$ and a temperature accuracy of $\pm 0.2°C$ and MPXA6115A from Freescale [26] for pressure measurement.

5. Hardware design

The following subsections present the implementation details of the air quality-sensing node.

5.1. Mobile node for air quality monitoring

The developed sensor node for air quality monitoring is a complete scalable system for real-time monitoring and data recording. The detailed block-diagram of the node is shown in *Fig. 1*. It comprises a main board and an expansion board. The processor and memory are located on the main board. In this design a PIC18F4533 microcontroller from Microchip is used. The other modules which are changed depending on the different application requirements are placed on the expansion board.

The developed sensor node can be used for concentration measurement of air pollutants such as CO, CO_2, NO_2. Further basic physical parameters - atmospheric pressure, temperature relative humidity and O_2 concentration - are measured.

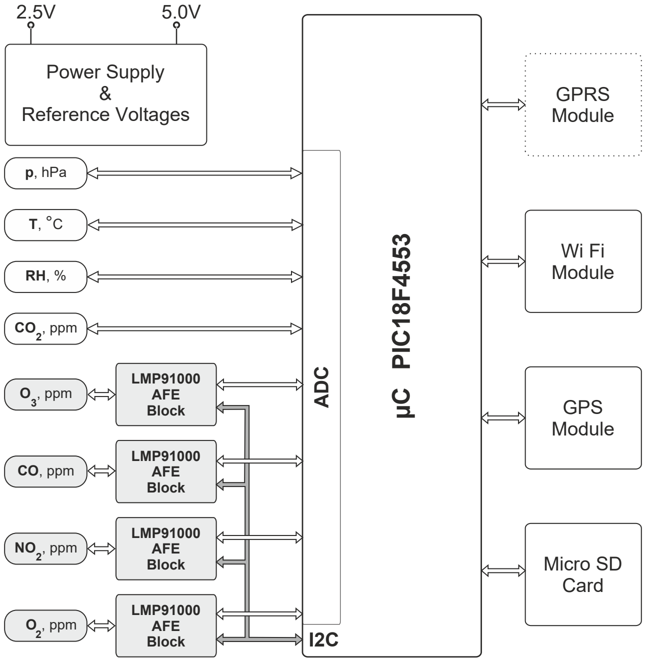

Fig. 1. Block-diagram of the developed node.

The sensors outputs are processed through signal conditioning circuits and are digitalized with the ADC built in the microcontroller. The sensor outputs are then saved together with time stamps in the micro memory card (MMC). The card is interfaced with a microcontroller using the SPI protocol. The proposed design of the sensor nodes allows for their easy modification and expansion. In a system based on a microcontroller with multiple LMP91000 connected to the I^2C bus, the I^2C lines (SDA and SCL) are shared, while the MENB of each LMP91000 is connected to a dedicated GPIO port of the microcontroller.

In addition, as an add-on module, a WiFi ESP8266 adapter is connected to the proposed system. The connection is made via an SPI interface. This adapter supports the 802.11 b/g/n standards and has an integrated TCP/IP stack.

Beside the WiFi module, the developed node has a GPS receiver with a MT3339 chipset from MediaTek. This GPS module has an accuracy of about 3 meters and allows us to find the exact location of the measured parameters. Every 5 seconds the microcontroller reads the values from the sensors, makes calculations, reads the GPS coordinates and writes a record in a simple comma separated values file to the MicroSD memory card attached to the module.

5.2. Gas sensor signal conditioning

The signal conditioning circuits for the amperometric sensors are based on potentiostatic circuit. For this implementation we have chosen the Configurable analog front-end (AFE) Potentiostat for Low-Power Sensing Applications LMP91000 from Texas Instruments [27]. A simplified functional block diagram of the AFE is shown in Fig. 2.

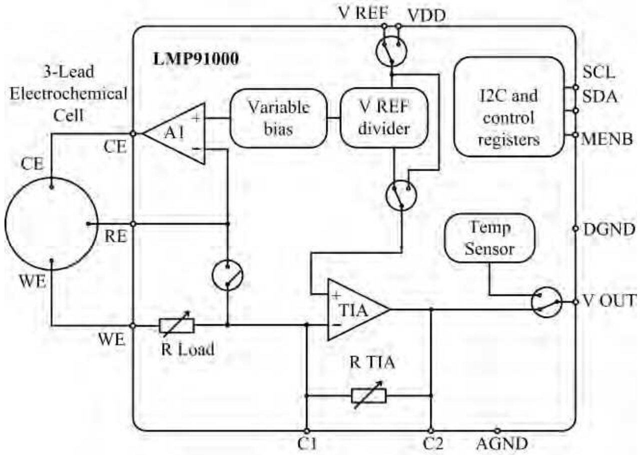

Fig. 2. Functional block diagram of LMP91000.

The LMP91000 is designed for 3-lead gas sensors and for 2-lead galvanic cell sensors. This device provides all the functionality for detecting changes in gas concentration based on a delta current at the working electrode. The LMP91000 generates an output voltage proportional to the cell current. Transimpedance gain is user programmable through an I^2C compatible interface from 2.75 $k\Omega$ to 350 $k\Omega$ making it easy to convert current ranges from 5 µA to 750 µA full scale. As described in Table 2, the LMP91000 current range completely satisfies the operating output current range of the selected sensors. The AFE is optimized for micro-power applications and works over a voltage range of 2.7 V to 5.25 V.

6. Preliminary results

Using the aforementioned module for air quality monitoring we conducted several real time tests in the urban area of Sofia, Bulgaria. The results are positioned on the map of the city and can be seen in Fig. 3. They clearly show the pollution present in the area with heavy traffic – "Sample 4" while "Sample 1" and "Sample 2" are taken in parks and demonstrate a good "green" environment. The sensor system can be installed in fixed stations or on public transport vehicles to record air pollution profiles along the vehicle routes. Depending on the available communications infrastructure the measurement data is either stored locally or transmitted in real time at certain points along the route to a remote database.

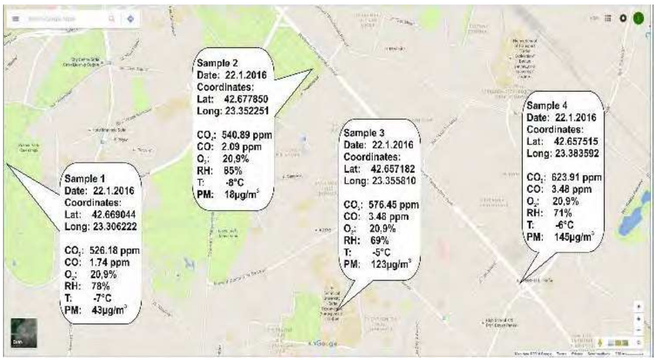

Fig. 3. Test measurements of air quality taken on 18.12.2015 in Sofia, Bulgaria.

In order to validate the preliminary results, we have compared them with the measurements obtained by the municipality environmental control authority, which are published daily and are freely available on the official website. We have used the values from the public station in Mladost district in Sofia which is closest to the experimental sensor node.

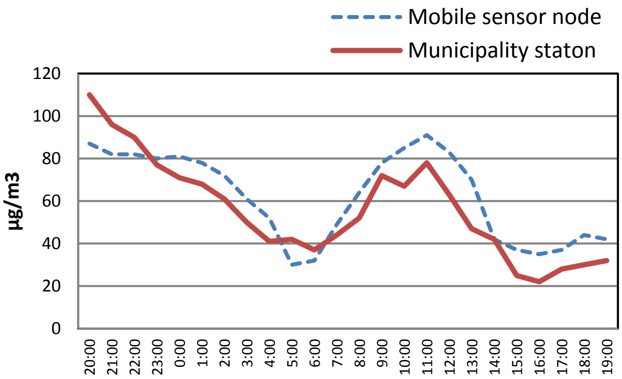

Fig. 4. Comparing the data for the daily course of NO_2 concentration measurement (averaging each hour): values provided by the municipality station and a mobile sensor node.

Fort the nitrogen dioxide concentration measurement a NO2-A42F amperometric sensor from Alphasense was used and a two point calibration was performed [24]. As it can be seen in Fig. 4, our results for the daily course of NO_2 concentration measurement closely match the values of the official municipality station.

The preliminary results of the measurements with other types of sensors show that the measurements obtained by the low-cost sensors are comparable in their accuracy with those from the official sources, and they can provide important information about air quality in a specific location.

7. Conclusion

The use of multi-parameter air quality measurement systems makes it possible to have a detailed level analysis and localisation of the main pollution sources. These measurement systems are important components in many actual Smart-City-projects [28].

This study presents the development of a mobile multisensor node for real time monitoring of important environment parameters. In comparison to other solutions described in the literature, the present solution relies on small, low-power sensor nodes, provided with long-lasting rechargeable batteries and WiFi communication modules. In this way, they can be easily moved and deployed outside, wherever there is WiFi coverage.

The node includes an array of amperometric gas sensor and basic physical parameters sensors. The usage of amperometric sensors together with a programmable analog front end for low-power chemical-sensing applications offers more advantages, such as low power consumption, low cost, fast response, ability to produce real-time measurement, etc.

It is necessary to point out that the quality of the measured data provided by the sensor nodes largely depends on the accuracy of the sensors. As technology evolves, more accurate low-cost sensors will be made available and data quality will improve. From this perspective the implemented nodes can be considered to be an evolving low-cost monitoring platform whose quality can benefit from the developments in sensor technology.

The establishment of data collection protocols involved the adoption of different approaches in order to achieve success (e.g., WiFi hot spots, SD card, proprietary web data portals). Among those were iterative upgrades to communication protocols and hardware.

In future work, we plan to add sensors for additional air pollutants measuring such as volatile organic compounds (VOCs).

REFERENCES

[1] 7 million premature deaths annually linked to air pollution. World Health Organization, 2012.

[2] U.S. Environmental Protection Agency. Air Pollution Monitoring. [Online]. Available: http://www.epa.gov/airquality/montring.html. [Accessed 09 April 2015].

[3] "Smart City-Strategie Berlin," Senatsverwaltung für Stadtentwicklung und Umwelt - Berlin, 2015.

[4] "Impact Analysis," European Commission, 2013.

[5] "Directive 2002/49/EC of the European parliament and of the council of 25 june 2002 relating to the assessment and management of environmental noise," Off. J. Eur. Communities, vol. L189, p. 12–25, Jul. 2002.

[6] ASHRAE, "Indoor environment monitoring," in ASHRAE Hand Book, Hong Kong, 2001, p. 9.1–9.20.

[7] Bales, E., N. Nikzad, C. Ziftci et al. Personal Pollution Monitoring: Mobile Real-Time Air-Quality in Daily Life. San Diego, 2014.

[8] Williams, R., R. Long, M. Beaver et al. Sensor Evaluation Report. Environmental Protection Agency, Office of Research and Development , Washington, DC, May 2014.

[9] Piedrahita, R., Y. Xiang, N. Masson. The next generation of low-cost personal air quality sensors for quantitative exposure monitoring. Atmospheric Measurement Techniques. vol. 7, 2014, pp. 3325–3336.

[10] Marinov, M., G. Nikolov, E. Gieva, B. Ganev. Improvement of NDIR Carbon Dioxide Sensor Accuracy. Electronics Technology (ISSE), 2015 38th International Spring Seminar, Eger, 6-10 May 2015.

[11] "Executive Environment Agency - Air Quality Monitoring," [Online]. Available: http://eea.government.bg /airq/bulletin.jsp.

[12] Kim, S., E. Paulos. InAir: sharing indoor air quality measurements and visualizations. CHI 2010, Atlanta, Georgia, April 10–15, 2010.

[13] Jiang, Y., K Li, L. Tian et al. MAQS: A personalized mobile sensing system for indoor air quality monitoring. Proceedings of the 13th ACM International Conference on Ubiquitous Computing, Beijing, 17–21 September 2011.

[14] Pillai, M.A, S. Veerasingam, D. Yaswanth Sai. CAN based smart sensor network for indoor air quality monitoring. Computer Science and Information Technology (ICCSIT) 3rd IEEE Int. Conference, 9-11 July, 2010.

[15] De Vito, S., E. Massera, G. Burrasca et al. TinyNose: Developing a wireless enose platform for distributed air quality monitoring applications. IEEE Sensors, 26-29 Oct. 2008.

[16] Chengbo Yu, Yanzhe Cui, Lian Zhang, Shuqiang Yang. ZigBee Wireless Sensor Network in Environmental Monitoring Applications. Wireless Communications, Networking and Mobile Computing, WiCom '09, 5th Int. Conference, 24-26 Sept. 2009.

[17] Ching-Biau Tzeng, Tzuu-Shaang Wey. Design and Implement a Cost Effective and Ubiquitous Indoor Air Quality Monitoring System Based on ZigBee Wireless Sensor Network. Innovations in Bio-inspired Computing and Applications (IBICA), 2011 2nd Int. Conf., 16-18 Dec. 2011.

[18] Dutta, P., P.M. Aoki, N. Kumar et al. Common Sense: Participatory urban sensing using a network of handheld air quality monitors. Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems, Berkeley, CA, USA, 4–6 November, 2009.

[19] Nikzad, N., N. Verma, C. Ziftci, C. et al. CitiSense: Improving geospatial environmental assessment of air quality using a wireless personal exposure monitoring system. Proceedings of the ACM Conference on Wireless Health, San Diego, CA, USA, 23–25 October 2012.

[20] Hasenfratz, D. O. Saukh, C. Walser et al. Deriving high-resolution urban air pollution maps using mobile sensor nodes. Pervasive Mobile Comput., vol. 16, 2015, pp. 268–285.

[21] U.S. Environmental Protection Agency. Air Quality Index - A Guide to Air Quality and Your Health, EPA-456/F-14-002. Office of Air Quality Planning and Standards, February 2014.

[22] "About the Air Quality Health Index," Environment Canada - Air, Ec.gc.ca. 2013-07-16, Retrieved 2015-03-20.

[23] Sukwon Choi, Nakyoung Kim, Hojung Cha, Rhan Ha. Micro Sensor Node for Air Pollutant Monitoring: Hardware and Software Issues. Sensors, vol. 9, 2009, pp. 7970-7987.

[24] Alphasense Ltd., Sensor Technology House, April 2015. [Online]. Available: http://www.alphasense.com.

[25] "CO_2 Engine K30-LP T/RH Sensor Module and OEM Platform," SenseAir AB, 2012.

[26] MPXA6115A High Temperature Accuracy Integrated Silicon Pressure Sensor for Measuring Absolute Pressure. Freescale Semiconductor Inc., 2012.

[27] Texas Instruments Inc., LMP91000 Configurable AFE Potentiostat for Low-Power Chemical-Sensing Applications, Dallas, Texas, 2014.

[28] "Department for Health and Environment of the City of Munich (Germany)," 1 Feb. 2014. [Online]. Available: http://tinyurl.com/2gg7dl.

Assoc. Prof. Dr. Marin B. Marinov *received a M.Sc. degree in Technical Cybernetics from the Technical University of Ilmenau, Ilmenau, Germany in 1985 and a Ph.D. degree in Computer science from the Technical University of Ilmenau, in 1989. Since 2001, he has been an Associate Professor at the Department of Electronics, Faculty of Electronic Engineering and Technologies, Technical University - Sofia, 8, Kliment Ohridski Blvd., 1000 Sofia, Bulgaria.*

e-mail: mbm@tu-sofia.bg.

Received on: 31.08.2015