Location based calibration of low cost particulate matter sensors

Standortbasierte Kalibrierung von kostengünstigen Partikelsensoren

Ivan P. Topalov [*]

[*] Department of Electronics, Technical University of Sofia
Sofia, Bulgaria, vantop@hotmail.com

***Abstract* —** Air pollution nowadays is reaching levels beyond the human body can live with and health issues caused by bad air quality are increasing and in particular cases leading to death. Analyzing air quality has no meaning if not backed up by real measurements. The biggest problem with measuring air quality is the price of the particulate matter equipment which sometimes goes over tens of thousands of dollars. Very often such a big investment can be afforded only by big companies or government/municipal agencies which leaves ordinary people "blind" regarding what they breathe in their residential area. This paper provides a device for measuring air particulate matter using off the shelf, low cost sensors. To improve the accuracy of the sensor data, the system localizes itself and performs calibration procedures using data from the nearest government or municipal air quality station.

***Zusammenfassung* —** Die Luftverschmutzung erreicht heutzutage ein Niveau, mit dem der menschliche Körper nicht leben kann, und Gesundheitsprobleme, die durch schlechte Luftqualität verursacht werden, nehmen zu und führen in bestimmten Fällen zum Tod. Luftqualität hat keine Bedeutung, wenn sie nicht durch reale Messungen unterstützt wird. Das größte Problem bei der Messung der Luftqualität ist der Preis der Feinstaubmessysteme, der oft mehrere Tausende Euro übersteigt. Sehr oft kann eine so große Investition nur von großen Unternehmen oder Behörden / Stadtverwaltungen geleistet werden. Diese Arbeit präsentiert ein mobiles System zur Messung von Luftpartikelnzentrationen mit handelsüblichen, kostengünstigen Sensoren. Um den erhaltenen Ergebnissen zu vertrauen, lokalisiert das System sich selbst und vergleicht die Daten mit der nächstgelegenen staatlichen oder kommunalen Luftqualitätsstation.

I. INTRODUCTION

One of the main components in the air pollution is the particulate matter (PM). PM is made of a mixture of solid particles and liquid droplets. Some particles, such as dust, dirt, smoke, are big and dark enough to be seen with a naked eye while others are so small that can be seen only through a microscope. When talking about particle sizes, PM is divided into size groups – $PM_{2.5}$ and PM_{10} are of a main importance. PM_{10} are inhalable particles which can pass through a size-sensitive inlet with diameters that are equal or less of 10 micrometers while $PM_{2.5}$ are fine inhalable particles like PM_{10} but with diameters that are equal or less of 2.5 micrometers.

The sources of the PM are diverse and the particles are made up of hundreds of different chemicals. Some of them are coming straight from a source, such as constructions areas, fields, unpaved roads and fires and other particles are formed in the atmosphere as a result of complex chemical reactions which produce sulfur dioxide, nitrogen oxides and others which are all pollutants emitted from power plants, industries and combustion vehicles [1].

The smaller the size of particles, the bigger is the impact on human's health. Small particles PM_{10} are the source of the greatest problems because they can penetrate deep into the lungs and $PM_{2.5}$ can even get into the bloodstream. Extreme and prolong exposure to such pollutants can impact human's lungs and heart and thus lead to variety of problems like premature death in people with heart or lung diseases [2], heart attacks, irregular heartbeat, asthma, respiratory symptoms like coughing and others.

Poor air quality is a growing global health problem which attacks millions of people worldwide, mainly in big cities. Big industry, which is increasingly situated outside of metropolitan regions and urban areas, is no longer considered the main cause of air quality problems. Recent studies indicate that road traffic is the primary 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].

The official monitoring networks for particulate matter are usually concentrated on a small number of locations where the measurements are made high accuracy and thus with high costs. This approach is very convenient for monitoring of long term trends of timely averaged particulate matter indexes mainly if the concentrations of the pollutants are poorly influenced by local sources of pollution. In such cases, the accuracy of the measurement equipment allows for detecting even the lowest changes of the tendencies of the main pollutants, in our case particulate matter. On the other hand, the above mentioned approach doesn't allow a complete spatial visualization of minor changes in particulate matter concentration and short term variations caused by local sources.

The use of cheap sensors is still questionable because of their error and reliability. But if somehow the output of the particulate matter sensors can be calibrated they can be accepted as a trustful solution for air quality monitoring which is the idea in the presented paper.

II. PARTICULATE MATTER MEASUREMENTS – PARAMETERS AND STANDARDS

Nowadays there is no specific standard or algorithm describing the measurement process of particulate matter because the health impact was not considered a big threat. Usually, aerosols and particles are side effect product of natural and human engaged processes and are found in different shapes, densities, chemical structures and biological properties.

A. Basic parameters

There are a number of significant parameters of PM in ambient air that should be taken into account:

- particle number concentration
- total mass concentration of selected fractions of particulate matter,
- particle size distribution,
- 24-hour variations of concentrations with peak values,
- chemical composition, etc.

Currently, the most common health applicable metric is mass related to particle size, which is represented as PM_x.

In most sources, the PM_x abbreviation is incorrectly defined as "all fine particles with size smaller than x μm". The correct definition is "particulate matter which passes through a size-sensitive inlet with a 50% efficiency at x μm aerodynamic diameter" [5].

PM limits and targets for 24 hours and annual averages differ significantly from country to country. This is shown in Table 1 which provides examples of PM standards and objectives of some countries and the World Health Organization (WHO).

TABLE I. STANDARDS AND OBJECTIVES FOR PM MONITORING IN URBAN AREAS IN SOME COUNTIES [6]

Country	**PM fraction**	**Averaging period**	**Limit /Standard μg/m³**
EU	PM_{10}	Annual	40
		24 h	50
	$PM_{2.5}$	Annual	25/20
US	PM_{10}	24 h	150
	$PM_{2.5}$	Annual	12
		24 h	35
China	PM_{10}	Annual	70
		24 h	150
	$PM_{2.5}$	Annual	35
		24 h	75
India	PM_{10}	Annual	60
		24 h	100
	$PM_{2.5}$	Annual	40
		24 h	60
WHO	PM_{10}	Annual	20
		24 h	50
	$PM_{2.5}$	Annual	10
		24 h	25

Apart from diverse national and international standards, there is the challenge that air quality varies non-linearly by locations and a by a great number of factors, such as the weather conditions, traffic, land use, etc., which affect it and make it very complicated to be modeled. In fact, unless there is a monitoring station, we do not really know what the air quality of a location is.

B. Fractions of particulate matter

The size of the particles is directly related to the potential they have to cause health problems - the finer the particles, the more difficult they are to disperse and the deeper they can penetrate into the lungs and even into the blood stream thus causing more harm. PM_{10} enters the respiratory tract, and has been associated with health risks such as bronchitis, asthma, and upper respiratory tract infections. PM_{10} magnifies symptoms of existing diseases rather than triggers new conditions.

Fine particles in the $PM_{2.5}$ size range get into the respiratory tract and can reach the lungs and the blood stream causing cardiovascular problems.

The statistics show that 7 % of the urban population in the EU-28 was exposed to $PM_{2.5}$ levels above the EU limit value, and approximately 82 % was exposed to concentrations exceeding the stricter WHO AQG value for $PM_{2.5}$ in 2015 [7].

Advances in embedded systems and new sensors technologies have made it possible for a new generation of low-cost PM monitoring systems to emerge. Portable and autonomous sensors have the potential to take measurements with sufficient accuracy and in this way to capture effectively the spatial variability of the air pollutants. The number of those commercially available devices has increased considerably over the last five years although the quality of the data which they provide is still questionable [8]. The main goal of our study is to test the quality of the data obtained by off-the-shelf cheap sensors and compare these results with those reported by the official authority stations. We want to find out whether such cost-effective systems can provide reliable results and indications about air quality and can be used in practice.

III. ARCHITECTURE OF THE PROPOSED MEASUREMENT

The overall system architecture and the design of hardware and software components are presented in details in this section.

- High reliability and availability of the device for long-term measurements.
- Ability to measure PM_{10} and $PM_{2.5}$.
- Use of off-the-shelf cost-effective components for Wi-Fi implementation.
- Computing power to perform on-board calculations, scalable architecture that supports easy expansions with peripherals and environmental parameter sensors.
- Capability for remote status monitoring, GPS localization and software updates.
- Battery powered operation

Fig. 1 shows the overall system architecture of an environmental PM monitoring system that we have developed. The system consists of a development board based on the microcontroller ESP32 with integrated Wi-Fi, a GPS module with integrated RTC, a temperature/humidity/pressure sensor and an Optical Particle Counter SDS011 for measuring $PM_{2.5}$ and PM_{10}.

The heart of the system is the System-on-Chip (SoC) ESP32 from the company Espressif [9]. Main advantage of this SoC is its price tag – between €5 and €10 depending on the peripherals included on the board. The SoC is an Xtensa LX6 dual core 32bit microprocessor with performance up to 600

DMIPS. It has an integrated Wi-Fi 802.11 b/g/n and Bluetooth connectivity. The SoC has a lot of peripherals implemented but in our case of interest are the I2C, the UART and SPI interfaces. In our particular case the board used is Wemos Lolin32 operating at 80MHz and has 4MB of FLASH memory.

For temperature, humidity and pressure is used the BOSCH sensor BME280 packed in 2.5 mm x 2.5 mm x 0.93 mm metal lid LGA [10]. This is an I2C device with a temperature range -40…+85 °C, relative humidity range 0…100 % and pressure range 300…1100 hPa. The accuracy of the temperature is ±1.0°C, the accuracy of the relative humidity is ±3 % and the accuracy of the pressure is ±1.0hPa.

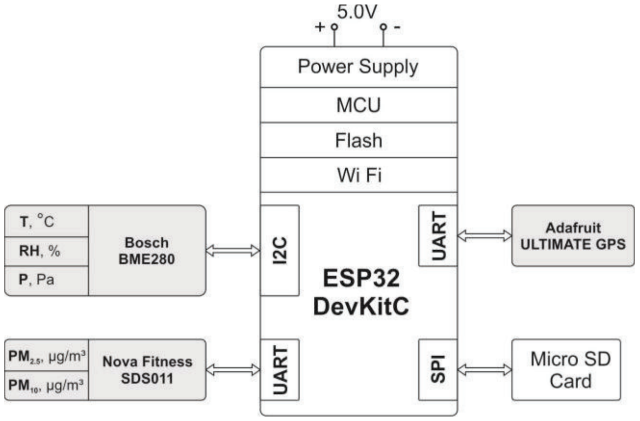

Fig. 1. Block diagram of the developed system

Regarding the particulate matter measurements we have used a low cost sensor SDS011 from the company Nova Fitness [11]. It is a counting particle device using laser scattering method. It can output via a UART the concentration of the PM particles in two sizes – 2.5µm and 10µm. The output range of both sizes is 0.0-999.9 µg/m3 with a maximum error of +/- 15%. The price tag of this sensor is around €20.

As for the location, a GPS from Adafruit is used [12]. Ultimate GPS is a very compact, with built in antenna and has a maximum update rate of 10Hz.

IV. SOFTWARE AND PROGRAM WORKFLOW

The software is developed using the Arduino IDE since the ESP32 fully supports the environment.

At the start of the program, the microcontroller initializes the Wi-Fi, the sensors, the GPS and also the SD Card. Then it sets its own real time clock using either time server on internet or time provided by the GPS. After all these procedures the software goes in measurement mode. Every minute the software measures $PM_{2.5}$, PM_{10}, temperature, humidity and pressure and records the location of the current measurement. Every hour, an average of all of the above readings is calculated and is saved to a CSV file on the SD Card together with the same readings from the closest government or municipal air quality station. The problem of finding the closest government or municipal air quality station and getting the data from it was solved using a service from the aqicn.org website. This is an information website on internet where most of the government and municipal air quality station submit their data. The website aqicn.org provides Application Programing Interface (API) through which data from any air station can be downloaded locally. One of the API functions can be used to search for the nearest station from a given latitude/longitude. Using this method the system downloads air quality data from the nearest government or municipal station using the coordinates from system's GPS. This data is saved together with the data measured by system's sensors.

V. EXPERIMENTAL RESULTS

The experimental results were conducted on 14.11.2018 at the location of the Technical University of Sofia, Bulgaria with coordinates for latitude 42.655642 and for longitude 23.356051. Using the above mentioned coordinates and with the help of aqicn.org the closest municipal air quality station was reported to be in the area of Mladost, which is roughly 2km away from our testing point. The measurements were made continuously for 24 hours, saving each hour the values for $PM_{2.5}$ and PM_{10} which are an average for 1 hour and saving them together with the data from the Mladost air quality station. As can be seen on Fig. 2 the samples of the sensor SDS011 are very close to the public environmental air quality station Mladost. The linearity of both samples (from SDS011 and from Mladost station) is equal.

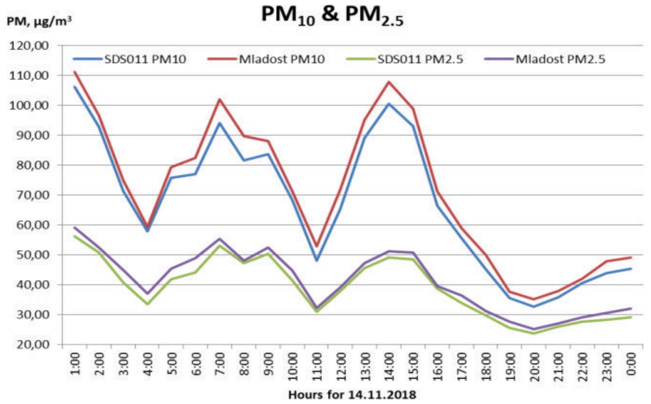

Fig. 2. Measurement results for $PM_{2.5}$ and PM_{10} taken on 14.11.2018 by the proposed system using the particulate matter sensor SDS011 and the public environmental air quality station Mladost in Sofia, Bulgaria

On Fig. 3 can be seen the error in percentage between the samples from SDS011 and the values the public environmental air quality station Mladost which can be used as references.

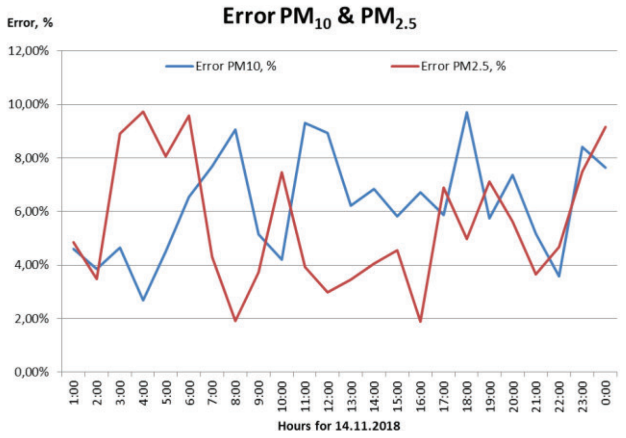

Fig. 3. Error in percentage of the measurement results for $PM_{2.5}$ and PM_{10} taken on 14.11.2018 by the proposed system using the particulate matter sensor SDS011 and the public environmental air quality station Mladost in Sofia, Bulgaria

Since the suggested particulate matter is a low coast sensor using a laser scattering method, its technical parameters need to be verified before the measurements can be trusted. As it is seen on Fig. 3 the error never goes beyond 10% for both $PM_{2.5}$ and PM_{10}. The specification of the particulate matter sensor SDS011 says that maximum error of the measurements is +/-15% and with the above mentioned results we can be assured that sensor's performance is according to the datasheet. The error is always positive which means that area of the Mladost station is dirtier than the area of Technical University where the real measurements were made assuming that the samples from the sensor SDS011 are trustworthy. The chosen date 14.11.2018 was selected amongst several other days because the weather was stable, no wind, no high humidity and the results for particulate matter from other nearby government air quality stations were nearly equal presuming the same conditions. The equipment used as a reference for particulate matter measurements in Mladost air quality station is from the company "Thermo Scientific" Model "5030 SHARP" [13]. It is a synchronized hybrid ambient real-time particulate monitor with an accuracy of +/- 5%. The results from the Mladost station are official and are collected and analyzed by the European Environment Agency. For calibrating our system we used the so called "Blind calibration" model whose idea is to reach high correspondence between all sensors in a given network. A basic condition is that nearby sensors should have almost equal readings, Fig. 4s. This method was developed at the beginning for general sensor networks and especially for temperature and relative humidity [14], [15]. In our case, we are adding an offset to our lost cost sensor which offset is the difference between SDS011 particulate matter sensor and the government air quality station [14].

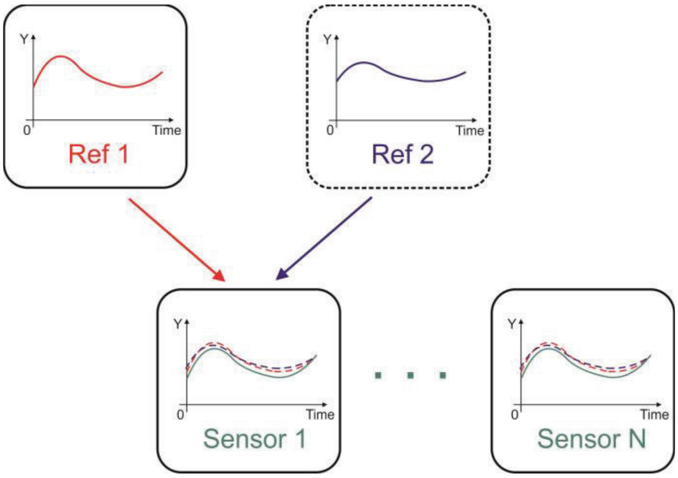

Fig. 4. Blind calibration scenario with urban sensors Sensor 1 - Sensor N and urban reference Ref. 1 and Ref. 2.

VI. CONCLUSION

From the experimental results is obvious that the use of low-cost off the shelf particulate matter sensors is reliable and after a short period of time calibration with a reliable source of samples like the public air quality stations the data can be used for further analyses of the quality of the air at the sampled location. The proposed system automatically finds the closest reference station and saves its data together with the data from the SDS011 sensor. In case of errors from the reference values of more than 10% the data can be considered untrustworthy. In the experimental test the biggest calculated error was 9.7%.

REFERENCES

[1] „Air Pollution Monitoring, [Online]. Available: http://www.epa.gov/airquality/montring.html. [Accessed 9 Novemberl 2018].," U.S. Environmental Protection Agency, 2018.

[2] „7 million premature deaths annually linked to air pollution," World Health Organisation, 2012.

[3] „Impact Analysis," European Commission, 2013.

[4] M. Jovasevic-Stojanovic, „On the use of small and cheaper sensors and devices for indicative citizen-based monitoring of respirable particulate matter," *Environmental Pollution,* том 206, pp. 696-704, 2015.

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

[6] „Air Quality in Europe report," European Environment Agency, ISSN 1977-8449, 2017.

[7] *Smart City-Strategie Berlin,* Berlin: Senatsverwaltung für Stadtentwicklung und Umwelt, 2015.

[8] E. M. Viana, „Urban Air Quality in Europe, Berlin Heidelberg: Springer-Verlag," 2013.

[9] „ESP32 datasheet," [Онлайн]. Available: www.espressif.com.

[10] „BME280 datasheet," [Online]. Available: www.bosch-sensortec.com.

[11] „SDS011 datasheet," [Online]. Available: www.inovafitness.com/en.

[12] „Ultimate GPS description," [Online]. Available: www.adafruit.com.

[13] „Thermo Scientific Model 5030 SHARP," [Online]. Available: www.thermofisher.com.

[14] Y. Wang, A. Yang, Z. Li, X. Chen, P. Wang and H. Yang, „Blind drift calibration of sensor networks using sparse bayesian learning," *IEEE Sensors Journal,* pp. vol. 16, no. 16, pp. 6249–6260, 2016.

[15] L. Balzano and R. Nowak, „Blind calibration of sensor networks," *in Proc. of IPSN. IEEE/ACM,* pp. 79-88, 2007.

[16] B. Maag, Z. Zhou and L. Thiele, „A Survey on Sensor Calibration in Air Pollution Monitoring Deployments," *IEEE Internet of Things Journal,* pp. Volume 5, Issue 6, December 2018.