



# High spatial resolution IoT based air PM measurement system

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## Abstract

Air pollution is one of the global problems of the current era. According to World Health Organization more than 80% of the people living in metropolitan areas breathe air which exceeds the guideline limits. Particulate matter, the mixture of liquid and solid particles having diameters less than 10  $\mu\text{m}$ , is one of the important pollutants in the air. The main source of the Particulate matter is mostly burning reactions associated with industry, vehicles and homes. Several studies have shown the lethal impact of particulate matter to public health and environment. The rise of particulate matter amount in air has been linked to several health problems such as not only respiratory diseases but also mortality in infants and heart attacks. Currently, bulky stations which are high-cost and have limited spatial resolution are used to monitor the air quality. In this study we developed an alternative particulate matter measurement system which is portable and low-cost (less than 200 USD) and also integrated with cloud computing. The system allows real time distant monitoring of PM particles with high spatial resolution (meter range). The developed sensor system is able to provide air quality data in correlation with the existing stations ( $R^2=0.87$ ). The statistical comparison between the developed system and the reference methods revealed that two systems produced statistically equal results in detecting the variations of the particulate matter.

**Keywords** Air pollution · Cloud computing · High spatial resolution · Internet of things · Optical sensing · Particulate matter · PM2.5

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## 1 Introduction

According to the Clean Air Act (1970) of USA there are six air pollutants; particulate matter (PM), ozone (O<sub>3</sub>), carbon monoxide (CO), sulphur dioxide (SO<sub>2</sub>), nitrogen dioxide (NO<sub>2</sub>) and lead (Pb). Environmental Protection Agency (EPA) and European Environment Agency (EEA) set the upper limits of these pollutants in air to protect the public health and the environment. The pollutant concentrations are used to determine the air quality and have to be below the limits. Unlike other pollutants, PM does not have a single chemical composition but it is a complex mixture of liquid and solid particles of different sizes and compositions. The amount of particulate matter and movement in air are dynamic, some particles act as nuclei which vapor condense around, some particles collide, adhere and fall to ground, some particles move in the air (Vallero 2015; Russell and Dyer 2017). Smaller and lighter particles are suspended in air for long periods compared to larger particles. Combustion engines, factories, burning, and mining are some of the main sources of PM (Florentina and Io 2011). PM particles usually have spherical shapes but one of the most dangerous PM is asbestos which are in the form of fibers (Sanchez et al. 2009). The particles in air mix and travel by turbulence and wind and they can travel hundreds of miles (Vallero 2007).

Exposure to PM has several health effects, and the severity depends on several factors such as duration of exposure, sensitivity of the individual and composition of the particles (Biswas et al. 2015). The main entry point of PM to human body is airways. There are filters in the airway of human body that stop the PM. For example, PM > 10 µm is accumulated in the extrathoracic region, PM between 5 and 10 µm is accumulated in the tracheobronchial region, PM < 2.5 µm is accumulated in the alveolar region (Sierra-Vargas and Teran 2012). Accumulation degree may differ based on gender, it was reported that particles between 3 and 5 µm accumulated more in women compared to men (Kim 2006). People having respiratory disease are more sensitive to particles as compared to healthy individuals (Brown et al. 2002). PM < 0.1 µm is highly toxic and can penetrate to blood stream and even translocate to central nervous system which can cause destructive effects in the body (Oberdörster et al. 2004; Terzano et al. 2010).

Since air pollution can cause serious health and environmental problems, continuous monitoring is required by laws and monitoring stations generally operated by governments are placed in the cities. By investigating the air pollution data, various financial and economic analysis were also performed (Amin et al. 2020; Dogan et al. 2020; Dong et al. 2020). The conventional air pollution monitoring stations are bulky and usually 2–3 of them installed for a mid-size city. The cost of such a station is around 6000\$–36,000\$ (Castell et al. 2017). The surrounding local factors can affect the measurements of the stations thus the data may not represent the air quality of a larger area where the station is located (Su 2018). The disadvantages of the conventional stations lead researchers to explore modeling studies to increase spatial resolution (Pollice and Lasinio 2012; Park et al. 2004; Silva Paez et al. 2005) and alternative air quality monitoring systems. The advantages of new generation devices are being low-cost, having high

spatial resolution and having a small form factor. In addition to these advantages, an air quality monitoring system should provide real time, accurate and robust measurements (Kumar et al. 2015). Usually low-cost systems focus on measuring either gas or PM measurements (Borghini et al. 2017). Beyond the sensor part, other design considerations of the low-cost systems include power consumption, data management, and sensor network. Several low-cost systems have been demonstrated in the literature. One of them is HazeWatch (Sivaraman et al. 2013), which is composed of a CO sensor, a microcontroller with built-in Analog to Digital Converter, a Bluetooth module and a battery. The measurements are transmitted to a cell phone using the Bluetooth device. Researchers also developed an app for uploading data to a database along with the GPS information. The sensor box is located on top of a car and as car traveled, air quality measurements performed. The cost of the sensor system is \$150 excluding the cell phone. Using the uploaded data on MySQL database, and estimation models, contour map of the CO concentration was obtained. The system is tested in Sydney where 15 conventional monitoring stations are located.

A similar system which is composed of an Arduino microcontroller, a Wi-Fi module, a GPS module and a CO sensor was tested together with a prediction algorithm (Sudantha and Elvitigala 2017). Another cell phone-based system, GasMobile, is introduced in Hasenfratz et al. (2012) where an Ozone sensor was connected to a cell phone through RS232-TTL interface. Ozone pollution maps were created after collecting data. A personal environmental monitoring system integrating multiple (UV, PM, Noise, Temperature and Humidity) sensors is developed and reported in Wong et al. (2014). For PM measurements, Sharp GP2Y dust sensor consisting of an infra-red emitting diode and a phototransistor is used in the device. The device has an Arduino microcontroller and Bluetooth module to communicate with the app on a cell phone. The data on the cell phone is transferred to a server. Both indoor and outdoor measurements performed with carrying the unit where six AA alkaline batteries provided 30 h usage time. The comparison of Sharp GP2Y dust sensor along with two low-cost sensors (Shinyei (PPD), Samyoung (DSM)) based on light-scattering were compared previously and findings suggest that Sharp GP2Y sensor demonstrates high linear response, precision and sensitivity (Wang et al. 2015).

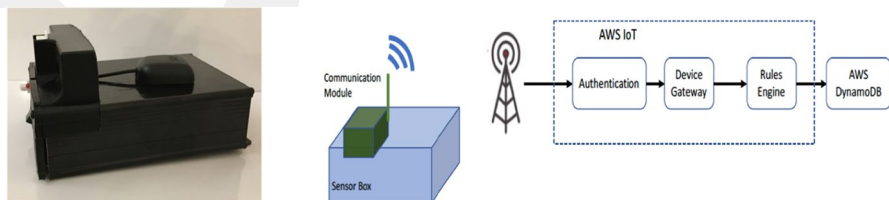
This research work contributes to the existing literature by introducing the design and implementations of the low-cost sensor box. We developed the sensor box containing Sharp GP2Y dust sensors, a microcontroller, and a communication unit. The sensor box is able to communicate with cloud computing and transmit data to a server. The measurements can be monitored real-time from a distant computer. We compared the performance of the system with a reference device both indoors and outdoors and also, we collected data to compare the results with the existing monitoring station. Our aim was to show that the developed low-cost system can provide statistically same outcome with high-cost devices in detecting the variations of PM. Even though low-cost systems have some limitations, one important capability of the developed systems is the ability of providing real time high spatial resolution data. The developed units in the future can form a sensor network and provide valuable air pollution data with meter resolution.

## 2 Materials and methods

### 2.1 System components and communication

The sensor box is composed of Arduino Uno, SIM 808 GSM/GPRS module, ESP 8266 Wi-Fi module, Lithium polymer battery and two Sharp GP2Y dust sensors. Cloud Computing has several advantages for internet of things (IoT) projects such as providing high computation power, network integration and data analysis. Amazon Web Services (AWS) provide Elastic Computing Cloud (EC2) for dynamic computing needs, and Simple Storage Service (S3) for extensible storage space which make it attractive for IoT applications (Lee et al. 2010). For the aforementioned reasons AWS was used for the cloud computing needs of this study (Fig. 1). There are mainly four communication protocols used in IoT applications, namely Message Queuing Telemetry Transport (MQTT), Constrained Application Protocol (CoAP), Advanced Message Queuing Protocol (AMQP), Hyper-Text Transfer Protocol (HTTP) (Naik 2017). Each protocol has advantages and drawbacks, e.g. HTTP, the global web protocol, has the highest message size and overhead compared to other methods. On the other hand, CoAP has the lowest power consumption and resource requirements (Naik 2017). The decision of which protocol to implement depends on the user requirements and accessibility. In this study, since a web-based user interface was designed, HTTP protocol was preferred.

The microcontroller (Arduino) runs attention (AT) commands to establish the communication between the SIM 808 module and the HTTP server. The communication process between the sensor box and the cloud computing includes these steps: (1) SIM 808 module sets GPRS connection through the sim card 2G data service, (2) Microcontroller gets GPS location info (via AT Commands) from SIM 808 module, (3) Microcontroller establishes HTTP connection (via AT Commands) to AWS API Gateway, (4) Microcontroller sends GPS location data and sensor data through HTTP connection, (5) Data is captured by AWS Lambda (Rules Engine) and inserted into AWS DynamoDB. Amazon DynamoDB is a NoSQL database service to create database tables to store the data received from the sensor box. In this project, the data includes time column Coordinated Universal Time (UTC), latitude, longitude and Particulate matter (PM) values. Once the data is received on AWS DynamoDB it can be further processed using other platforms such as Java or Python.



**Fig. 1** Image of the sensor box (width: 16 cm, height: 9 cm, depth: 11 cm) and the block diagram of the established cloud computing system

## 2.2 Verification tests

The sensor Sharp GP2Y is a low-cost dust sensor designed to measure PM<sub>2.5</sub>. In order to verify the performance of the Sharp GP2Y, comparison experiments with a reference system (Fluke 985 Airborne Particle Counter) were performed. The sensor box and Fluke were placed in a closed chamber and the vapor of solder paste was measured with both systems. The second sets of measurements were performed outdoor to measure the PM in the gases from a car's exhaust. The third measurements performed to show the capability of the sensor box and to compare the outputs of the air quality measurement station (38°43'02.3"N 35°29'12.5"E) located in city of Kayseri.

## 2.3 Statistical analysis

The reference system measured number of particles but not the density, for some experiments we had small sample size and our data did not have normal distribution. For those reasons, we choose non-parametric Mann–Whitney test. To compare two systems measuring in different units, we first normalized the data simply using Microsoft Excel Standardize function and then we used IBM SPSS to apply non-parametric Mann–Whitney tests to compare the output of the developed sensor box with the output of the reference system (Fluke) and to compare the output of the developed sensor box with the output of the conventional monitoring station. The statistical significance was considered at  $P < 0.01$  for both comparisons.

When we applied the statistical test, our hypothesis was

$H_0$  The developed sensor box and Fluke (or monitoring station) there is no statistical difference.

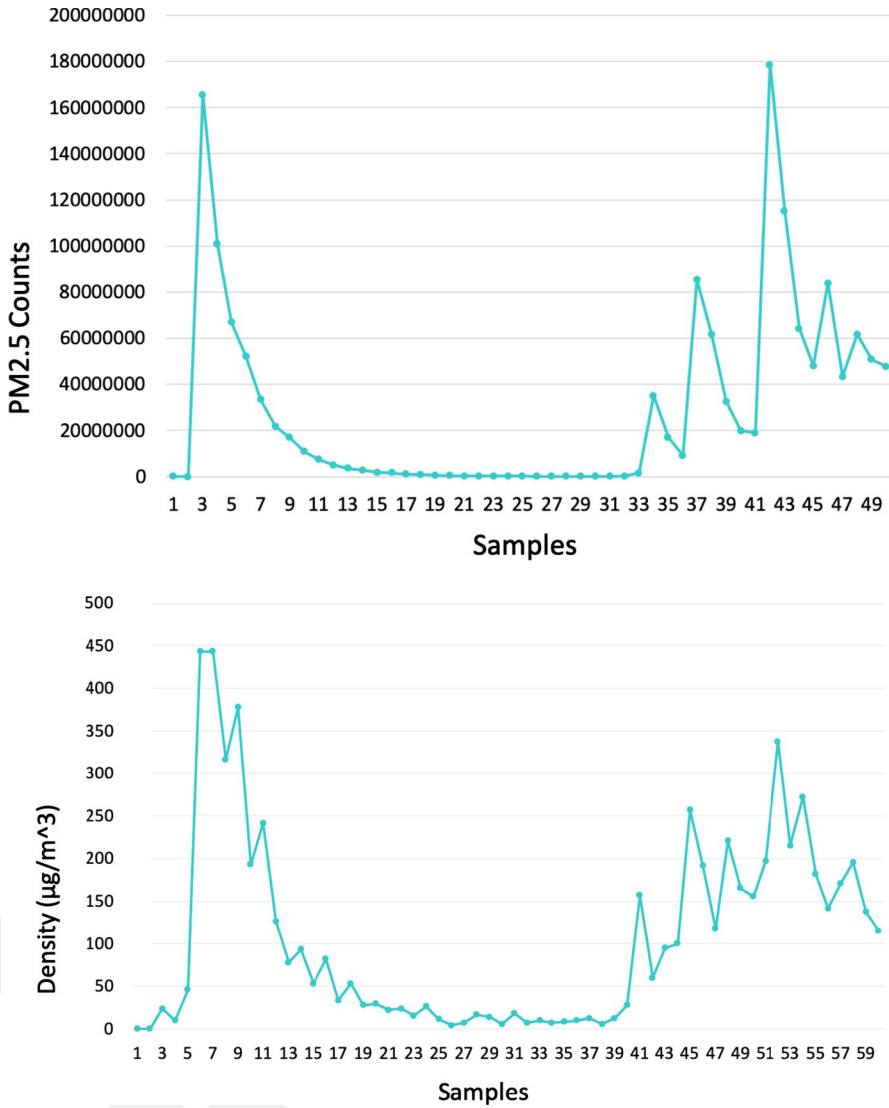
$H_1$  The developed sensor box and Fluke (or monitoring station) statistically differ.

Also reference system has a wider dynamic range, so we tested the data where the developed system is not saturated.

## 3 Results

### 3.1 Sharp GP2Y performance comparison with Fluke

The results of a closed chamber experiment are depicted in Fig. 2. The vapor of 0.1 mg solder paste was flowed in the chamber using a fan. The PM in the vapor was measured both with the Fluke and the sensor box. The sharp peaks at the beginning represent the response of the systems when the vapor source was close to the ventilating fan. Later the vapor source was slowly moved to 15 cm away from the fan



**Fig. 2** The measurements of Fluke (top) and Sensor Box (bottom) to vapor of 0.1 mgr solder paste

thus, the vapor uniformity was disturbed. As seen in Fig. 2 the Sharp sensor has a saturation level around a density of  $450 \mu\text{g}/\text{m}^3$  corresponding almost 160,000,000-part counts of Fluke.

### 3.2 Outdoor measurements

The Fluke and the sensor box were placed close and away from a car's exhaust tail pipe. The engine was run at different revolutions per minute (RPMs) and also

the position of the both sensors were changed to observe the impact of the distance (Fig. 3). The RPM was first raised to 1500 then gas pedal released for a short time and then RPM was increased to 3000 followed by release of the gas pedal.

The exhaust tail pipe measurements showed that both systems have similar response to changes in the exhaust tail pipe due to the changes of RPM and burning of gasoline. When the both sensors were close (30 cm) to the exhaust tail pipe, the Sharp sensor was saturated as it has a limited dynamic range compared to the Fluke. When both systems were placed 1 m away from the car exhaust tail pipe, it was also observed that wind blow significantly affect the distribution of PM in air. Even though the wind blow distributed the PM in air, both systems were able to detect PM variations.

To compared the performance of the system with the existing air quality monitoring station located in Kayseri, the sensor box was mounted on a car and a 6 km round trip route around the station was ridden. The collected PM measurements was compared with the stations data which is open to public online.

In Fig. 4, the monitoring station 1-h average PM data was shown as  $7 \mu\text{g}/\text{m}^3$ . The sensor box average data for approximately 30 min time frame around the monitoring station was  $10 \mu\text{g}/\text{m}^3$ . Also, sensor box can provide high spatial resolution measurements indicating the specific locations where PM levels were elevated. During the trip it was observed that at the traffic lights when cars were stopped at red light, high PM values were recorded. The monitoring station was not able to detect variations at different locations.

In order to investigate the performance of the sensor box on a day when the PM level is higher than  $50 \mu\text{g}/\text{m}^3$ , we performed a comparison measurement. The car carrying the sensor box traveled along the route shown in Fig. 5. The sensor box detected higher PM values while passing in the underpass tunnel and travelling on Osman Kavuncu Boulevard.

When the car parked close to the monitoring station for approximately 15 min, the sensor box recorded an average of  $32 \mu\text{g}/\text{m}^3$  of PM value whereas the monitoring station 1-h average data was  $91 \mu\text{g}/\text{m}^3$ . Even though the sensor box provided high spatial resolution PM measurements during the travel, the comparison with the monitoring station were not close. The main reason might be the allocated time for the samples collected around the station. The monitoring station data was for 1-h, however we collected data for 15 min. In order to test the system for a longer period of time, the sensor box was located in open air (AGU campus, coordinates 38.741498, 35.477751) and measurements recorded from 6:00 in the morning until 00:00 midnight (Fig. 6).

As seen in Fig. 6, the increase in average dust measurements after 18:00 indicates the elevated particulate matter due to the homes using stove heaters and burning of coal and also increased car traffic in the neighborhood. We also conducted measurements showing the impact of smoking indoors (Fig. 7).

When the cigarette lit up, the density of PM increased and saturated the sensor just in few seconds. The amount of PM is tremendously high in the closed room during smoking. When the windows were opened and air was ventilated through the natural wind the sensor measurements returned back to regular values.

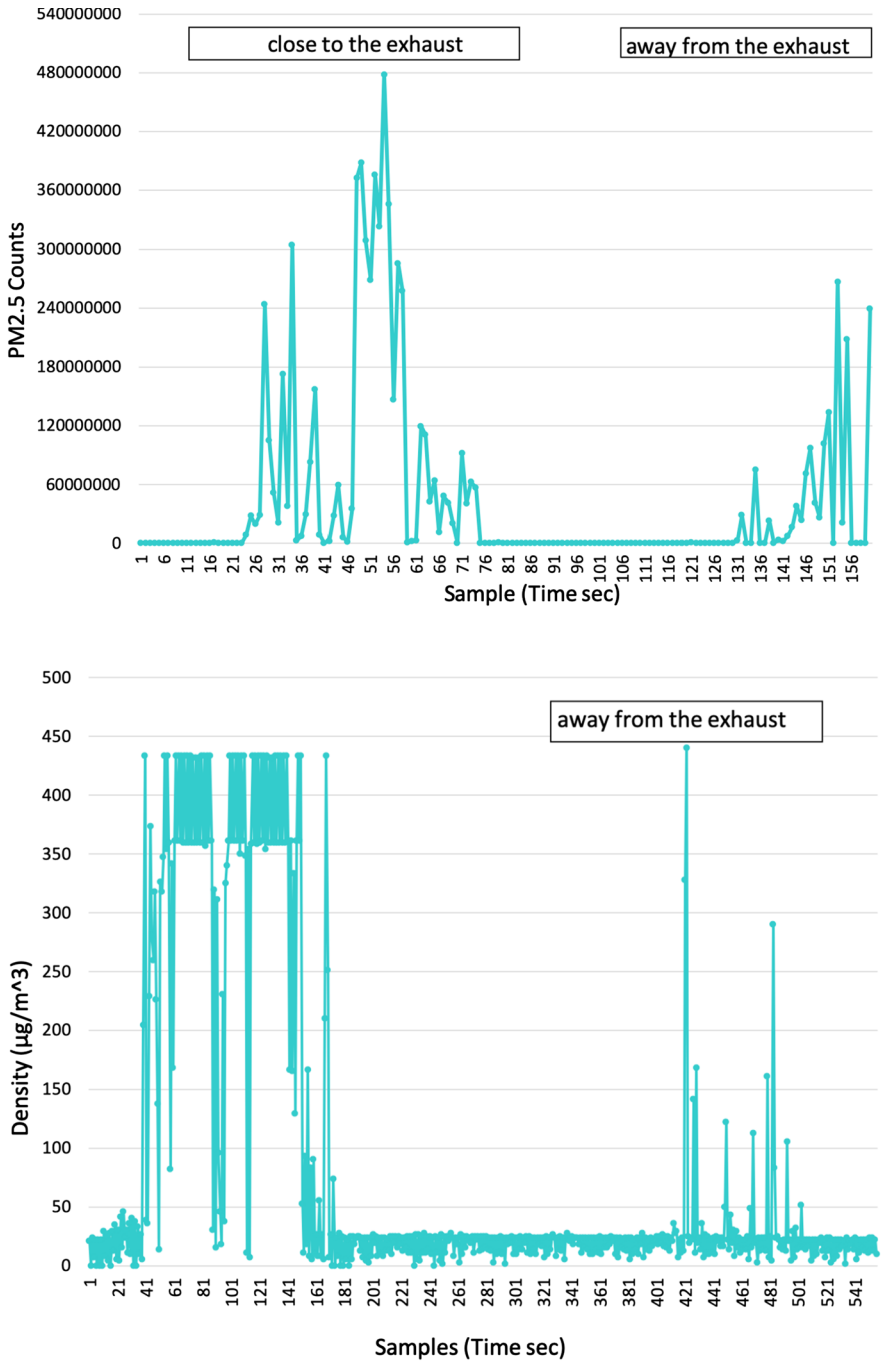


Fig. 3 The outdoor measurements of Fluke (top) and Sensor Box (bottom) around a car exhaust tail pipe

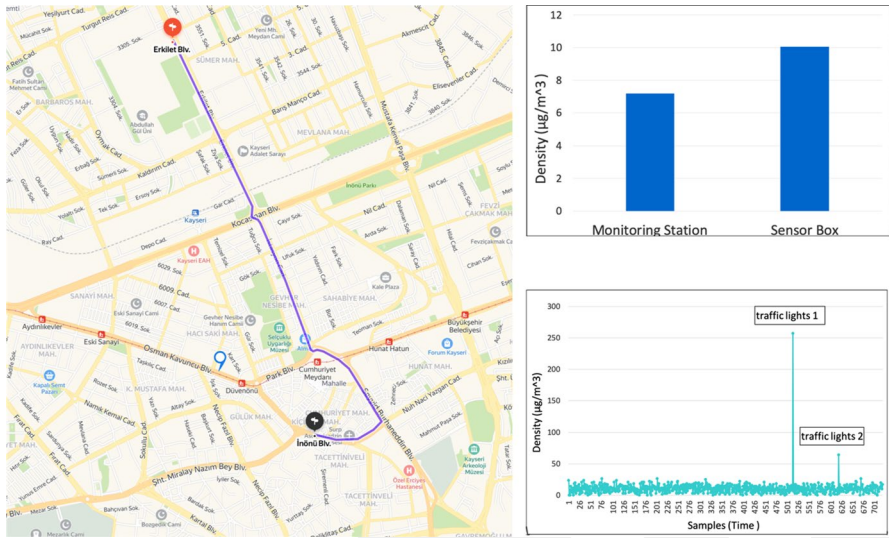


Fig. 4 The outdoor measurements of the sensor box (right bottom) and the monitoring station (right top), route 1 (left)

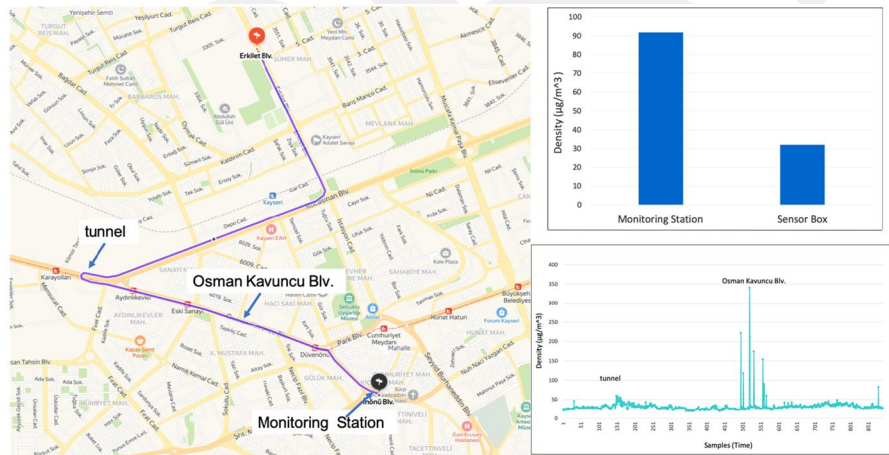
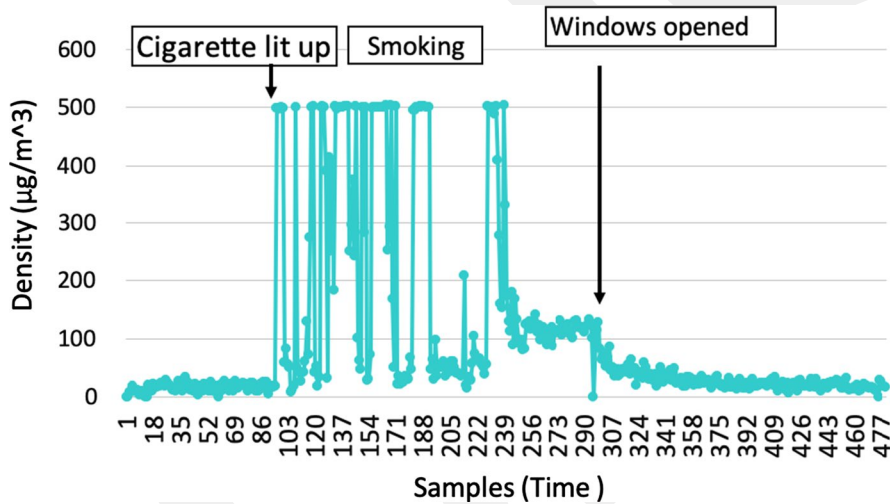


Fig. 5 The outdoor measurements of sensor box (right bottom) and the monitoring station (right top), route 2 (left)

The indoor and outdoor measurements revealed that the sensor box has high correlation with the Fluke (reference system) and responsive to the changes in the environment. Also, comparison with the monitoring stations show that the sensor box was able to detect the PM elevations in air. The monitoring station measured higher PM value but did not provide any spatial resolution. Although the sensor



**Fig. 6** Sensor box average dust measurements for a 12-h time period, an image of the neighborhood PM sources



**Fig. 7** Sensor box PM measurement of smoking a cigarette in a closed room

box measured lower PM values, it was able to provide spatial resolution and specific locations where PM levels are higher.

When we used non-parametric Mann–Whitney test to compare the output of the developed system with the output of the reference device (Fluke) (data in Fig. 2), we found that Mann–Whitney Test Statistics Asymp. Sig. (2-tailed)  $P=0.159 > 0.01$ , and there is no significant statistical difference in detecting the changes in PM amount. When we used non-parametric Mann–Whitney test to compare the output of the developed system with the output of the monitoring station (data in Fig. 6), we found that Mann–Whitney Test Statistics Asymp. Sig. (2-tailed)  $P=0.848 > 0.01$ , there is no significant statistical difference in detecting the changes in PM amount. The statistical analysis show that there is no significant statistical difference between the developed system and reference systems in detecting the variations of PM, however the dynamic range of the sensor box is shorter than the reference system and the developed sensor box needs calibration.

## 4 Discussion and conclusion

We presented an IoT based system to monitor the PM<sub>2.5</sub> in air, the portable system provides high spatial resolution measurements. The system is composed of a sensor box which houses low-cost Sharp dust sensor and GSM/Wi-Fi communication modules. Compared to the system reported in (Broich et al. 2012), our sensor box has smaller form factor and designed to be an IoT platform. The measured data was communicated real-time to a center station using cloud computing. We compared the performance of the Sharp sensors with a calibrated reference system both indoors and outdoors. Then we mounted the sensor box over a car roof to collect data, while traveling in the city of Kayseri (Turkey). We also collected the data of a monitoring station and compared with the data of the sensor box. Our measurements revealed that the low-cost Sharp dust sensor provides highly correlated measurements with the reference system. However, when compared to the reference system, the Sharp dust sensor had a lower linear range and had a saturation level less than 450  $\mu\text{g}/\text{m}^3$ . According to WHO, PM<sub>2.5</sub> level should be less than 25  $\mu\text{g}/\text{m}^3$  24-h mean for air quality (World Health Organization, n.d.), exposure to PM increases the risk factors of lung cancer and cardiopulmonary diseases (Pope et al. 2002). As a result, the communities and individuals want to access air quality data and take necessary precautions which means a paradigm change in air quality monitoring (Snyder et al. 2013). Currently, there are three air quality monitoring stations in Kayseri (Turkey), and the data from these monitoring stations only provide information for a limited neighborhood. To increase the accuracy in predicting air pollution, several modelling and analysis approaches have been reported (Lindström et al. 2014; Ignaccolo et al. 2013; Estévez-Pérez and Vilar 2013).

Previously it was shown that the low-cost systems have high correlation  $R^2 > 0.8$  with reference systems in a test environment but field tests are necessary to better characterize these systems (Li et al. 2020). In our experiments we obtained  $R^2 = 0.87$  for the measurements performed in the closed chamber which is comparable to the results reported in (Li et al. 2020). The measurements of a low-cost IoT system based on HM-3301 PM sensor were compared with a reference system (LVS3) both indoor and outdoor (Vila-real, Spain) environments (Trilles et al. 2019). This system used 3G connectivity and MQTT protocol for communication, the outdoor measurements were performed in a stationary fashion different than our system which we collected data while travelling. In a study performed in Taiwan, the data of low-cost systems and the data from conventional monitoring stations were fused to benefit from the advantages of both systems and it was shown that by applying data fusion methods the spatial resolution of stationary low-cost systems can be improved (Lin et al. 2020). A similar study was performed in Imperial Valley of Southern California (USA) where the data of twenty low-cost stationary monitors were used to estimate the spatial distribution of air quality (Ahangar et al. 2019). In another study performed in Southampton (UK), six stationary IoT devices were located across two school districts (Johnston et al. 2019). The total cost of a single unit was approximately 900 USD which included four different PM sensors, a Raspberry Pi as the microcontroller and LoRaWAN network module for communication. In a study

performed in Graz (Austria), three communication networks LoRa, Sigfox and NB-IoT were compared as the building block of air quality measurement systems and NB-IoT was considered as it is supported by communication business (Knoll et al. 2018). When compared with the previous similar works, in our approach, the low-cost sensor box is not stationary but mobile and the cost of the system is approximately less than 200 USD. In the future we would like to implement data fusion methods to test if there is any improvement in the data reliability and explore the NB-IoT. We would like to further develop a network of many sensors and analyze the data. The high spatial resolution air pollution data from such a sensor network would provide a street level resolution and indicate the pollution sources so that preventive actions can be taken. It would also change the financial and economic analysis, since the resolution of air pollution data is increased, the financial analysis can be extended further from city level to district level or even street level.

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