Sensors & Transducers, Vol. 250, Issue 3, March 2021, pp. 1-9

Sensors & Transducers
Published by IFSA Publishing, S. L., 2021
http://www.sensorsportal.com

A Calibrated Intelligent Sensor for Monitoring of Particulate Matter in Smart Cities

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Received: 4 February 2021 /Accepted: 5 March 2021 /Published: 31 March 2021

Abstract: Air pollution is directly related to both the cause and aggravation of various diseases and the cause of ecological damage to the environment. According to the World Health Organization (WHO), 4.2 million deaths are attributed to air pollution each year and 91 % of the World's population lives in places that exceed the indicated air quality limits. In this work, an intelligent and compact wireless sensor for air pollution monitoring is presented having as main target to alert the population and to allow certain control of pollutants emissions by governing authorities. The proposed wireless intelligent sensor monitors Particulate Matter (PM) using the cheap and compact PPD42NS sensor, which uses light scattering to measure particles concentration. To consider the PPD42NS sensor as the PM sensor to the proposed wireless sensor, a calibration process was conducted using as the reference equipment the HiVol HVS 3000, fabricated by the Ecotech and approved by the EPA as a Federal Reference Method. After the calibration process, the PPD42NS shows to be very effective to measure PM concentration in real time allowing the proposer wireless sensor to compute the Air Quality Index (AQI) in the area it is deployed. Another result takes the PPD42NS power consumption in consideration and points out a possible approach to reduce it, namely, eliminating its electronic circuit. The conclusion is that just 5% of power consumption is achieved with this solution since the most responsible for the consumption is the heater resistor.

Keywords: Air quality, Particulate matter, PPD42NS sensor, HiVol HVS 3000.

1. Introduction

Air pollution is a major environmental issue associated with several diseases in humans and being the cause of millions of deaths worldwide annually [1]. In addition, air pollution also is responsible for ecological damage to the environment [2]. The World Health Organization (WHO) has estimated that 4.2 million deaths are attributed to air pollution each year and 91 % of the World's population lives in places that exceed the indicated air quality limits [3].

Outdoor air pollutants have complex chemical and their physical features are direct dependent on their sources, which can be from human activities, such as industrial and vehicles emissions, agricultural activities or natural hazards [4].

The pollutants presented as inorganic forms that cause the greatest health concerns are Particulate

Matter (PM), Ozone (O_3), Nitrogen Dioxide (NO_2), Sulfur Dioxide (SO_2), Lead (Pb), and Carbon Monoxide (CO) [3]. In developing countries, due to their huge industrialization, the main sources of atmosphere pollutants including the means of transport, such as cars and trucks, and industries [5].

Several studies have demonstrated the negative health effects related to PM emissions [6, 7]. PM can cause numerous health damage as it can be deposited in various sites of the respiratory system and in the bloodstream, and, as a result, it is associated with serious respiratory and cardiovascular problems [8]. In addition, emissions of PM into the atmosphere have been contributing to global warming, climate change and air pollution increase [8].

PM is formed by solid and liquid micro-sized particles from different sources, such as carbon-centered and secondary inorganic combustion. According to the U.S. Environmental Protection Agency (EPA), PM can be classified in three different categories according to its diameter:

- TSP (Total Suspended Particulate Matter): particles with aerodynamic diameter less than or equal to 50 µm;
- PM_{10}: Inhalable Particles with aerodynamic diameter particles less than or equal to 10 µm. When inhaled, they can pass through the body upper airways;
- $PM_{2.5}$: Fine Inhalable Particles with aerodynamic diameter less than or equal to 2.5 µm. When inhaled, they can pass through the body lower airways, settle in the lungs and cause great health risks.

For average concentration of $PM_{2.5}$, PM_{10}, and TSP, EPA defines the 24-hour reference period as the basis for assessing the risk for PM.

In general, PM measuring devices are based on the following methods: gravimetric, microbalance, and optical [9] as shown in Fig. 1. The gravimetric method consists of a quantitative analytical method based on the difference between the final and initial value of the mass of the particles collected by a filter in a pre-defined sampling period [10]. The gravimetric method is defined as the reference method for measuring PM concentration by EPA.

In the microbalance method, the particles are deposited on the surface of an oscillating device and the MP concentration value can be obtained based on the modified oscillation period [11].

Considering the optical method, there are three types for measuring concentration of MP according to the interaction of the light behavior through the particles, namely: light scattering, light absorption, and light extinction, as pictorially shown in Fig. 2. In the light scattering method, when the incident light beam hits the particles, they are dispersed in several directions. In light absorption, a part of the light on the particles is absorbed and can be transformed into another form of energy, such as heat, and the PM concentration can be measured by particles heating and light attenuating [11]. Finally, light-extinction based PM concentration measurement is obtained from the difference between the incident and the transmitted light through the particles and the PM concentration is obtained from the fraction of the incident light that hits the receiver (opacity meter) [9].

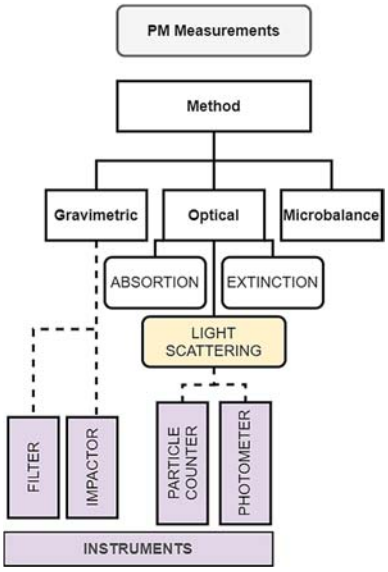

Fig. 1. Methods and instruments for measuring PM concentration [9].

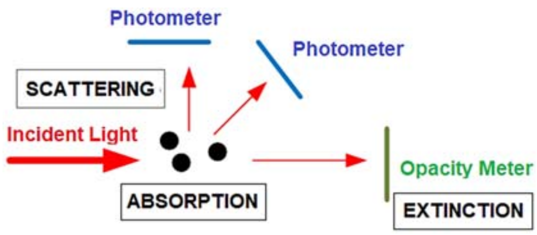

Fig. 2. Optical methods for PM measurement [11].

In a practical point of view, acquiring environmental data by monitoring techniques are needed to assess air pollution in the environment and the results of such actions are very important to government for environmental policy making. However, particularly in developing countries, air pollution monitoring stations are rare since they are very expensive to deploy and to maintain. Low-cost sensor-based approach can be of helping in this context. In addition, despites their precision, a large amount of them deployed around a given area, for instance, a city or a portion of it, can form a spatially distributed air pollution monitoring making possible to identify specific places and times with higher levels of emissions and, then, adopt local strategies to reduce the levels of pollutants. In this scenarios, Internet of Things (IoT) may be a very interesting approach.

IoT is a paradigm that allows several kinds of interaction actions between real-life objects (called “things”), embedded with sensors, microcontrollers and radio transceivers, share data wirelessly to the internet [12] making them able to communicate autonomously with each other and also with the users [13] for getting data and, optionally, make decisions.

For distributed environmental monitoring, IoT is a solution for sharing data of environmental variables in real time [14] such as PM concentration, temperature, atmospheric pressure, humidity, harmful gases concentration, etc. and also computing the Air Quality Index (AQI).

A limitation of an IoT solution for real-time air quality monitoring systems is the calibration of the used sensors [15], mainly, when low-cost sensors are taken in consideration to guarantee some level of data quality.

Although, low-cost sensors have low accuracy for certain applications, they can be considered suitable to provide information on levels of environmental pollution [16]. In this way, low-cost sensors must be evaluated according to the applications and the application needs for high or low precision. On the other hand, air quality can be assessed in several sites covering a large area by using an adequate number of low-cost sensors [17].

There are some alternatives for low-cost environmental monitoring and several commercial sensors for measuring PM. One of them is the PM sensor model PPD42NS, which is based on light scattering method. However, the use of such a sensor has to be validated through calibration against to a Reference Method approved by an environmental agency, like the EPA/ EUA, to verify the quality of the data.

The main objective of this work is to evaluate the performance of the PPD42NS sensor as the PM sensor to a proposed wireless sensor for distributed PM monitoring where a calibration process was conducted using as the reference equipment the HiVol HVS 3000, fabricated by the Ecotech and approved by the EPA as a Federal Reference Method. In addition, some considerations about the PPD42NS power consumption are taken and possible solution to reduce it is addressed.

2. PPD42NS PM Sensor

A low-cost PM sensor unit fabricated by SHINYEI Technology is the PPD42NS that is based on the light scattering method [18]. The sensor is capable to detect particles continuously and consists of three main parts: an Infrared LED (IRED) and a phototransistor (PT), as seen in Fig. 3, and a signal condition electronic circuit, shown in the Fig. 12. The air flow is self-aspirated by means of a built-in heater resistor that drive external airborne particles into the sensor enclosure from the bottom inlet towards the top outlet, as seen in Fig. 3, and when the IRED emits infrared light beam that hits the particles, they scatter the incident light and part of them are sensed by the PT.

The signal condition electronic circuit of the PPD42NS converts PT output signal into a pulse output that corresponds to the concentration per unit volume of particles measured. Specifically, to get the PM concentration from the sensor, it is needed firstly to compute the ratio between the LPO (Low Pulse Occupancy) time, which corresponds to the cumulative time at low level, and the a given time period, normally, 30 seconds, as shown in Fig. 4. After this and using the computed ratio, it is possible to find the corresponding PM concentration value using the characteristic curve provided by the manufacturer.

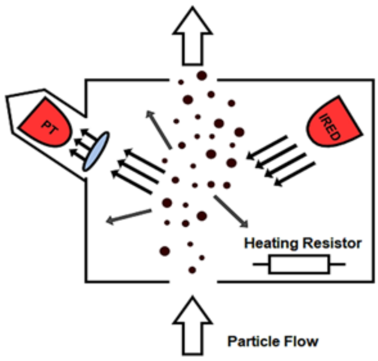

Fig. 3. Light scattering method used in the PPD42NS sensor [19].

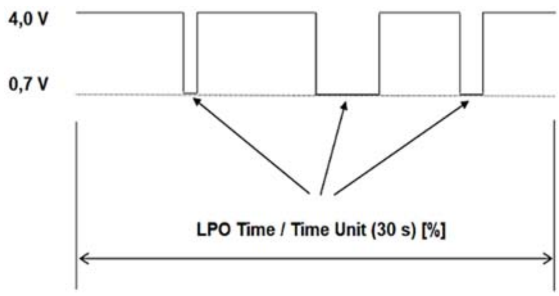

Fig. 4. Low Pulse Occupancy (LPO) [20].

The smallest particle diameter that can be detected by the PPD42NS is 0.5 µm and it is an adequate alternative to estimate PM concentration levels in environments exposure to air pollution when calibrated against a reference equipment [21]. As humidity can influence measurements from PPD42NS sensor since at humidity levels above 90 %, its measurement is affected [19] as the water particles absorb part of the infrared radiation, reducing the light intensity received by the phototransistor and interfering with the operation of the sensors circuit. For this reason, the das sensor BME680 from Bosch Sensortec was used as it measures relative humidity and other variable: barometric pressure, ambient temperature and some Volatile Organic Compounds (VOC) gases.

3. HiVol 3000 Reference Equipment for PM Measurement

The HiVol HVS 3000 equipment is fabricated by Ecotech Pty Ltd and is a particulate sampler and performs remote unattended sampling of $MP_{2.5}$, MP_{10} or PTS and others basic meteorological parameters. It presents the following dimensions: 380 mm (W) x 380mm (D) x 1200mm (H), and is shown in Fig. 5. The HiVol 3000 allows to sample $MP_{2.5}$, MP_{10} or PTS depending on the particle separator mechanism [22] and holds approval of the U.S. EPA as a Federal Reference Method.

The first stage of the HiVol 3000 is the air sampling where an electronic volumetric flow control system, using acceleration nozzles, maintains a constant air flow to collect a representative sample of particulate matter. In the acceleration process, the heavier particles gain greater momentum and are trapped on an impact plate with a greased surface to stick them. After this first stage, only the smallest particles are left and dragged to the second stage through a porous-material filter that collect the remainder particles [22].

Fig. 5. A picture of the HiVol HVS3000 particulate sampler [22].

After a pre-determined sampling period, generally, 24 hours, the filter, with the accumulated particles deposited on it, is weighed to measure the final mass of the filter after the sampling period, M_f, and the PM concentration, PM, can be computed by the following equation:

$$PM = \frac{(M_f - M_i)\cdot 10^6}{vol}, \tag{1}$$

where PM is the PM concentration in µg/m³, and M_i, the initial mass of the filter before the sampling period, 10^6 means the conversion to µg and vol is the total volume of air sampled in m³.

It is important to highlight that the weighting process and the computation of the PM concentration by using the HiVol HVS 3000 is manually accomplished.

4. The Intelligent Sensor for PM Monitoring

The developed compact and low-cost intelligent sensor scheme for PM monitoring and measurement of others basic environmental parameters is presented in Fig. 6. The intelligent sensor is composed of PM sensor PPD42NS and the BME680 sensor for environment variables, such as ambient temperature, humidity, barometric pressure, and VOC gases. An ARM Cortex MO+ is used to process the sensor signals and a LoRa-communication transceiver (TX) is used to transmit sensor data to a receptor module (RX), which can be interconnected to a PC computer by a USB connection.

Both the processor and the transceiver are part of a development board from Adafruit, called Feather M0 RFM95. The intelligent sensor is powered by a battery charged by a 6 V / 2 W solar panel. LoRa-communication solution has been chosen because it allows the sensor to be deployed in a very large distance (≈ 3 km) from the receptor module.

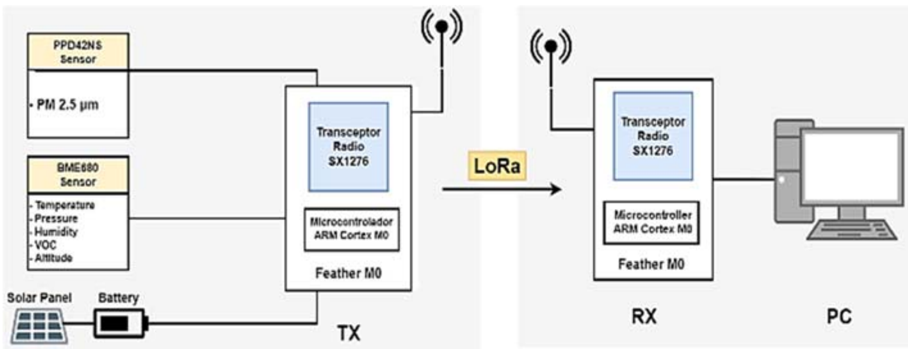

Fig. 6. Transmitter and receiver connections.

The sensors (PPD42NS and BME680) are enclosed into a climate shelter formed by a pile of plates to let air flows thought them and protect them from rain. The electronic parts of the intelligent sensor are enclosed IP66-protection-level case, as shown in Fig. 7.

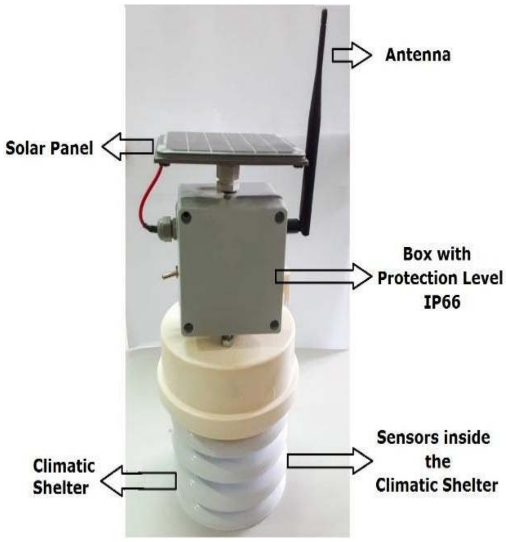

Fig. 7. Portable sensor for monitoring particulate matter and environmental variables.

In the Table 1, it is described the basic algorithm running in the sensor processor to acquire a set of measuring data along 3 minutes with steps of 30 seconds.

This approach has been used to reduce the number of transmissions and, consequently, reduce power consumption decreasing the use of the LoRa radio. In this way, after each 3 minutes, the set of data is transmitted: PM_{30}, PM_{60}, PM_{90}, PM_{120} PM_{150}, PM_{180}, where PM_t is the PM2.5 concentration at the time $t = \{30, 60, 90, 120, 150, 180\}$ and the BME outputs (ambient temperature, humidity, barometric pressure, and VOC gases) in a single LoRa package. However, despite this transmission rate, the sampling rate is 30 seconds.

Table 1. Algorithm for Sensors Reading and Transmission.

Algorithm: Sensors Reading and transmission.
{Step 1} Reset the Timer
Wait 30 seconds
{Step 2} Read the PPD42NS and save as PM_{30}
Wait 30 seconds
{Step 3} Read the PPD42NS and save as PM_{60}
Wait 30 seconds
{Step 4} Read the PPD42NS and save as PM_{90}
Wait 30 seconds
{Step 5} Read the PPD42NS and save as PM_{120}
Wait 30 seconds
{Step 6} Read the PPD42NS and save as PM_{150}
Wait 30 seconds
{Step 7} Read the PPD42NS and save as PM_{180}
Read the BME680
{Step 8} Transmit $PM_{30}, PM_{60}, PM_{90}, PM_{120}$ PM_{150}, PM_{180} and BME outputs
{Step 9} Go back to Step 1

Fig. 9 shows the obtained PM2.5 data obtained during 4 days. As can be observed the higher PM2.5 concentration values occur from 6 am to 3 pm, approximately, and the highest near 12 noon when the local temperature is the highest and humidity is the lowest. The field experiment took place in the city of João Pessoa in northeastern Brazil. On the weekend, it is possible to observe that the PM2.5 concentration decreases compared with the other days and even more notable on Sunday when the movement of people and vehicles is reduced.

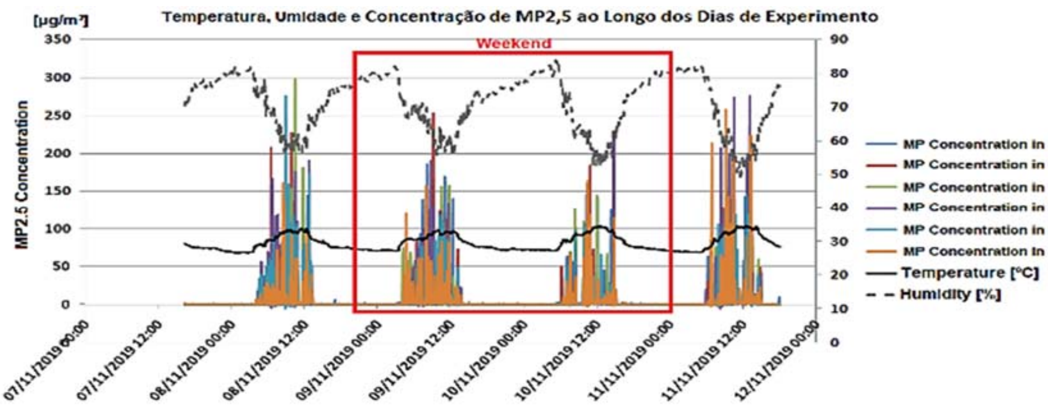

Fig. 9. Concentration data of $PM_{2.5}$ during the days of the field experiment.

5. Results and Discussion

The HiVol 3000 provides data on a daily base, that is, a PM2.5 measurement is obtained every 24 hours as preconized by EPA that defines 24-hour reference time period for PM risk. In a practical point of view, the filter of the HiVol3000 is weighted and changed at 5 pm every day of the experiment and the considering 24-hour time period if from 5 pm of the day to 5 pm of the other coming day. Therefore, the same time period was considered to compute the 24-hour-basis PM2.5 concentration using the PPD42NS.

To convert the 30-seconds measurement values during 24 hours to a 24-hour-basis PM2.5 concentration, PM_{24}, the Eq. (2) was used:

$$PM_{24} = \frac{\sum_{k=1}^{n}\left(PM_{30}^{k} + PM_{60}^{k} + PM_{90}^{k} + PM_{120}^{k} + PM_{150}^{k} + PM_{180}^{k}\right)}{6n}, \quad (2)$$

where n represents the number of receiver packets in 24 hours and PM_t^k, the PPD42NS reading as describes in Table 1, at a k sample.

The experimental results for the average daily PM2.5 concentration of the HiVol3000 and the PPD42NS sensor are in the Table 2.

Table 2. Experimental obtained measurement values.

Day	Reference Equipment HiVol 3000 (μg/m³)	PPD42NS Sensor (μg/m³)
1	10.345	7.558 ± 0.725
2	10.681	7.347 ± 0.715
3	7.838	5.057 ± 0.763
4	10.969	8.112 ± 0.881
Average	9.958	6.483 ± 0.771

5.1. Calibration Curve

Taken in consideration the data from the Table 2, the calibration curve was obtained by using the *polyfit* function of Octave tool, in which returns the coefficients of the polynomial that best fits the data. The obtained calibration curve was the first-order polynomial $y = 1.278x + 0.983$ and the curve is shown in the Fig. 10.

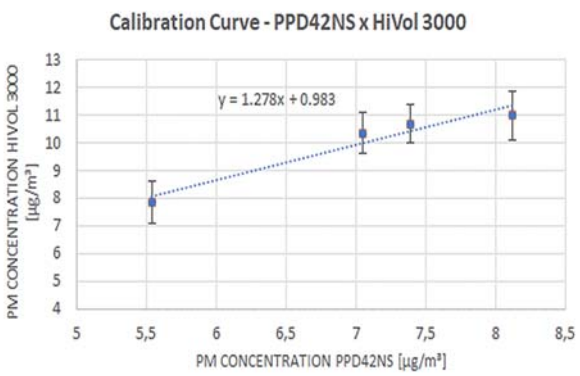

Fig. 10. Obtained calibration curve: PPD42NS sensor *versus* HiVol3000.

5.2. Air Quality Index (AQI)

The obtained PM2.5 concentration measurement values obtained from the calibrated PPD42NS sensor can be used to compute the Air Quality Index (AQI) to provide the people a simplified air quality information at a given site, and varies from 0 to >200, which is categorized in 5 Quality Level: N1, N2, N3, N4, and N5. The higher the AQI value, the worse the air quality, for example, N5 indicates poor air quality, and N1 means good air quality, that is, no impact on health. The categories of AQI and its different impacts on human health are summarized in Table 3.

Table 3. Air Quality Index categories and their different health impacts [23].

Quality Level	AQI	Health Effects
N1 Good	0-40	It has no effect on health.
N2 Moderate	41-80	People from sensitive groups (children, elderly and people with respiratory and heart disease) may experience symptoms such as dry cough and tiredness. The population, in general, is not affected.
N3 Bad	81-120	The entire population may experience symptoms such as dry cough, tiredness, burning eyes, nose and throat. People in sensitive groups can have more serious health effects.
N4 Very Bad	121-200	The entire population may experience worsening symptoms such as dry cough, tiredness, burning eyes, nose and throat and shortness of breath and wheezing. Even more serious effects on the health of sensitive groups.
N5 Hazardous	>200	The entire population may present serious risks of manifestations of respiratory and cardiovascular diseases. Increase in premature deaths in people from sensitive groups.

The AQI is a dimensionless value that represents the concentration of pollutants in the atmosphere and is computed using the Eq. (3) given as follows:

$$AQI = I_{ini} + \frac{I_{fin} - I_{ini}}{C_{fin} - C_{ini}}(C - C_{ini}), \quad (3)$$

where

- I_{ini}: Index value that corresponds to the initial concentration of the range;
- I_{fin}: Index value that corresponds to the final concentration of the range;
- C_{ini}: Initial concentration of the range where the measured concentration is located;
- C_{fin}: Final concentration of the range where the measured concentration is located;
- C: Measured pollutant concentration.

The AQI was also computed considering the PM2.5 data of the PPD42NS sensor obtained during the 4 days of experiment shown in the Fig. 9.

Fig. 11 shows the computed AQI calculated during the days of the experiment and the colored horizontal lines indicates the AQI quality levels. It can be observed that the great majority of the time the air is good or moderate, and sometimes the air is very unhealthy (above he purple line).

6. PPD42NS Power Reduction

The circuit diagram of the PPD42NS is shown in the Fig. 12 where can be seen the Infrared LED (LED1), the phototransistor (PIC1), and the heating resistor (RH1=100 Ω). The PM sense signal is at the test point, TP16, that is input to the signal conditioning circuit based on operational amplifiers forming filtering stage (*a* and *b*) and 2 comparators (*c* and *d*). The outputs of these comparators are P1 and P2 that digitally indicate the PM concentration of particles whose size is around 1 µm or larger and 2.5 µm or larger, respectively, as shown in Fig. 4.

The attempt to reduce the PPD42NS power consumption came from the premise that the OpAmp-based signal conditioning circuit can be bypassed or eliminated since normally the PPD42NS is interconnect to an embedded ADC of the used microcontroller-based SoC (System-on-Chip).

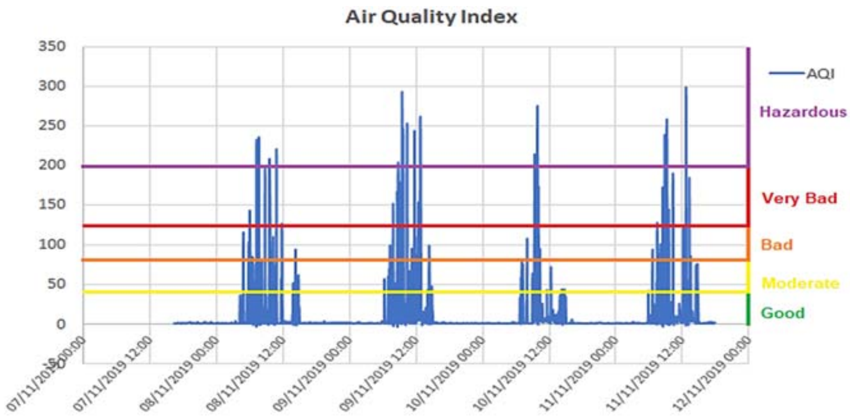

Fig. 11. Air Quality Index (AQI) during the days of the experiment.

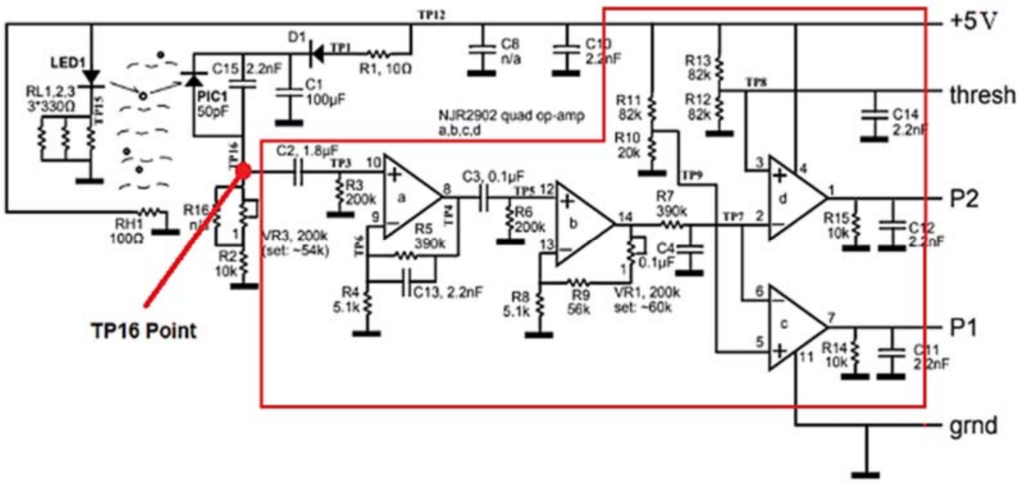

Fig. 12. Schematic diagram of the PPD42NS [24].

In this way, the TP16 signal is directly connect to a 12-bit ADC input and the filtering stage and comparators can be digitally processed by the microcontroller using a first-order type IIR digital filter and comparator code.

To evaluate the PM2.5 concentration measurement based on the TP16 signal with digitally processing and compare it with the PPD42NS Sensor Response.

In laboratory, in order to create different levels of PM2.5, an amount of some paper sheets was burned to generate the particulate. This laboratory experiment began with a certain amount of paper sheets burned at a determined distance from the PPD42NS sensor. After this, the same experiment is conducted but with the double amount of paper sheets. This last step was carried out more three times. Table 4 describes the amount of paper sheets in the four stages of PM generation. Between the end of a stage to the following one, 10 minutes was waited to clean the air.

Fig. 13 shows the TP16 signal with digitally processing (blue line) and the PPD42NS Sensor Response (red line). As can be observed, the signals are very similar and, as a result, to eliminate the PPD42NS signal conditioning circuit is possible option to reduce power consumption or even its cost.

The issue after proving that it is possible to eliminate PPD42NS signal conditioning circuit and still be possible to accomplish PM2.5 measurement is to evaluate the power consumption reduction. For this, the PPD42NS sensor was simulated using the software Proteus, as seen in Fig. 14. The simulation result showed that the current of the PPD42NS sensor is 90 mA and it without the signal conditioning circuit is 84.8 mA, result in power reduction of 5.8 %. It can be concluded that the most power consuming part is the heating resistor and any solution of power reduction needs to consider it.

Table 4. Number of burnt paper sheets *per* stage.

Stage	Number of Papers
1.	3 paper sheets
2.	6 paper sheets
3.	12 paper sheets
4.	24 paper sheets

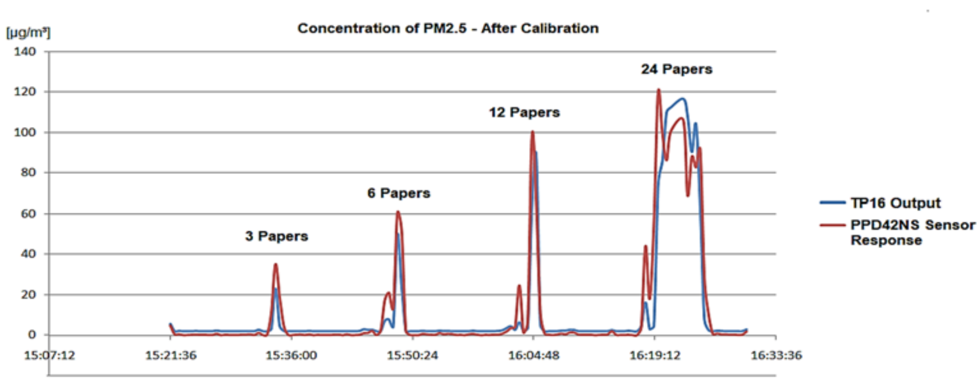

Fig. 13. Concentration curve of $PM_{2.5}$ obtained by the TP16 signal with digitally processing (blue line) and the PPD42NS Sensor Response (red line).

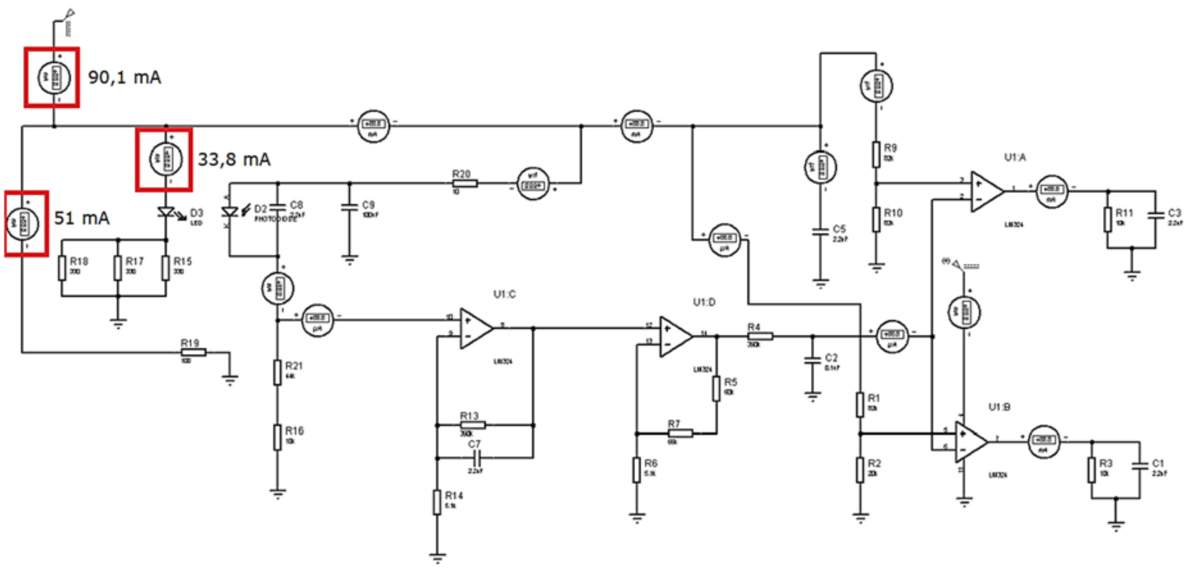

Fig. 14. Schematic diagram of the PPD42NS in Proteus.

7. Conclusions

A portable and wireless intelligent sensor was introduced, which is composed by the environmental sensor BME680 informing data of temperature, humidity, among others, and the PPD42NS sensor, providing concentration data of $PM_{2.5}$ from light scattering method. In order to analyze the data quality of the PPD42NS, the PPD42NS sensor was calibrated using the reference equipment Ecotech HiVol 3000. The low cost, the linear correlation above 0.9 observed in the calibration process, and the dispensability of daily filter changes, as need when HiVol 3000 is used, suggests that the proposed PPD42NS-based intelligent sensor can assist in sampling $PM_{2.5}$ for monitoring the quality of the air. In addition, aiming to reduce the current consumption, the electronic part of the PPD42NS was replaced by digital processing, but the observed power reduction was not significant.

Acknowledgements

This study was financed in part by the *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil* (CAPES) – Finance Code 001". This work also was supported by the PRONEX project funded by the Paraíba State Research Foundation (FAPESQ-PB/Brazil, and the Brazilian National Council for Scientific and Technological Development (CNPq) under Grant Number 009/2019, by the National Institute of Science and Technology of Micro and Nanoelectronics Systems (Proc. 573738/2008-4 INCT NAMITEC), by the National Council for Scientific and Technological Development (CNPq, Brazil: Research Productivity fellowship - under Grant Number 309371/2019-8 PQ and PIBIC/CNPq/UFPB scholarship).

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