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A PROJECT REPORT **(15CSP85)** ON

"IoT based Air Pollution Monitoring"

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Bachelor of Engineering in Computer Science & Engineering

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CERTIFICATE

Certified that the project work entitled **"IoT based Air Pollution Monitoring"** carried out by **Mr. MIHIR MOHAN M**, USN **1CR16CS090**, **Ms. S MEGHANA PESHWA**, USN **1CR16CS139**, bonafide students of CMR Institute of Technology, in partial fulfillment for the award of **Bachelor of Engineering** in Computer Science and Engineering of the Visveswaraiah Technological University, Belgaum during the year 2019-2020. It is certified that all corrections/suggestions indicated for Internal Assessment have been incorporated in the Report deposited in the departmental library.

The project report has been approved as it satisfies the academic requirements in respect of Project work prescribed for the said Degree.

Dr. Shanthi M B	**Dr. Prem Kumar Ramesh**	**Dr. Sanjay Jain**
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Name of the examiners — Signature with date

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DECLARATION

We, the students of Computer Science and Engineering, CMR Institute of Technology, Bangalore declare that the work entitled "**IoT Based Air Pollution Monitoring**" has been successfully completed under the guidance of Prof. Shanthi M B, Computer Science and Engineering Department, CMR Institute of technology, Bangalore. This dissertation work is submitted in partial fulfillment of the requirements for the award of Degree of Bachelor of Engineering in Computer Science and Engineering during the academic year 2019 - 2020. Further the matter embodied in the project report has not been submitted previously by anybody for the award of any degree or diploma to any university.

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ABSTRACT

These days air pollution levels are increasing beyond our control and crossing the safety limits. There is a need for people to be aware of how much air pollution they are exposed to and take steps to reduce their susceptibility to the same. “Awaire” is an air pollution monitoring system implemented using IoT. It collects PM (Particulate matter) readings from a sensor and a microcontroller connected to and sends the readings to an android app. It is a portable air pollution monitoring and awareness system. This app is created to raise awareness on the increasing air pollution levels and with the aim to help people with breathing difficulties to understand the air pollution levels in their environment.

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LIST OF ABBREVIATIONS

AQI	**Air Quality Index**
DB	**Database**
IDE	**Integrated Development Environment**
IoT	**Internet of Things**
PM	**Particulate Matter**

CHAPTER 1

INTRODUCTION

Air pollution is a mixture of natural and man-made substances in the air we breathe. There could be several causes for air contamination which could be due to human activities or natural processes. But by far the greatest contributors to air pollution today are those that are a result of human impact. These are largely the result of human reliance on fossil fuels and heavy industry, but can also be due to the accumulation of waste, modern agriculture, and other man-made processes. The main source of air pollution and in all major cities is due to vehicles and the second major source remains the industries. The massive use of vehicles has resulted in a vital increase in toxins in the atmosphere [1].

Major pollutants emitted into the atmosphere by human activity include CO2, SO2, NO2, CO, particulate matter (PM) and CFCs. Pollutants are generally categorized into two groups as primary pollutants and secondary pollutants. Primary air pollutants are the direct results of natural or human-induced activity, on the other hand, secondary pollutants are created by the interaction between the primary pollutants. Sulphur-dioxide emitted from through the burning of fossil fuels in factories or by vehicles is primary pollution whereas smog caused by the interaction of several primary pollutants is an example of a secondary pollutant [2], [3]. It is well known that some of these chemical pollutants have increased the occurrence of diseases such as lung cancer, pneumonia, asthma, chronic bronchitis, coronary artery disease, and chronic pulmonary diseases [4]. According to the 2014 World Health Organization report, air pollution in 2012 caused the deaths of around 7 million people worldwide, an estimate roughly echoed by the International Energy Agency.

Amongst the major pollutants, particulates are the most harmful form of air pollution due to their ability to penetrate deep into the lungs and bloodstreams unfiltered, causing heart attacks, respiratory disease, and premature death [6]. Particulate matter or atmospheric aerosol is a mixture of extremely small solid and liquid particles in the air. PM2.5 and PM10 are particulate matter with an aerodynamic diameter of less than 2.5μm and 10μm respectively. Most particles are formed in the atmosphere from chemical reactions or pollutants emitted from power plants, industries, and automobiles.

AQI Category, Pollutants and Health Breakpoints

AQI Category (Range)	PM_{10} (24hr)	$PM_{2.5}$ (24hr)	NO_2 (24hr)	O_3 (8hr)	CO (8hr)	SO_2 (24hr)	NH_3 (24hr)	Pb (24hr)
Good (0–50)	0–50	0–30	0–40	0–50	0–1.0	0–40	0–200	0–0.5
Satisfactory (51–100)	51–100	31–60	41–80	51–100	1.1–2.0	41–80	201–400	0.5–1.0
Moderately polluted (101–200)	101–250	61–90	81–180	101–168	2.1–10	81–380	401–800	1.1–2.0
Poor (201–300)	251–350	91–120	181–280	169–208	10–17	381–800	801–1200	2.1–3.0
Very poor (301–400)	351–430	121–250	281–400	209–748	17–34	801–1600	1200–1800	3.1–3.5
Severe (401–500)	430+	250+	400+	748+	34+	1600+	1800+	3.5+

Fig 1.1 AQI range, pollutants and health break points

AQI	Associated Health Impacts
Good (0–50)	Minimal impact
Satisfactory (51–100)	May cause minor breathing discomfort to sensitive people.
Moderately polluted (101–200)	May cause breathing discomfort to people with lung disease such as asthma, and discomfort to people with heart disease, children and older adults.
Poor (201–300)	May cause breathing discomfort to people on prolonged exposure, and discomfort to people with heart disease.
Very poor (301–400)	May cause respiratory illness to the people on prolonged exposure. Effect may be more pronounced in people with lung and heart diseases.
Severe (401–500)	May cause respiratory impact even on healthy people, and serious health impacts on people with lung/heart disease. The health impacts may be experienced even during light physical activity.

Fig 1.2 Health impacts associated with different AQI ranges

PM2.5 is found to be 6th highest-ranking risk factors for early deaths and also worldwide exposure to PM2.5 contributed to 4.1 million deaths from heart disease and stroke, lung cancer, chronic lung disease, and respiratory infections in 2016 [8]. Many different sources of air pollution have been investigated as causes of adverse health effects. These include, among others, municipal waste incinerators, residential heating and especially wood smoke, local point sources and even desert sand. But more than any other source, road transport has been linked to adverse health effects [5]. Dust from unsealed roads is a major source of PM10 particles and also is a source of PM2.5. Other sources are construction sites, unpaved roads, fields, smokestacks or fires. Hence in heavily polluted cities there is no doubt that people are exposed to these particles frequently. Herein comes the dire need to monitor an individual's exposure which will help create awareness and take appropriate actions. AQI (Air Quality Index) estimation is done in several countries. For example, there are 342 monitoring stations spread across 240 cities in India. These stations provide precise information about various pollutants. There are AQI categories and their respective health impacts as shown in Fig. 1.1 and Fig. 1.2. But there are certain drawbacks to these stations. These include 1) Infrastructure essential for establishment as a result of the colossal size, 2) Operational necessities are basically mind-boggling, 3) The common costs of setting up, day by day support and alignment [7]. Therefore, installations are less and monitoring air pollution in several areas might not be possible. Even if it is possible, the estimates will be approximate values and not exact. Another drawback is the AQI is updated every few minutes or hours. Hence these stations do not provide real-time values.

The advent of IoT has enabled the usage of wireless network technologies in monitoring different real-time sensor data, like temperature, pressure and air pollution. The data retrieved by the devices are sent wirelessly to a database on a remote server for future analysis and processing [4]. As mentioned, people are exposed to pollutants such as particulates mostly through road transport and they can keep track of their exposure using our proposed. If the user is wearing a mask then the exposure values will be deducted accordingly. It will also give a visual representation of the exposure wherever the user travels throughout the day by plotting it on a map. The goal of the paper is to monitor air pollution exposure in a personalized way and to create awareness.

1.1 Relevance of the Project

These days air pollution levels are increasing beyond our control and crossing the safety limits. There is a need for people to be aware of how much air pollution they are exposed to and take steps to reduce their susceptibility to the same. Our proposed system consists of a design that helps in achieving this. It is an IoT based air pollution monitoring system. To implement this, we will be using NodeMCU esp32 and Nova PM sensor SDS011. The sensor reads the real-time pollution levels and sends the data to the microcontroller which in turn communicates it to an android app via the cloud. The app aims at monitoring the daily PM2.5 and PM10 exposure of the user. It shows the current PM levels and indicates how safe it is. Another functionality involves plotting the real-time PM values on a map. At the end of the day, it shows the average exposure of that day and gives tips on how to reduce the exposure. Thus, by doing so, the users will be able to keep track of how much air pollution they are exposed to daily and take appropriate measures to alleviate their exposure.

The latest estimates for the global burden of disease due to ambient PM2.5 air pollution make clear that it takes its greatest toll in the elderly and middle-aged, in particular from non-communicable diseases (cardiovascular disease, stroke, lung cancer, and COPD). All told, in 2016, ambient PM2.5 air pollution contributed to 1.8 million deaths and 22 million DALYs in those older than 70 years and 1.3 million deaths and 37 million DALYs in those between 50 and 69 years old from these diseases. The growing importance of these non-communicable diseases in the burden of disease for air pollution exposure reflects worldwide increases in life expectancy at birth over the last 50 years and improvements in prevention and treatment for communicable diseases (malaria, pneumonia, etc.).

In India, the GBD MAPS study also found significant burdens from all forms of combustion, albeit with a different mix of the most important sources (Figure 16). In 2015, the baseline year for this study, particulate matter air pollution from a range of major sources was responsible for approximately 1.1 million deaths, 10.6% of the total number of deaths in India.

The study also reported that if no further action is taken, population exposures to PM2.5 are likely to increase by over 40% by 2050. Three different energy efficiency and air pollution control scenarios were evaluated. Only under the most aspirational scenario, in which aggressive emission reductions were assumed, were exposures projected to be reduced in a major way — by nearly 35% from 2015 to 2050, reaching about 48 µg/m3. Even with the projected exposure decreases, the burden of disease is expected to grow in the future relative to the baseline year as the population ages and grows and leaves more people susceptible to air pollution.

The Indian government has begun taking actions to improve air quality. However, the study reported, the most aggressive action — with all major sectors achieving reductions in air pollution — could avoid up to 1.2 million deaths in 2050 compared with just instituting currently planned policies. Achieving such reductions will require particular attention to reducing emissions from household biomass combustion, coal burning, and dusts related to human activities. Depending on the scenario, coal combustion has the potential to emerge as the leading contributor to the disease burden from air pollution in the future [8].

One of the main aspects of the project is to determine the significance of various PM value ranges and its associated cautionary statement.

1.2 Problem Statement

The main goal of this device is to give air pollution levels the user is exposed to in a personalized manner and hence raise awareness. There are android apps that have been developed to monitor the air pollution levels that display the daily average. Other implementations involve web applications that measure indoor air quality. Drawback in these are, they do not provide real time values and may not be portable. Another implementation is done by collecting data from their own sensors as well as existing sensors and predict the pollution of future days with the use of Artificial Neural Networks (ANN). In this case, the predictions might not be accurate and hence unreliable. There are existing sensors present in many places but these are expensive, stationary and do not provide personalized readings.

Our system overcomes these drawbacks. It is provides real time readings and is portable. It gives personalized exposure and the readings are not approximated and hence it is reliable. It will also give a visual representation of the user's exposure wherever he/she travels throughout the day by plotting it on a map.

The main goal of the project is to create a device that gives air pollution levels the user is exposed to daily in a personalised manner. We created a small device that can be carried along by the user throughout the day and will continuously monitor the surrounding air pollution levels. It then sends this data to the cloud for storage and further use. Meanwhile our android app sends GPS data to the server to indicate where the user is. The two datasets from both these sensors are synchronized in the cloud to match the location with the PM readings obtained. An android is developed which has various functionalities. It is responsible for sending the location readings to the cloud. Furthermore, it receives the merged data from the cloud and shows the real time PM values in the user's surroundings. It also shows a visual representation of the amount of exposure and the location associated with it. The app displays a map which shows the path the user has travelled throughout the day and it colour codes the travel route according to the PM levels recorded there. For example, if a certain stretch of road the user travelled had high pollution rates due to various factors like traffic, factories close by etc, then the app shows that stretch of the road on the map as red.

Using this the user can change his route or wear a mask and thereby reduce his exposure to air pollution.

The app also provides cautionary statements are aimed to help the user reduce his/her daily exposure. It keeps track of the daily exposure and the user can see the history of his travel and the amount of pollution he's been exposed to. The app also has a functionality to account for the usage of a mask. N95 masks block 95% of the particulate matter the user is exposed to. So if the user indicates he is using a mask to the app, it must account for it and reduce the exposure appropriately.

1.3 Objective

- Get real time PM level data.
- If the user is wearing a mask then the app should account for it and make appropriate changes to the exposed PM values.
- It should plot these values on a map using a color coding scheme as the user travels.
- It should also store historical data and also calculate daily average exposure.
- It should generate appropriate and useful health tips based on the exposure.
- Perform analysis of the collected data and gain insights.

1.4 Scope of the Project

The components required are the NodeMCU esp32 microcontroller along with the nova pm sensor sds011 to measure the PM levels. These are relatively inexpensive as compared to other sensors and microcontrollers. The esp32 has a built-in Bluetooth module through which we can send the sensor values to the cloud. While the user is on the go, the microcontroller will be making use of the mobile hotspot given by the user's mobile phone. We are making use of the phone's GPS sensor to get location data. The app should have a smooth experience. It will not be having any ads to give the user an optimum experience and also because the main aim is to create awareness and improve the health and lifestyle of the user.

In order to make the device portable, we will make use of a 3D printer to print a casing for our sensor, the power supply and the microcontroller. This can increase its portability and durability significantly. The casing can be attached to various things we carry around with us all day like a backpack or as a belt attachment. It also makes it easier to handle the device and provides a good look to the whole setup as well.

1.5 Agile Methodology

Agile Methodology is a people-focused, results-focused approach to software development that respects our rapidly changing world. It is centred around adaptive planning, self-organization, and short delivery times. It is flexible, fast, and aims for continuous improvements in quality, using tools like Scrum and eXtreme Programming. It abandons the risk of spending months or years on a process that ultimately fails because of some small mistake in an early phase.

It relies instead on trusting employees and teams to work directly with customers to understand the goals and provide solutions in a fast and incremental way. Table 1.1 describes the various requirements and user stories.

Table 1.1 Requirements and user stories description

Story ID	Requirement description	User stories/Task	Description
1	Get real time PM values	The user wants to know the current PM values of his surroundings	This can be achieved by a PM level sensor and a microcontroller
2	Plotting the air pollution on a map while travelling	The user wants to know the amount of air pollution he is exposed to throughout his journey	This can be achieved by using the phone’s GPS location and the sensor data

3	Calculating the average daily exposure and showing other statistics	The user wants to know the amount of air pollution he is exposed to on an average at the end of the day and also the pollution levels experienced in different modes of transport	This can be done by calculating the average
4	Providing cautionary statements and health impacts	The user wants to know how air pollution is affecting him	This can be done by displaying the cautionary statements and health impacts

1.6 Chapter Wise Summary

Chapter 1 involves introduction, relevance, problem statement, objectives and scope of the project. This chapter provides an overview of the system and why it is required. It also describes the various features and a brief of the components required.

Chapter 2 consists of literature survey. This describes the various existing systems and its characteristics. Comparison is made about the different approaches to address the same problem.

Chapter 3 is requirement specification. It gives a detailed information of all the functional and non-functional as well as the hardware and software requirements for this project.

Chapter 4 involves system analysis and design. This contains the system architecture, flow diagram, use case diagram and sequence diagram.

Chapter 5 is the implementation. Details about the algorithm, experimental setup, frontend and backend implementation are provided in this chapter.

Chapter 6 is results and discussion. It contains the screenshots of the android app and their descriptions.

Chapter 7 consists of testing details.

Chapter 8 is conclusion and future scope of the project.

CHAPTER 2

LITERATURE SURVEY

The National Air Quality Monitoring Programme (NAMP) is the flagship air quality monitoring programme of the Government of India. As of September 2018, four key pollutants—sulphur dioxide (SO2), nitrogen dioxide (NO2), PM10 /RSPM, and PM2.5—are monitored at 703 AQ stations across 307 cities and towns [6].

Focal Pollution Control Board (CPCB) has planned for distinguishing the urban communities which are not fulfilling the recommended national encompassing air quality norms. It has set up a system of mechanized air quality observing stations across urban areas in the nation. According to the study held in September 2018, there are 130+ Continuous Ambient Air Quality Monitoring Stations (CAAQM) stations in excess of 65 urban communities across India [6]. Fig. 2.1 shows the currently present air pollution sensors in India.

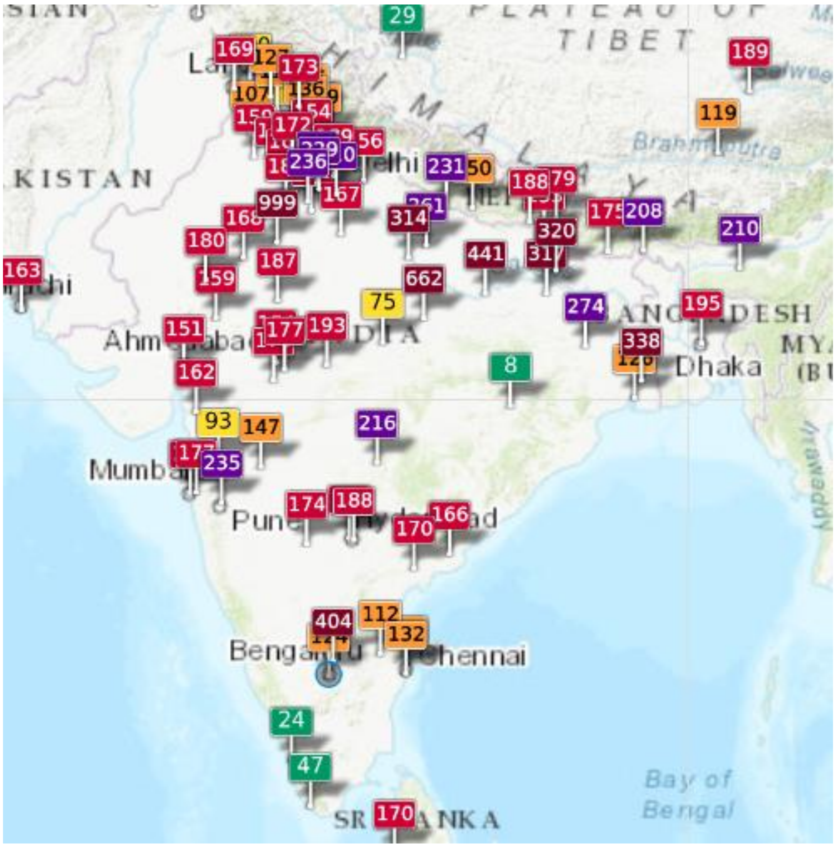

Fig 2.1 Air pollution sensors in India

The System of Air Quality and Weather Forecasting and Research (SAFAR) network has ten air quality monitoring stations (AQMS) in each city equipped with real-time, continuous monitors for a range of pollutants including PM1, PM2.5, PM10, O3, nitrogen oxides (NOx), SO2, black carbon (BC), methane (CH4), non-methane hydrocarbons (NHMC), VOCs (BTEX) and mercury (Hg), and meteorological variables including solar radiation, rainfall, temperature, relative humidity, wind speed, and direction. At some locations, ammonia (NH3) is also measured. SAFAR also has a smartphone app, disseminating calculated AQI values for the criteria pollutants (as a city average) and anticipated AQI for the 2 days [6].

There are android apps that have been developed to monitor the air pollution levels that display the daily average [1]. Other implementations involve web applications that measure indoor air quality [2]. Low cost semiconductor gas sensors have been used to keep track of the gas concentrations [4]. Air pollution monitoring devices that focus on power saving and the longevity of the sensors have been implemented [3].

Another implementation is done by collecting data from their own sensors as well as existing sensors and predict the pollution of future days with the use of Artificial Neural Networks (ANN) [7].

2.1 Comparison

Table 2.1 Comparison of various approaches

	Key features	Advantages	Disadvantages
Approach 1	Stationary sensors located in major cities	Provides precise values and is long-lasting	Not portable, data is not accessible to everyone, expensive, not personalized
Approach 2	Android and web apps that display daily or monthly average	User friendly and creates awareness	Does not provide real-time values and they may not measure PM values
Approach 3	Devices that predict future pollution levels by collecting data from sensors	Can foresee future pollution levels	Unreliable as pollution levels vary significantly over short durations of time

The already existing websites and android apps have made air pollution level data more accessible by using IoT and their sensors. The android apps and web apps implementation focuses on a stationary sensor located in the house or the office environment. It can give accurate exposure levels of the user within that environment. But most of the pollution exposure faced by people is from outdoors and not in a closed environment. It reduces the effectiveness of calculating the overall exposure faced by users.

Further, these systems are yet to extend in the future by allowing the public to use the app to see real-time pollution levels and providing a personalized user experience and provide location-based pollution levels.

Some implementations use stationary sensors to spread across the city, but pollution levels vary over a range of few kilometers and it is not feasible to install these sensors in every part of the city. They provide precise values for only the area they are located at. Although they can be functional for many years, the disadvantage with these is that they are expensive to set up and maintain, data is not accessible to everyone easily and they do not give a personalized reading for every user.

Few other implementations predict the pollution levels of future days and across all areas with the help of Artificial Neural Networks (ANN). The ANN uses data from existing sensors already set up by various organizations. The problem with this implementation is that they can be inaccurate as the pollution levels vary over short periods. Various local factors can change the pollution levels around a particular area which will not be accounted for by the prediction system.

These problems can be addressed by providing portable and cost-effective devices that can monitor air pollution level exposure to the user.

CHAPTER 3

REQUIREMENTS SPECIFICATION

Internet of Things (IoT) is an ecosystem of connected physical objects like sensors and microcontrollers which collect and transfer data over a network without any manual assistance or intervention. There has been a lot of development in the field of IoT including the hardware, sensor technology, software and advances in cloud technologies [11]. We can use IoT to collect data around us and provide a quantitative view of our surroundings. With this data in our hands we can take action or learn more about how our environment works and make use of the knowledge gained and make lives easier for people.

3.1 Functional Requirements

- **Real time PM2.5 and PM10 exposure levels should be shown in the app**: The app must receive PM2.5 and PM10 values from the sensor, reduce the values in accordance with the type of mask selected by the user and then display the PM2.5 and PM10 exposure to the user in the home page and must be updated regularly.
- **Showing travel history of the user**: The app should show the travel path of the user throughout the day on a map. The path must be colour coded based on the exposure recorded by the app at the respective locations and the map can be zoomed and panned. The user must also be able to see previous days' travel path.
- **Mask options**: The app should provide a set of mask types for the user to choose from. Based on the type of mask selected the app should reduce the exposure of the user by taking into account the efficiency of reducing the exposure of different types of masks, and these should be reflected in the home page.
- **Transport options**: The app should provide a set of transport options for the user to choose from. This will help the app perform better analysis and provide useful insights to the user.
- **Insights**: The app should show the average exposure of the user throughout the day. It also should provide health implications for the exposure faced and give cautionary measures needed to be taken. It also provides insights into the average exposure levels experienced in different mode of transports and how long the user has used it.

3.2 Non-Functional Requirements

- **User Interface:** The app should focus a lot on user interface, it should be very easy to get valuable information from it. It should not show too much or too less data in the home page.
- **Reliability:** The app should not crash at any time as this could lead to loss of valuable data and cause inconvenience.
- **Performance:** It should run smoothly and without any lag. It should show the required information quickly and show only the required information.
- **Visual Information:** It must provide information in a visually appealing and helpful way to the user and not just textual information. The app should show the appropriate Air Quality category associated with the exposure. This helps in the user to quickly tell how good or bad the air is. It also should colour code the category wherever possible to make it more apparent if the category is good or bad. It also should show data in a graphical manner and make it easier for the user to read their exposure data.
- **Availability:** The database must be always available and reliable to serve data and to upload data from the app.
- **Portability:** The device which includes the sensor, microcontroller and the power supply must be portable enough to be carried around by the user easily.

3.3 Hardware requirements

The air pollution monitoring system proposed in this research focuses on measuring the PM 2.5 and PM 10 levels exposed to the user of this system. The system is mainly composed of a sensing node, a cloud server and a mobile app that help the users visualize their exposure. The sensing node measures PM 2.5 and PM 10 levels every minute and transfers this data to the cloud server meanwhile the mobile app also sends the current GPS location to the server. To save power and data storage the sensing nodes read data in bigger time intervals when the user is stationary.

A. Microcontroller

The proposed framework is constructed utilizing the ESP-WROOM-32 microcontroller. ESP32 is a minimal effort, low-power framework on a chip microcontroller with coordinated Wi-Fi and double mode Bluetooth. The rest current of the ESP32 chip is under 5uA, making it appropriate for battery-fuelled and wearable hardware applications. A 3.3V DC power source controls the board. The PM sensor is associated with this board. Fig. 3.2 shows a point by point pin outline of the microcontroller.

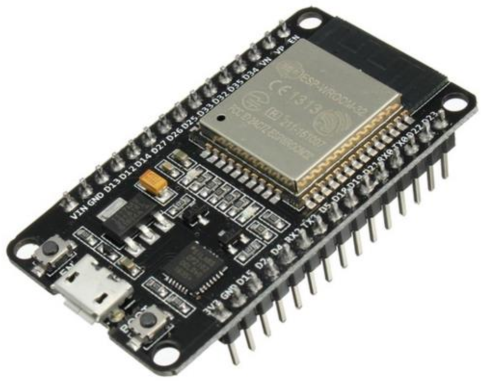

Fig 3.1 ESP32

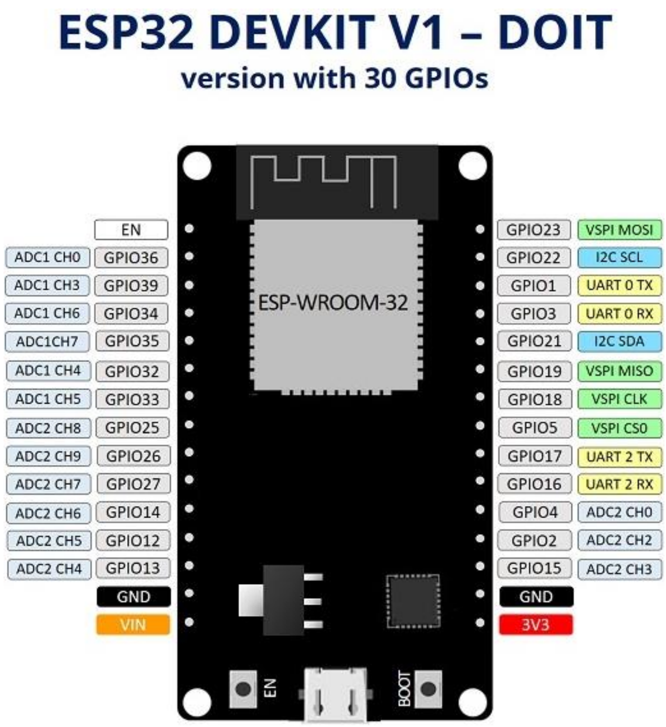

Fig 3.2 ESP32 Pin Diagram

B. PM Sensor

The SDS 011 Sensor is a quite recent Air Quality Sensor developed by inovafit, a spin-off from the University of Jinan (in Shandong). With its size, it is probably one of the best sensor in terms of accuracy: While other sensors tend to focus on shrinking the sensor size, the SDS 011 has opted for a size trade-off allowing it to use a larger fan. And the larger the fan, the better the quality. Fig. 3.3 shows an SDS 011 PM Sensor.

Specifications:

- Output: PM2.5, PM10
- Measuring Range: 0.0-999.9µg/m3
- Input Voltage: 5V
- Maximum Current: 100mA
- Sleep Current: 2mA
- Response Time1 second
- Serial Data Output Frequency: 1 time/second
- Particle Diameter Resolution: ≤0.3µm
- Relative Error: 10%
- Temperature Range: -20~50°C
- Physical Size: 71mm*70mm*23mm

The clever engineering in the SD011 is to use the PCB as one side of the casing (allowing to reduce the BOM cost). The diode is mounted on the PCB side (this is mandatory as any noise between the diode and the LNA should be avoided). The laser mounted on the plastic box and connected to the PCB via flying wire. The biggest problem of this design is that the entire sensor inside is getting very dusty, as shown on the picture below after running 24/7 for more than 6 months. This is actually not so bad since the dust did not get accumulated on the diode, nor on the laser frontend. Concerning the fan, dust accumulation is a "normal behaviour". Last, as concerns the PCB, is it quite simple. The main CPU is an 8bit processor (scratched to prevent from being reversed engineered). Under the shielding one can find the Low Noise Amplifier (directly mounted on the opposite side of the diode).

Fig 3.3 Nova PM sensor

C. GPS sensor

We make use of the GPS sensor available on the user's mobile phone to send location data at the same time the microcontroller sends the PM readings to the server.

Mobile phones use a system called assisted GPS (AGPS) as it can take a long time to get a position fix with a normal GPS. There are ways to speed this up, but unless you're carrying an atomic clock with you all the time, or leave the GPS on all the time, then there's always going to be a delay of between 5-60 seconds before you get a location.

In order to save cost, most cell phones share the GPS receiver components with the cellular components, and you can't get a fix and talk at the same time. People don't like that (especially when there's an emergency) so the lowest form of GPS does the following:

- Get some information from the cell phone company to feed to the GPS receiver - some of this is gross positioning information based on what cellular towers can 'hear' your phone, so by this time they already phone your location to within a city block or so.

- Switch from cellular to GPS receiver for 0.1 second (or some small, practically unnoticeable period of time) and collect the raw GPS data (no processing on the phone).
- Switch back to the phone mode, and send the raw data to the phone company
- The phone company processes that data (acts as an offline GPS receiver) and send the location back to your phone.

This saves a lot of money on the phone design, but it has a heavy load on cellular bandwidth, and with a lot of requests coming it requires a lot of fast servers. Still, overall it can be cheaper and faster to implement. They are reluctant, however, to release GPS based features on these phones due to this load - so you won't see turn by turn navigation here.

D. Power Bank

A power bank is a portable device that can supply power from its built-in battery through a USB port. Power banks are popular for charging USB charged devices and can be used as a power supply for various USB powered devices such as lights and small fans. They usually recharge with a USB power supply. The power bank includes a control circuit that both regulates charging of the battery and converts the battery voltage to 5.0 volts for the USB port.

E. 3D Printer

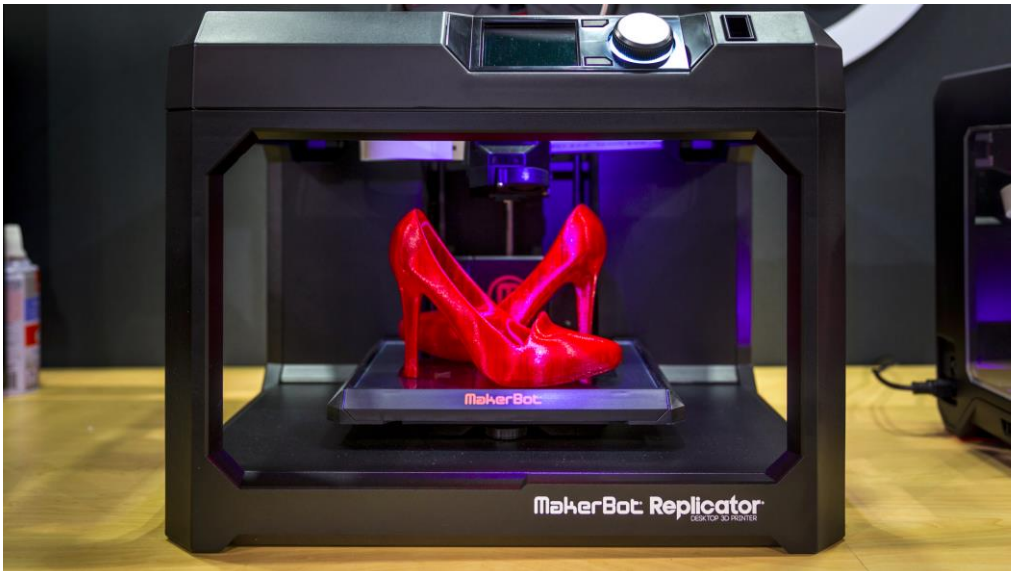

Fig 3.4 3D printer

The 3D printing process builds a three-dimensional object from a computer-aided design (CAD) model, usually by successively adding material layer by layer, which is why it is also called additive manufacturing, unlike conventional machining, casting and forging processes, where material is removed from a stock item (subtractive manufacturing) or poured into a mould and shaped by means of dies, presses and hammers.

The most-commonly used 3D-printing process (46% as of 2018) is a material extrusion technique called fused deposition modelling (FDM).[6] While FDM technology was invented after the other two most popular technologies, stereolithography (SLA), and selective laser sintering (SLS); FDM is typically the most inexpensive of the three by a large margin, which lends to the popularity of the process.

The term "3D printing" originally referred to a process that deposits a binder material onto a powder bed with inkjet printer heads layer by layer. More recently, the popular vernacular has started using the term to encompass a wider variety of additive-manufacturing techniques such as electron-beam additive manufacturing and selective laser melting. The United States and global technical standards use the official term additive manufacturing for this broader sense.

3D printable models may be created with a computer-aided design (CAD) package, via a 3D scanner, or by a plain digital camera and photogrammetry software. 3D printed models created with CAD result in reduced errors and can be corrected before printing, allowing verification in the design of the object before it is printed. The manual modelling process of preparing geometric data for 3D computer graphics is similar to plastic arts such as sculpting. 3D scanning is a process of collecting digital data on the shape and appearance of a real object, creating a digital model based on it.

CAD models can be saved in the stereo lithography file format (STL), a de facto CAD file format for additive manufacturing that stores data based on triangulations of the surface of CAD models. STL is not tailored for additive manufacturing because it generates large file sizes of topology optimized parts and lattice structures due to the large number of surfaces involved. A newer CAD file format, the Additive Manufacturing File format (AMF) was introduced in 2011 to solve this problem. It stores information using curved triangulations.

F. Jump Wires

A jump wire (also known as jumper wire, or jumper) is an electrical wire, or group of them in a cable, with a connector or pin at each end, which is normally used to interconnect the components of a breadboard or other prototype or test circuit, internally or with other equipment or components, without soldering. We make use of solid tip jump wires to connect the microcontroller and the sensor together.

3.4 Software Requirements

- Android Operating System greater than 6.0 (Marshmallow) - Android is a mobile operating system based on a modified version of the Linux kernel and other open source software, designed primarily for touchscreen mobile devices such as smartphones and tablets. Android is developed by a consortium of developers known as the Open Handset Alliance and commercially sponsored by Google. We have developed the application which can be compatible with Android OS 6.0 onwards as most of the smartphones today run the same or higher version.

- Android Studio - Android Studio is the official integrated development environment (IDE) for Google's Android operating system, built on JetBrains' IntelliJ IDEA software and designed specifically for Android development. Android Studio makes it easier to design UI by providing a layout editor that allows us to drag and drop UI elements and make it more user friendly. We makes use of the built-in support for Firebase and Google Cloud Platform. It makes it easier to make connections to the Firestore to send and receive data. It also provides Lint tools to catch performance, usability, version compatibility and other problems.

- Arduino IDE - The Arduino Integrated Development Environment (IDE) is a cross-platform application (for Windows, macOS, Linux) that is written in functions from C and C++. It is used to write and upload programs to Arduino compatible boards, but also, with the help of 3rd party cores, other vendor development boards. This IDE was used to write the code for the ESP32 microcontroller. This was possible due to existing ESP32 libraries in the Arduino IDE which helps it run the code on an ESP32 microcontroller. It also provides a serial monitor which helps us see the output of the microcontroller making it easy to debug and test the microcontroller code.

CHAPTER 4

SYSTEM ANALYSIS AND DESIGN

4.1 System Architecture

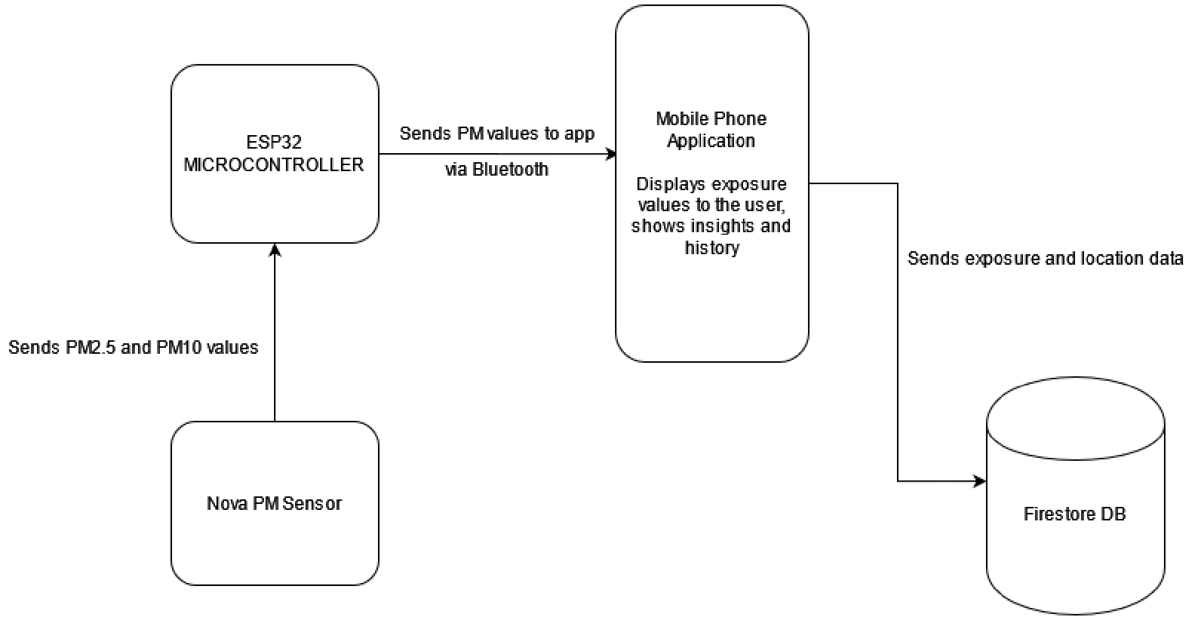

Fig 4.1 System Architecture

The main components of the system are the Nova PM sensor, ESP32 microcontroller, an Android Smartphone with 'Awaire' mobile application installed, and Firestore Database.

The Nova PM Sensor senses PM2.5 and PM10 levels in µg/m^3 and sends it to ESP32 microcontroller in the form of serial digital data. The microcontroller then sends these values to the mobile application via Bluetooth. The mobile application takes the values, shows the exposure to the user after taking into account certain factors, and shows history and additional insights from the data to the user. It then sends the data to the Firestore DB along with location data. Fig. 4.1 gives a diagrammatic overview of the system architecture.

4.2 Flow Diagram

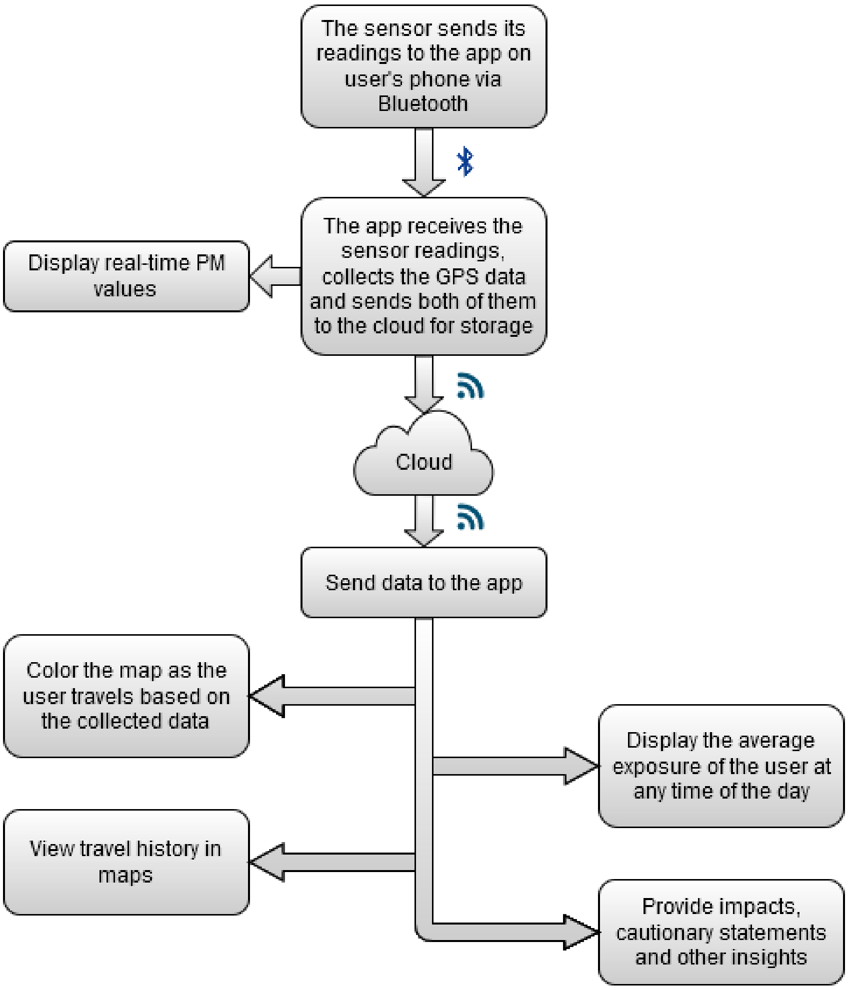

Fig 4.2 Flow Diagram

The flow diagram shown in Fig. 4.2 describes how the data is used and flows throughout the system. First, the sensor sends the PM2.5 and PM10 readings to the mobile application every 30 seconds via Bluetooth. The mobile application receives these readings, adjusts the exposure after taking into account certain factors and displays the values to the user. Simultaneously the app collects the location data from the GPS sensor inside the phone and sends these data to the Firestore DB which is stored in the cloud. The app can then receive data from the cloud and can display a map to the user showing his travel path and exposure. It also can provide average exposure in the day and provide valuable insights of the type of travel used and how it affects exposure. It can receive previous days' data and show on map previous days' travel path and exposure.

4.3 Use Case Diagram

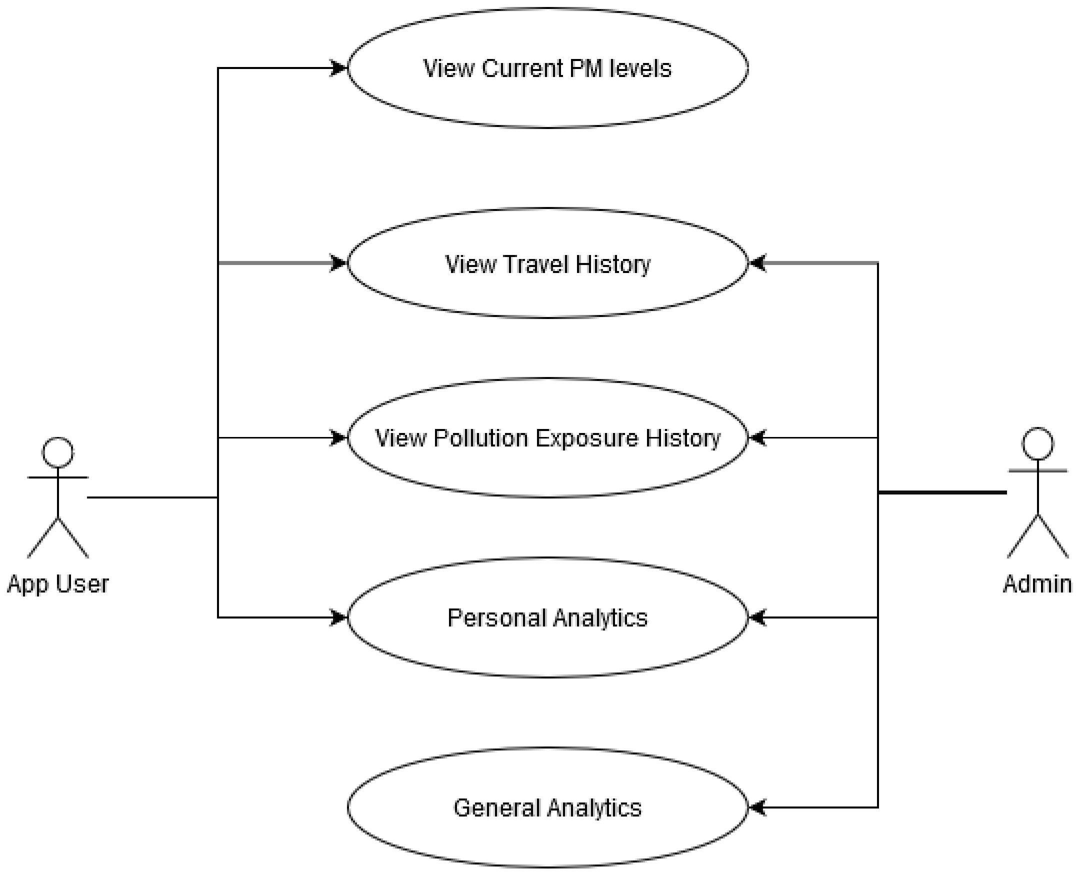

Fig 4.3 Use Case Diagram

There are only two main use cases as shown in Fig. 4.3. One is the Mobile Application user, who can see the current PM exposure levels with the help of his device. The user can also see his travel history on the maps and previous days' travel history as well as some personal analytics like average exposure throughout the day and gain insights on their personal travel habit. The other use case is of the Admin. The admin can see the travel history of the users and their exposures. They can perform user specific analytics as well General Analytics on the data of all the users.

4.4 Sequence Diagram

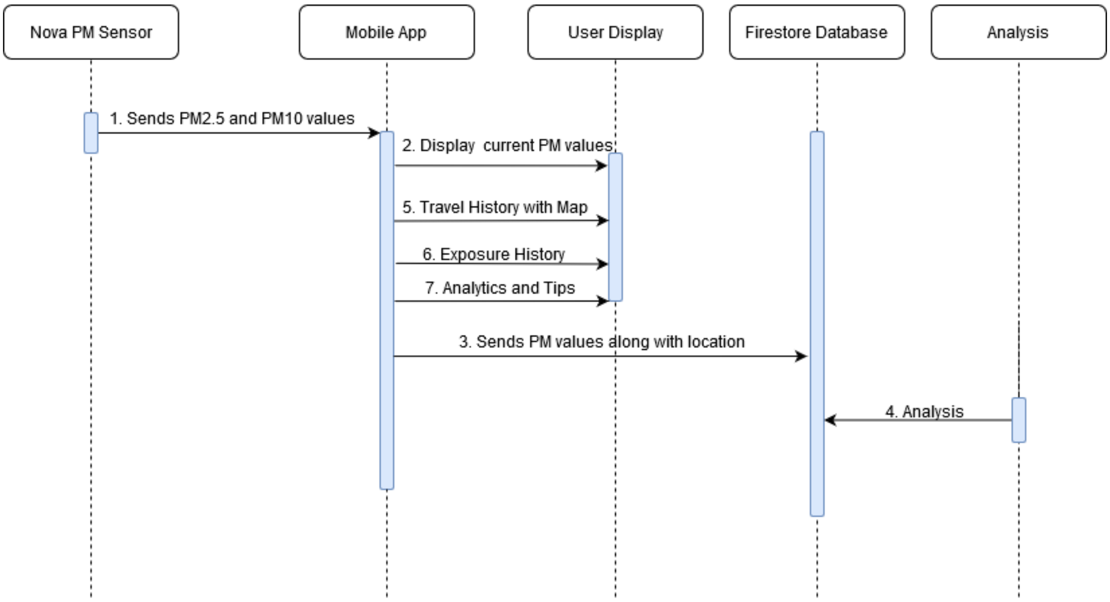

Fig 4.4 Sequence Diagram

The Sequence diagram in Fig. 4.4 shows the tasks that are done by different objects in the system with respect to time. The sensor sends PM2.5 and PM10 values to the Mobile Application first. The app displays the real time exposure levels to the user after taking into account certain factors. It then sends the exposure values, along with location data, type of mask and mode of transport to the Firestore Database in the Cloud. Analysis can be done on the data. The application then shows the travel path of the user on the map and colour codes the path. It also shows the average exposure of the user throughout the day. The app also does analytics and provides insights to exposure based on user behaviour and provides appropriate cautionary measures based on the average exposure.

CHAPTER 5

IMPLEMENTATION

5.1 Algorithm

The problem is formulated in the form of an algorithm. The steps involved are:

1. Collection of data from the Nova PM sensor.
2. Displaying real-time PM levels to the user.
3. Collect GPS data from the mobile phone.
4. Sending all data to the cloud server.
5. Retrieving the data from the cloud server to the phone.
6. Displaying colour-coded map based on the PM values as the user travels.
7. Showing average exposure and other statistics, including the health implications to the user.
8. The user can view the historical map data.

The sensor will acquire the data every 30 seconds. The time period can be changed in future if required. The sensor can be switched off when not in use in order to save power.

The Android app is user friendly and visually good. The first page consists of the real-time PM values got from the sensor. It shows the reading with the respective color code.

The map will be colored accordingly as the user travels. If the user is wearing a mask then that option can be selected and the exposure will be deducted a certain amount based on the type of mask.

Pop-ups will be displayed or notifications will be sent if the air pollution levels are hazardous. Appropriate statistics and insights is displayed to the user based on the data collected.

At the end of the day, the average exposure of the user will be calculated and displayed. The user can also view historical maps and compare how the exposure has changed over time.

5.2 Experimental Setup

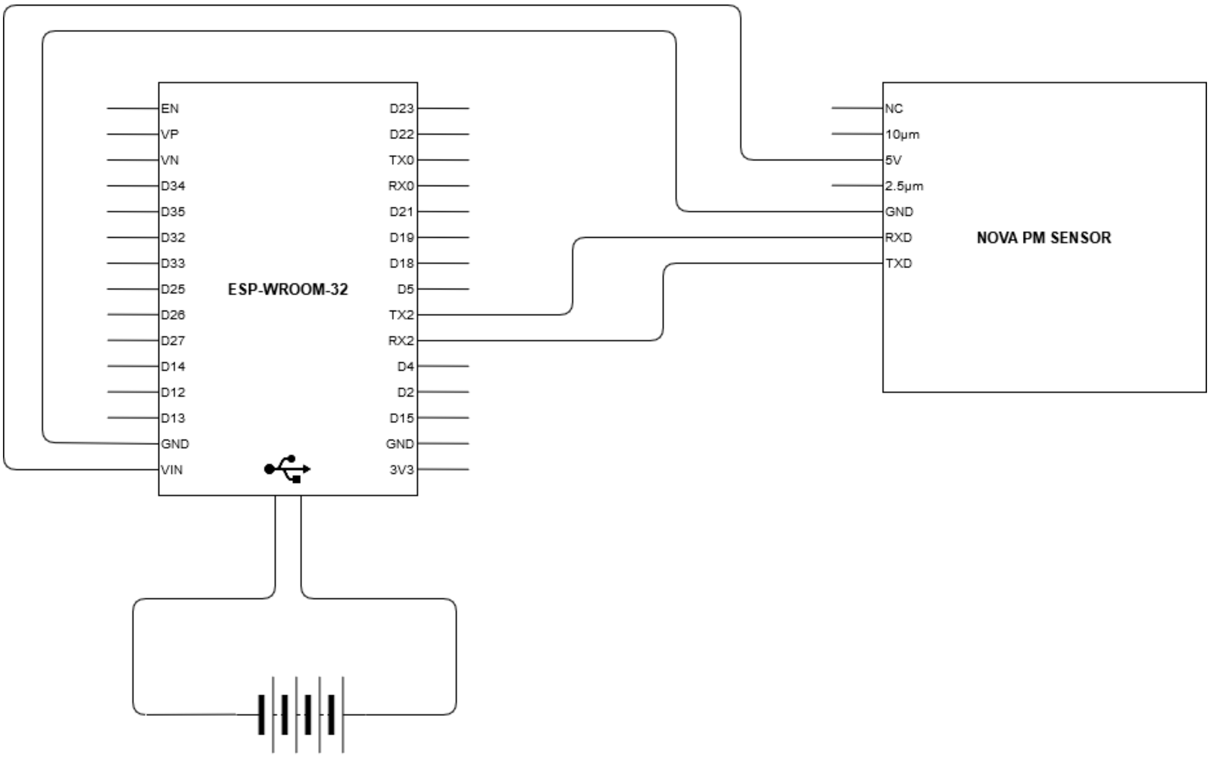

Fig 5.1 Circuit Diagram

The circuit diagram of the device is shown in Fig. 5.1. The ESP32 microcontroller is powered through the micro USB port with the help of a power bank. The Nova PM Sensor is powered by the microcontroller from the Vin and GND pins. The Sensor transmits serial data to the microcontroller from TXD pin of the sensor to the RX2 pin of the ESP32.

5.3 Frontend Implementation Details

In the front end we have a very user friendly mobile application which upon opening, asks user for the necessary permissions and displays the exposure levels in a clean manner.

It also shows the user's travel history and colour codes the path which makes up for a very intuitive design and the user can gain more information at a quick glance. The app makes use of Google Maps SDK to display the maps and draw paths on it. The Maps SDK provides various functionality to draw lines, mark places, and draw shapes etc. on the map. Our app makes use of drawing polyline functionality. The map is interactive, can be zoomed and panned.

The Insights page gives a clean view of the average exposure faced throughout the day. And also provides average exposure based on the mode of transport and the time spent in that mode of transport. It also shows a graphical view of the exposure throughout the day. For this we have made use of the GraphView library. We can make a list of data points to be plotted and the library plots the graph in a very informative way.

5.4 Backend Implementation Details

To receive Bluetooth data from the sensor to the mobile application we make use of the RxAndroidBle library which provides an easy way to receive Bluetooth information. RxAndroidBle is a powerful Android's Bluetooth Low Energy library. It is backed by RxJava, implementing complicated APIs as handy reactive observables. The library does the following:

- Fancy asynchronous operations support (read, write, notifications)
- Threading management in order to meet Android contracts
- Connection and operation error handling

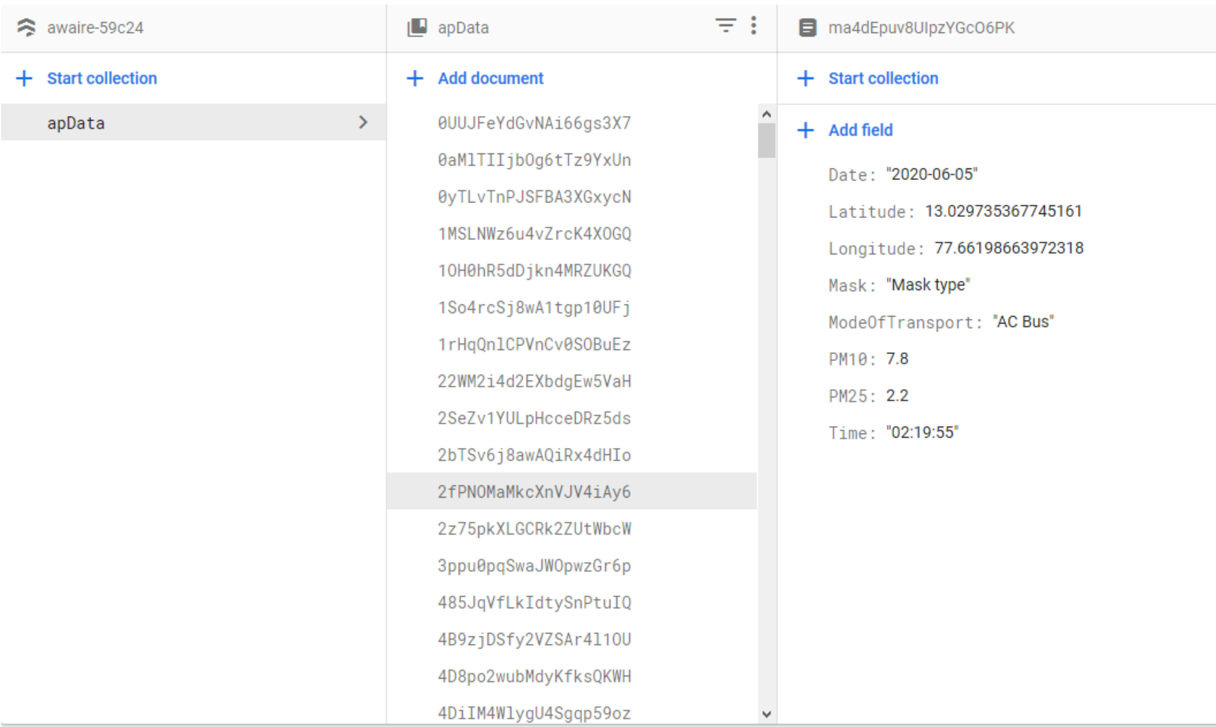

Fig 5.2 Firestore DB

For the Database we make use of Firestore DB. Cloud Firestore is a flexible, scalable database for mobile, web, and server development from Firebase and Google Cloud Platform.

Like Firebase Realtime Database, it keeps your data in sync across client apps through real time listeners and offers offline support for mobile and web so you can build responsive apps that work regardless of network latency or Internet connectivity. Cloud Firestore also offers seamless integration with other Firebase and Google Cloud Platform products, including Cloud Functions. We have made a collection called “apData” as shown in Fig. 5.2 and the app adds new documents to it every time a reading is taken.

CHAPTER 6

RESULTS AND DISCUSSION

AQI	Air Pollution Level	Health Implications	Cautionary Statement (for PM2.5)
0 - 50	Good	Air quality is considered satisfactory, and air pollution poses little or no risk	None
51 -100	Moderate	Air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution.	Active children and adults, and people with respiratory disease, such as asthma, should limit prolonged outdoor exertion.
101-150	Unhealthy for Sensitive Groups	Members of sensitive groups may experience health effects. The general public is not likely to be affected.	Active children and adults, and people with respiratory disease, such as asthma, should limit prolonged outdoor exertion.
151-200	Unhealthy	Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects	Active children and adults, and people with respiratory disease, such as asthma, should avoid prolonged outdoor exertion; everyone else, especially children, should limit prolonged outdoor exertion
201-300	Very Unhealthy	Health warnings of emergency conditions. The entire population is more likely to be affected.	Active children and adults, and people with respiratory disease, such as asthma, should avoid all outdoor exertion; everyone else, especially children, should limit outdoor exertion.
300+	Hazardous	Health alert: everyone may experience more serious health effects	Everyone should avoid all outdoor exertion

Fig 6.1 Health implications and cautionary statements

We make use of the health implications and cautionary statements shown in Fig. 6.1 to make the user aware of what their exposure means to their health and also to give them tips to adopt according to the category of the air quality. As seen from the Figure, if the AQI category is Good, the air quality poses little or no risk to the user and they need not worry about going out. This can be helpful especially for people with asthma and other respiratory illnesses. They can see the air quality and decide whether to go out or not and decide whether to wear a mask to reduce their exposure.

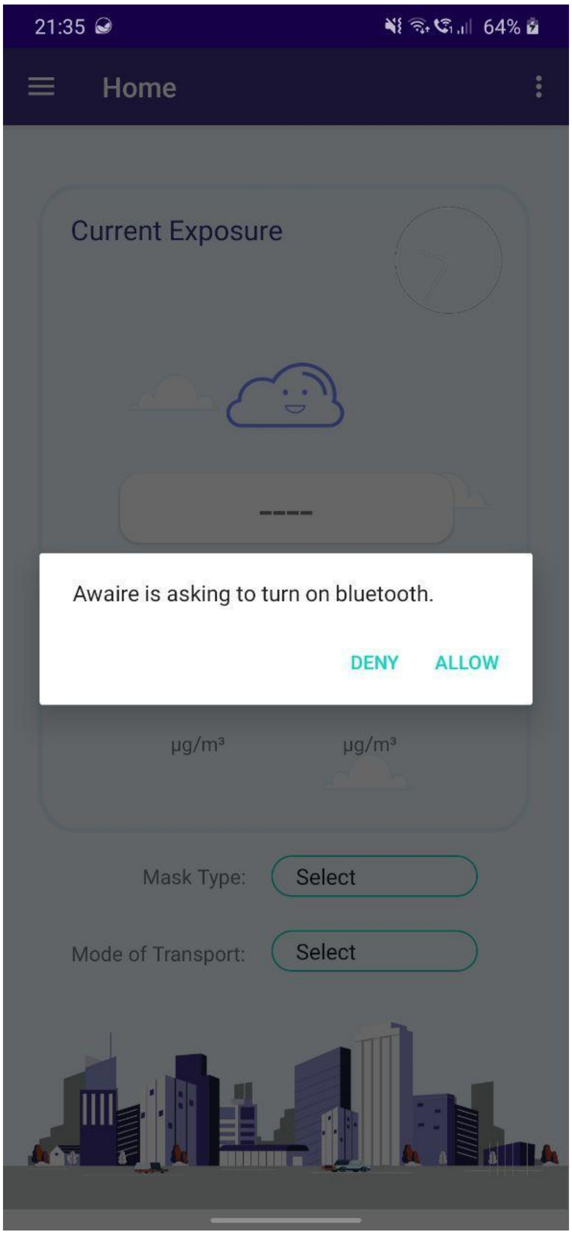

Fig 6.2 Bluetooth Permission

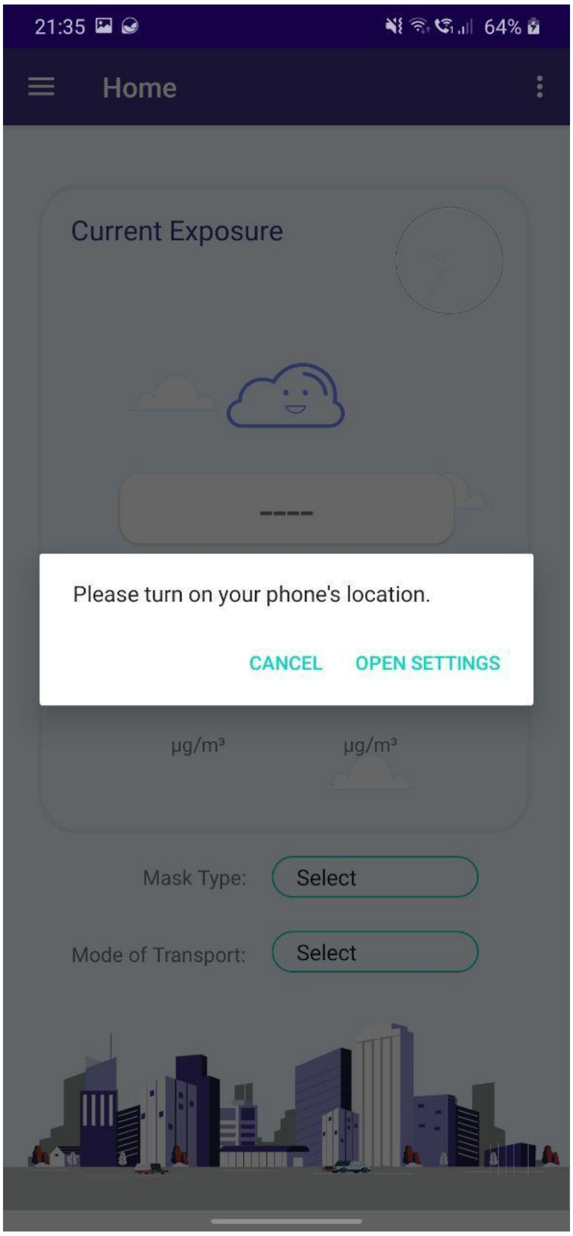

Fig 6.3 Location permission

"Awaire" app needs mainly two permissions from the phone of the user, that is, Bluetooth and Location. As the user opens the app on their android phone, if Bluetooth is switched off, the app shows a prompt asking the user to allow it to switch on Bluetooth as shown in Fig. 6.2. After the Bluetooth is switched on, if the location is switched off on the phone, the app shows another prompt asking the user to turn on the phone's location by going to the settings as shown in Fig. 6.3. Android OS does not allow any application to switch on location by itself. As a result, we give the option for the user to "Open Settings" and to turn on the location and press back button to come back to the application.

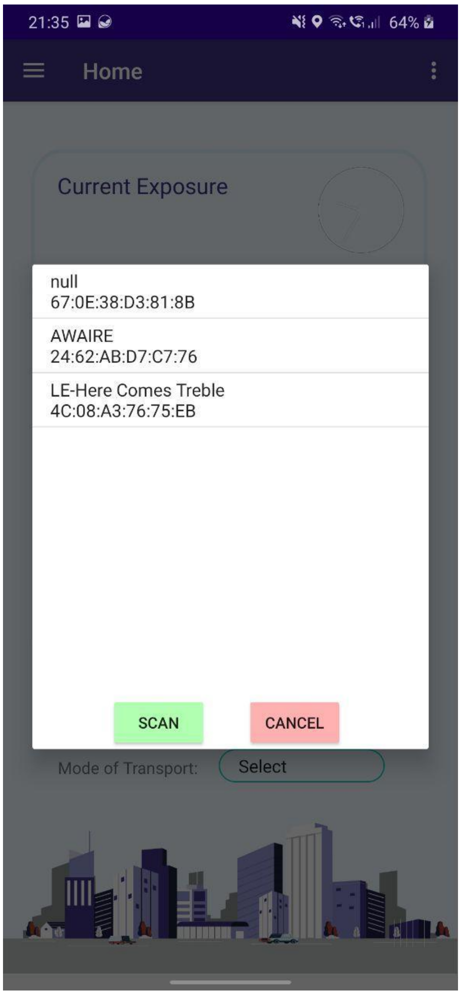

Fig 6.4 Device List

After the app has switched on Bluetooth and Location of the phone, the user is presented with a list of nearby Bluetooth devices. If the sensor is not found in the list, the user can press “Scan” button to search for devices again as shown in Fig. 6.4. Or if the user does not want to connect to any device he can press “Cancel” button. To connect to a device, the user can click on the device named “AWAIRE”. A confirmation dialog box opens up and gives the option to “Connect”. After clicking on connect button, the app establishes a communication with the sensor device and waits for a reading from the sensor.

Fig 6.5 Home Page

Fig 6.6 N95 mask as mask type

Once the app is connected to the device, the device sends PM2.5 and PM10 readings to the app via Bluetooth. The app receives this data and shows this real time readings to the user in the home page as shown in Fig. 6.5. There is a column which shows PM2.5 exposure and another column which shows PM10 exposure in $\mu g/m^3$. The exposures are coloured according to the AQI category with respect to the exposure. A combined category is displayed in the middle which takes the worst of the category of PM2.5 and PM10 exposures and is coloured accordingly. The categories can range from "Good", "Satisfactory", "Moderate", "Poor", "Very Poor" and "Severe". Each of these categories has a colour associated with them as shown in Fig. 1.1.

The exposure is calculated based on the type of mask selected by the user. N95 mask reduces exposure by atleast 95% [17], therefore the exposure will be reduced by 95% and shown to the user. This is made apparent in Fig. 6.6. Cotton handkerchief and surgical masks have efficiency of 28% and 80% respectively against particulates [12]. FFP1, FFP2 and FFP3 masks have efficiency of atleast 80%, 94% and 99% respectively [18]. We also show a cloud with emotion to visually indicate the level of exposure the user is exposed to. If the exposure category is Good, the emotion will be happy and other categories have different emotions associated with them.

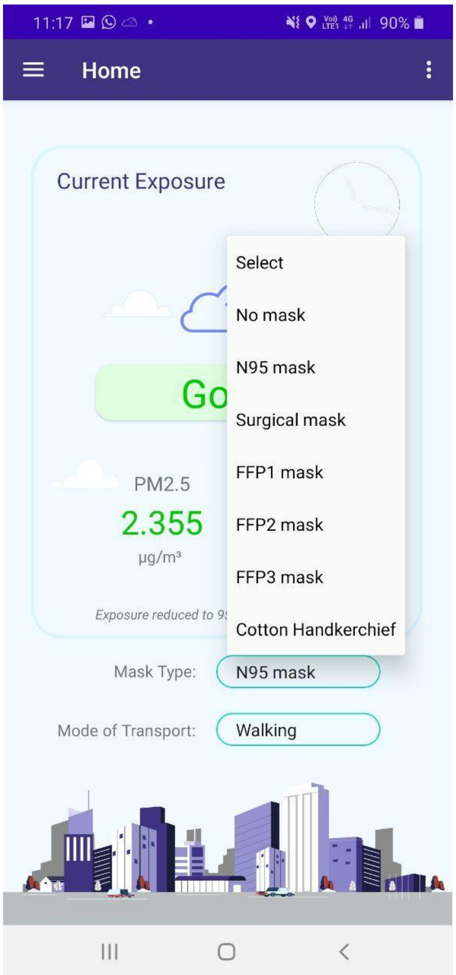

Fig 6.7 Mask type options

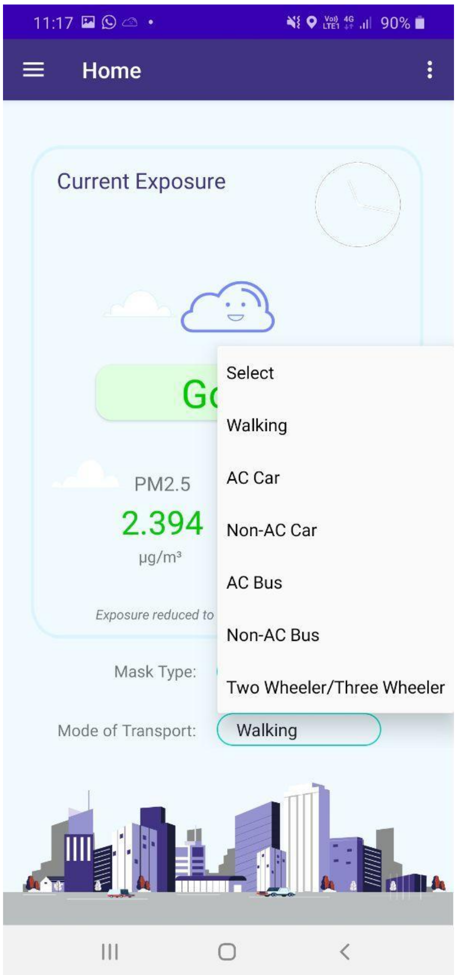

Fig 6.8 Mode of transport options

The app provides several types of masks that the user can select according to what he is currently wearing. Each type of mask reduces the exposure of the user to some degree. This reduction in exposure is taken into account by the app based on the type of mask the user has selected. The mask type options are shown using a Spinner as shown in Fig. 6.7. It also provides different types of mode of transports for the user to select from. This selection does not reduce any exposure but is useful for analysis and travel pattern of the user. The user can accordingly take steps to reduce their overall average exposure every day.

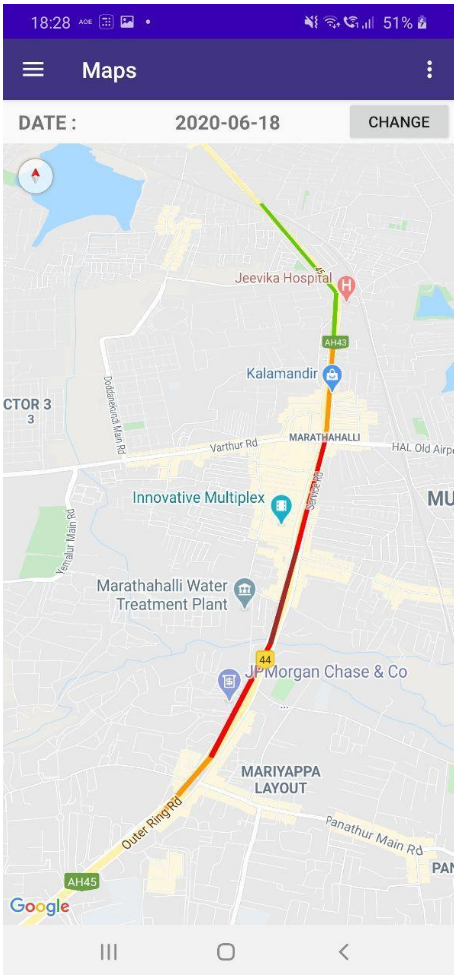

Fig. 6.9 Maps Page

The Maps page gives a visual representation of the travel history of the user and the exposure they face throughout the day. The path of travel is marked on the app which makes use of the Google Map service. The app also colour codes the path according to the exposure faced by the user at that location. The colours assigned to the path is in accordance to the category the PM2.5 and PM10 exposure values at that location and with reference to Fig. 1.1. It shows the travel history for the current day. The user can see previous days' history by selecting the required date from the date picker on top. The map then shows the selected days travel history. This gives the user a detailed view of where there is more pollution and accordingly change his travel path.

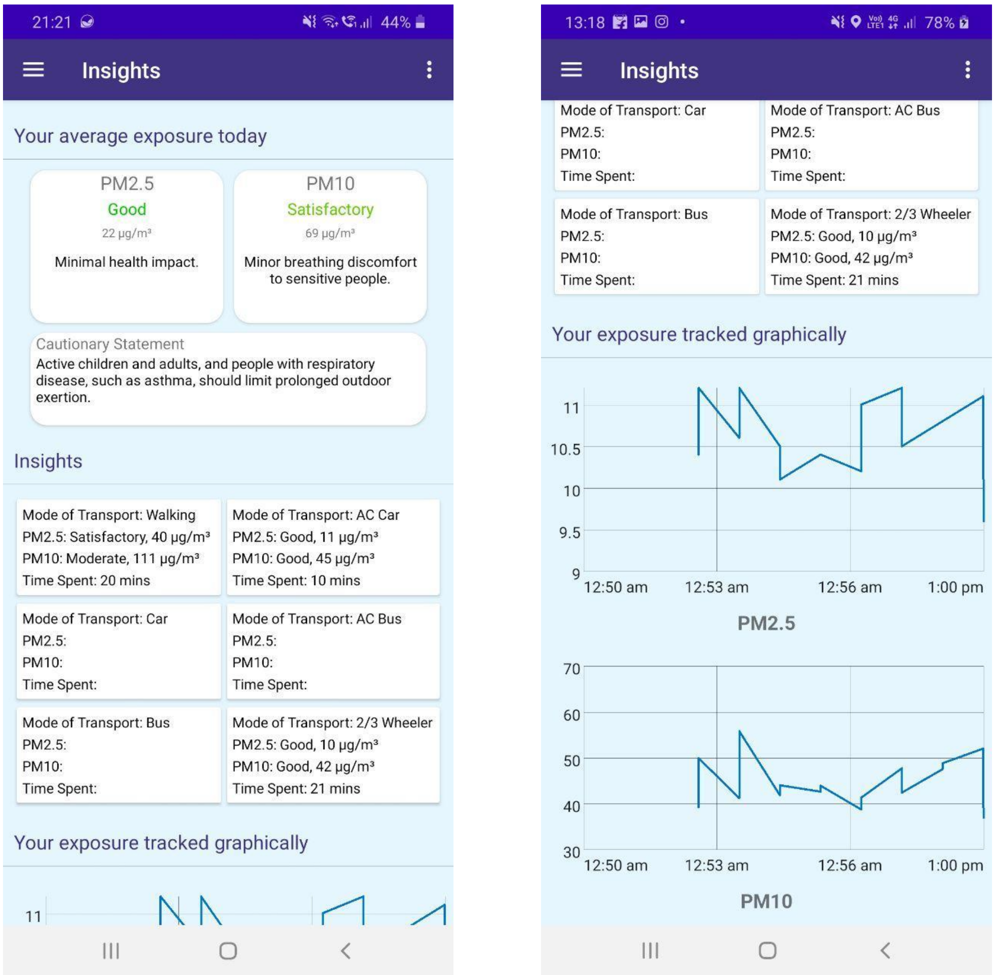

Fig 6.10 Insights

The Insights page gives the user useful information interpreted from all the data that has been collected so far by the app. The first thing the app shows is the Average Exposure of both PM2.5 and PM10 for the current day and shows the category of air quality. It also shows the health implications for the average amount of pollution you're exposed to in the day. This can help bring awareness to the user of the dangers that are associated with the high levels of PM exposure. The app also shows cautionary measures that needs to be taken with respect to the average exposure of the user. These are steps that the user can take in order to reduce their exposure and lead a more healthy life. The health implications and cautionary measures are derived from Fig. 6.1. The next section gives the user information about what mode of transport the user has used and for how long, as well as the average exposure in those mode of transports. This gives the user a good idea about which transport option gives the least exposure, for example, exposure can be significantly reduced by traveling in an AC Car than an open window car. The user can gain this insight and in future travel with the windows rolled up and AC switched on and notice the dip in subsequent exposures. The next section shows a visual representation of the exposure of the user in the form of a graph as shown in Fig. 6.10. The y-axis represents the PM2.5 and PM10 levels respectively and the x-axis represents the time of the reading. This provides a visual understanding of how exposure varies throughout the day and how it can be reduced in the future.

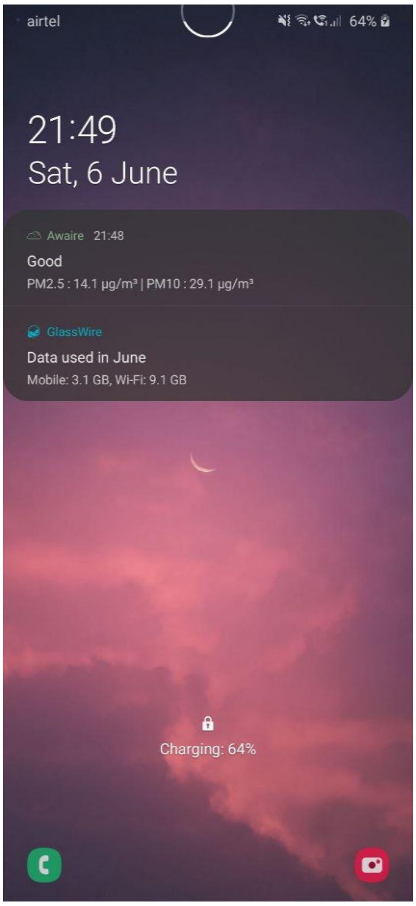

Fig 6.11 Lock screen notification

It will be difficult for the user to open the app every time he wants to see his exposure. So to make it easier, the app also shows a notification to the user with the real time PM2.5 and PM10 exposures. It also shows the Air Quality category of the current exposure. This can be seen on the lock screen as well as shown in Fig. 6.11, so the user does not even have to unlock their phone to see the exposure. The icon of the notification is the same as used in the home page and will show appropriate emotion with respect to the Air Quality category.

CHAPTER 7

TESTING

Testing was done at every stage of the project to make sure everything worked as expected and to ensure no unexpected behaviour was seen.

Unit Testing – We tested the various units in the system independently and made sure everything works as expected as independent units. The code on the ESP32 controller and connection to the sensor was tested using the Arduino IDE serial monitor as shown in Fig. 7.1. The mobile application was tested initially be sending dummy data from the sensor to the application and testing if all the functionality works as expected.

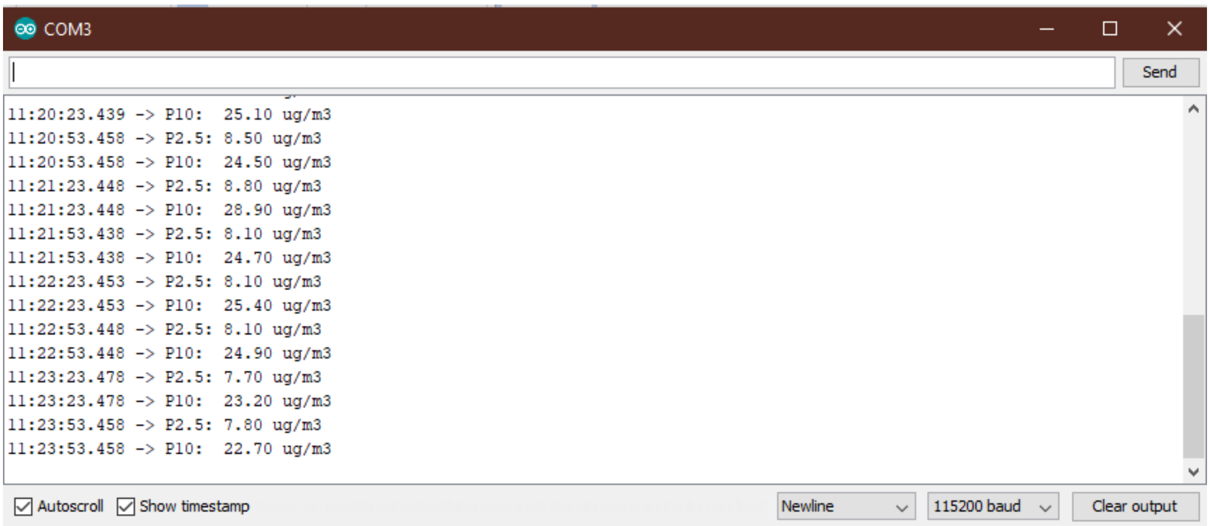

Fig 7.1 Arduino IDE Serial Monitor

Backend Testing – After every reading was received in the mobile application we tested and made sure this data was being sent to the Firsetore DB and also tested if the data sent was correct.

End to end Testing – A complete test of the system was done several times and after every change in the application in the development process. This testing is very important and makes sure the whole system works and provides the optimal result expected.

Usability Testing – One main focus was the user friendly interface of the mobile application. Usability testing was done by seeing if users can easily understand and navigate throughout the application with ease and without getting lost in the app.

CHAPTER 8

CONCLUSION AND FUTURE SCOPE

8.1 Conclusion

In this project, a personalized and portable air pollution monitoring system based on IoT is created. The readings from the Nova PM sensor is sent to the Android app, with the help of an ESP32 microcontroller. The app shows the real-time exposure of the user throughout the day and the average exposure at the end of the day.

It also indicates the pollution levels on a map while traveling. Its displays the significance of the pollution levels recorded along with its respective cautionary statement. The device will be made compact with a 3D printed case made for the sensor, microcontroller and the power supply to make the system durable and easy to carry. The sensor can be attached to an item that is always with the user, such as a bag.

This project is a unique implementation that is aimed to help people be aware and understand their exposure to air pollution. The Android app is user friendly, and easy to understand and use. It overcomes the drawbacks of existing systems and successfully monitors the user's exposure to PM2.5 and PM10 in a personalized way.

8.2 Future Scope

Future scope involves providing more security when it comes to connecting to the system and data collected.

More sensors can be added to the system, such as gas sensors, to determine levels of pollutants such as NO2, SO2 and others.

Also, use of Big Data Analysis to analyse the collected data when number of users increases. The data obtained by the devices of all the users can be consolidated, analysed and then displayed on a web application that can be accessed by anyone.

More statistics can be provided to get deeper insights into the collected data.

The gathered data helps the users to take precautions while travelling across highly polluted areas or to avoid visiting those regions. The data can be further supplied to the concerned authorities to take right measures to reduce pollution levels at the identified locations.

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APPENDIX A: Publications

Two research papers have been made for this project.

The first paper is about the project idea and the system design which has been accepted for publishing in "International Journal of Advanced Science and Technology" which is a Scopus Indexed journal. The paper is named "PERSONALIZED MONITORING OF AIR POLLUTION USING AN IoT BASED PORTABLE DEVICE".

The second paper consists of the implementation, result and conclusion. It is published in "Journal of Advanced Research in Dynamical and Control Systems" (JARDCS), which is again a Scopus Indexed journal. The paper is named "Personalized Monitoring of Air Pollution and Alert Generation Using an Android Application".

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APPENDIX B: PM Statistics

Around the world, ambient levels of PM2.5 continue to exceed the Air Quality Guideline established by the World Health Organization (WHO). WHO set the Air Quality Guideline for annual average PM2.5 concentration at 10 μg/m3 based on evidence of health effects of long-term exposure to PM2.5 but acknowledged that it could not rule out health effects below that level. For regions of the world where air pollution is highest, WHO suggested three interim targets set at progressively lower concentrations: 35 μg/m3, 25 μg/m3, and 15 μg/m3. Fig. 1 in Appendix B shows where these guidelines were still exceeded in 2016.

Based on these data and knowledge of the populations in each country for 2016, 95% of the world's population lived in areas that exceeded the WHO Guideline for PM2.5. Fifty-eight percent of the global population resided in areas with PM2.5 concentrations above the WHO Interim Target 1 (IT-1, 35 μg/m3); 69% lived in areas exceeding IT-2 (25 μg/m3), and 85% lived in areas exceeding IT-3 (15 μg/m3).

The highest concentrations of population-weighted annual average PM2.5 (see "Defining Ambient Air Pollution" textbox) in 2016 were in countries in North Africa (e.g., Niger at 204 μg/m3 and Egypt at 126 μg/m3), West Africa (e.g., Cameroon at 140 μg/m3 and Nigeria at 122 μg/m3), and in the Middle East (e.g., Saudi Arabia at 188 μg/m3 and Qatar at 148 μg/m3). The high outdoor concentrations in these regions were due mainly to windblown mineral dust. However, in some of these countries (Niger, Nigeria, and Cameroon), high proportions of the population burn solid fuels in the home and may also engage in open burning of agricultural lands or forests, both of which can also contribute substantially to outdoor air pollution.

The next-highest concentrations appeared in South Asia where combustion emissions from multiple sources, including household solid fuel use, coal-fired power plants, agricultural and other open burning, and industrial and transportation-related sources, are the main contributors. The population-weighted annual average PM2.5 concentrations were 101 μg/m3 in Bangladesh, 78 μg/m3 in Nepal, and 76 μg/m3in both India and Pakistan. The population-weighted annual average concentration in China was 56 μg/m3. Estimates for population-weighted annual average PM2.5 concentrations were lowest (≤ 8 μg/m3) in Australia, Brunei, Canada, Estonia, Finland, Greenland, Iceland, New Zealand, Sweden, and several Pacific island nations.

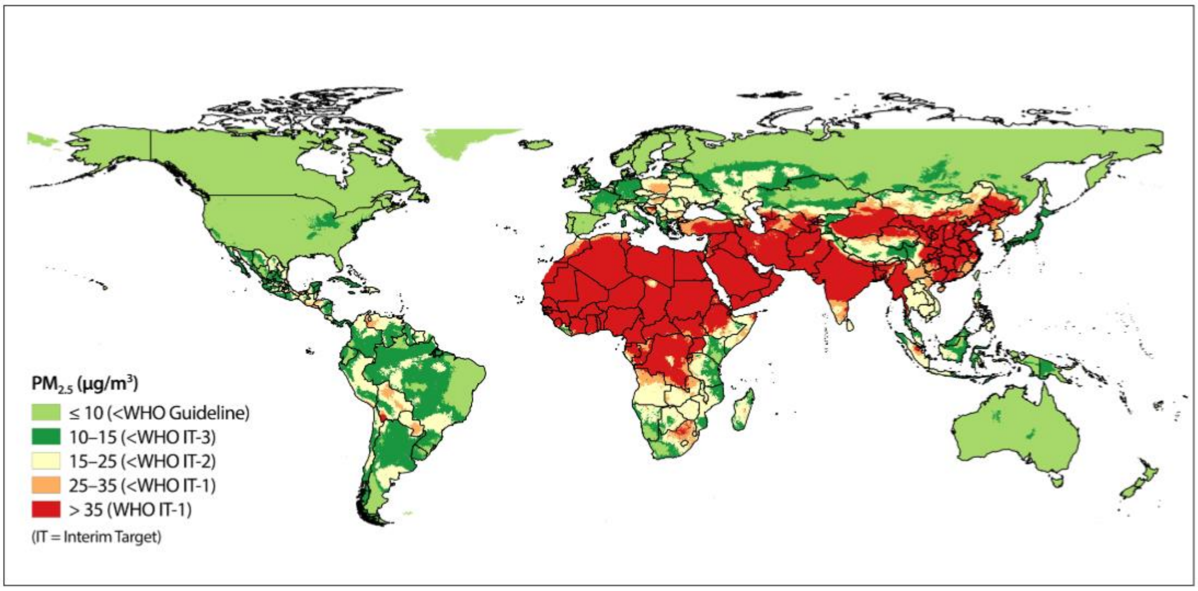

Fig 1 World average PM2.5 values

Main Trends in PM2.5 concentrations

Global population-weighted PM2.5 concentrations increased by 18% from 2010 (43.2 μg/m3) to 2016 (51.1 μg/m3). As the previous discussion on the most recent country data suggests, the global level of population-weighted PM2.5 is influenced strongly by the levels of air pollution in populous regions and countries.

China's air pollution exposures have stabilized and even begun to decline slightly; Pakistan, Bangladesh, and India, in contrast, have experienced the steepest increases in air pollution levels since 2010.

Fig. 2 in Appendix B illustrates the trends in population-weighted PM2.5concentrations for the 10 most highly populated countries in the world along with the European Union from 2010 to 2016 (see the interactive site for all years 1990 to 2016). India, Bangladesh, Pakistan, and China have all experienced both high concentrations and increasing trends in PM2.5 exposure, but there are noteworthy distinctions. Although China experienced substantial increases in population-weighted exposures before 2010 — reflecting in part the dramatic scale of economic development in recent decades — since then the exposures have stabilized and even begun to decline slightly. Pakistan, Bangladesh, and India, on the other hand, have experienced the steepest increases in air pollution levels since 2010 and now present the highest sustained PM2.5 concentrations among the countries shown here.

While Saharan Desert dust events are common and annually affect North Africa, between 2015 and 2016 anomalous wind patterns led to major dust events that also affected highly populated regions of West Africa. Nigeria, in particular, saw dramatic increases in PM2.5 concentrations resulting from an extensive dust storm in late 2015 and early 2016. However, longer-term trends suggest declines in PM2.5 exposures in Nigeria over the last 26 years, with limited evidence pointing to general declines in mineral dust emissions and open burning. Concentrations in the other highly populated countries (Russia, Indonesia, Japan, Brazil, and the United States, as well as the European Union) declined since 1990, yet, with the exception of the United States, remain above the WHO Guideline value.

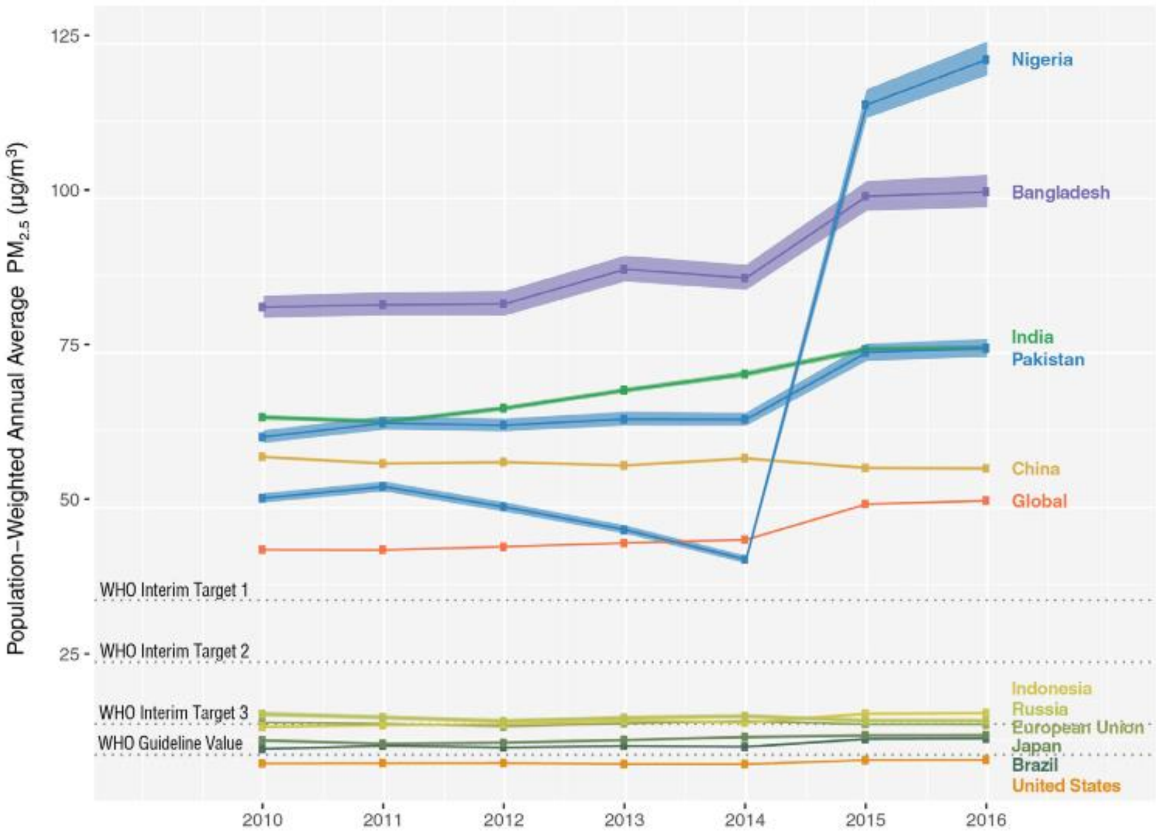

Fig 2 History of population-weighted PM values

Excluding the recent evidence of stabilization and slight declines in population-weighted concentrations in China, the disparities among these large countries have grown substantially over time. Less-polluted locations have become cleaner, while PM2.5 concentrations have increased in the more polluted locations, especially in South Asia. As a result, what was a 6-fold range in 1990 in population-weighted average concentrations among these countries (excluding Nigeria, given the likelihood of the 2015–2016 increase being transient) increased to an 11-fold range in 2016.