

Development of Cellular IoT-Based, Portable Outdoor Air Quality Monitoring System for Pollution Mapping [†]

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Abstract

In contrast to the existing Wi-Fi-based systems, we have developed a GSM-based, cellular-Internet of Things (C-IoT) enabled, portable air quality monitoring system that collects the critical air quality parameters through advanced sensors as well as location of the device using Global Positioning System (GPS). Our system utilizes sensors to monitor temperature, humidity, carbon dioxide, and Particulate Matter concentrations along with the location information. These sensors are integrated with ESP32 microcontroller which is interfaced with the GPS module for location information as well as with the GSM module to transmit the sensor data and location information to a central IoT gateway using existing cellular infrastructure. The developed C-IoT sensor node is powered through a portable power bank allowing complete mobility of the developed sensor node within the cellular coverage in the entire city. The data collected through the mobile C-IoT system is displayed in a live dashboard as well as over a live map for location-aware air quality monitoring. As a pilot run, we collected localized environmental data through developed node by moving around a pre-defined urban area to create a pollution map of the area.

Keywords: air quality monitoring; sensor node; Internet of Things (IoT); Cellular IoT; Localized Sensing

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1. Introduction

Air pollution is a serious issue that has been recognized as a global threat due to its contribution to premature deaths annually reaching 7 million [1]. Research has demonstrated a direct link between elevated pollution levels and adverse health outcomes within the population. Several factors contribute to this concerning situation such as rapid urbanization, industrial expansion, and population growth have led to increased emissions coming from vehicles. Heavy traffic has emerged as one of the primary challenges in urban environments [2]. A study indicated that, during identical trips, vehicles produced greater pollution due to increased fuel consumption in congested traffic conditions compared to less congested scenarios [3]. Additional challenges stem from outdated and inadequately maintained public transportation systems, as well as industrial emissions

from factories and power plants, which release high levels of harmful pollutants including sulfate, ammonium, nitrate, and black carbon [4]. Moreover, the burning of waste, emissions from household stoves and generators, and dust generated from construction activities and unpaved roads further deteriorate air quality in a more localized fashion [5]. In this scenario, there is a need to effectively monitor the air-quality in more localized fashion particular along road-side with heavy traffic.

Monitoring air quality is particularly challenging in urban and semi-urban areas where localized emissions from vehicles and industries vary dramatically. The advent of Internet of things (IoT) has enabled to develop low-cost sensor-based air quality monitoring systems (AQMS). The data collected through IoT systems is typically stored in cloud platforms for monitoring, visualization and data analysis [6]. However, existing systems generally rely on the Wi-Fi based connectivity that limits the usage of the AQMS at indoor or in a fixed location [7–10]. Therefore, large number of AQMSs are needed to monitor wider geographical area.

In this work, we have proposed and developed an AQMS that uses existing cellular infrastructure instead of conventional Wi-Fi to collect AQMS data. The proposed cellular-IoT (C-IoT) based AQMS is useful to monitor the air quality while moving around the city and record air quality parameters for a wide area thereby giving an opportunity to prepare a pollution map of a region.

In this paper, we report the design and development of C-IoT based portable AQMS for pollution mapping of an area. The developed system uses the specialized sensors to measure temperature, humidity, Particulate Matter (PM) concentration and Carbon Dioxide (CO₂) concentration. The sensors are integrated with ESP32 microcontroller collects the sensor data and periodically transmit to a central gateway through SMS messages by using a GSM modules. In order to identify the correct location of the sensor node, we used Global Positioning System (GPS) module to simultaneously collect the location information and send to central gateway along with the air quality data. The node is powered through a portable battery to ensure complete mobility of the system.

Rest of the paper is organized as follows. Section 2 presents system model for the development of the AQMS system. Section 3 describes the hardware configuration for the developed system. Section 4 provides a brief about the data collection and visualization at the cloud storage. We present the samples of data collected during drive test of the developed system in Section 5. Section 6 concludes the paper.

2. System Model

Our proposed C-IoT-based AQMS comprises two segments as illustrated in Figure 1. The first segment is the outdoor portable sensor node that is controlled by ESP32 microcontroller [11] and powered by a portable battery bank to ensure mobility. The microcontroller provides an interface between the air quality sensors and the GPS module [12] with the GSM modules. The location data collected through the GPS modules, and the air quality data collected through the sensors is aggregated by the microcontroller and communicated to the GSM module [13]. The GSM module transmits the collected data to the central gateway [14] as a SMS using the existing cellular infrastructure. This node also offers live data visualization of the sensed parameters through the OLED display.

The second segment of the system is the central gateway which is placed at a fixed location and provides the interface to route collected data to the cloud storage. The central gateway is also equipped with a GSM module to receive the data SMS. The GSM module in the gateway is connected to ESP32 microcontroller which can transmit data to the cloud using Wi-Fi as well as using USB connection with a dedicated computer. The comma-separated data in the SMS, as shown in Figure 2, is transmitted to a cloud for storage and

analysis. A web-based dashboard is also developed to for live visualization of the collected data.

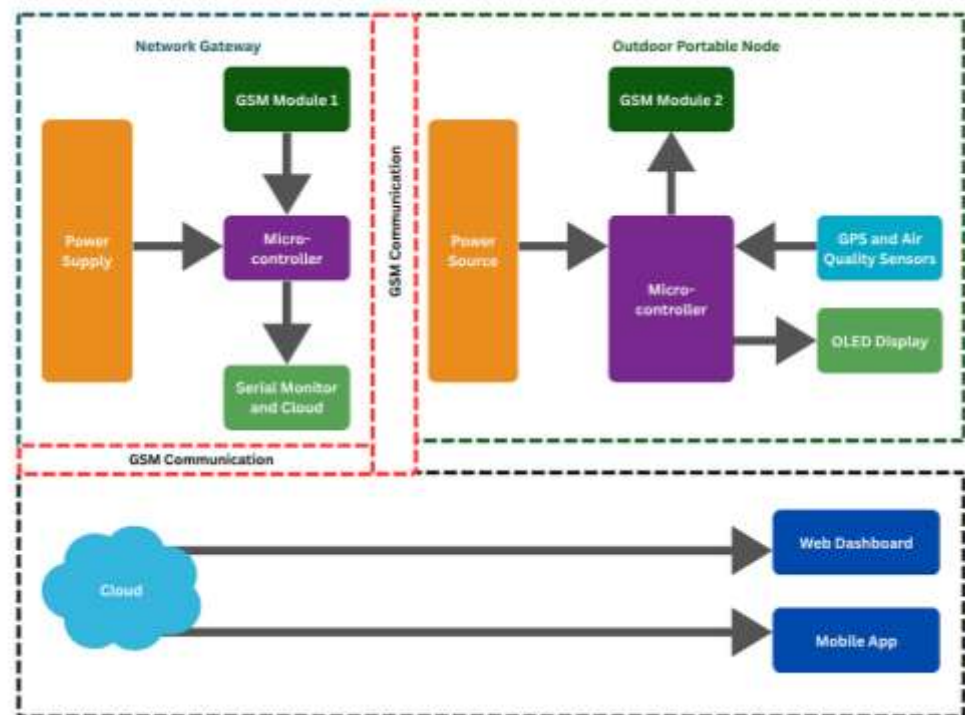


Figure 1. The system model for C-IoT based AQMS.

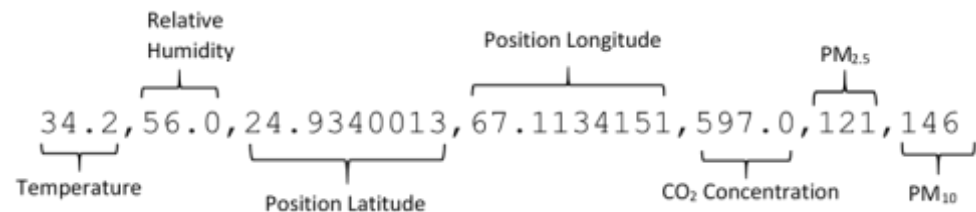


Figure 2. A sample of SMS containing the data transmitted from sensor node to the gateway using GSM module. For each value, the corresponding parameter is also indicated.

3. Hardware Development

The hardware development started with the selection of the appropriate components at for system development. In this work, we used ESP32 microcontroller [11] as the main processing unit for the mobile sensor node. From sensor side, we used DHT-11 sensor [15] to sense relative humidity and temperature, MQ-135 sensor [16] calibrated to measure CO₂ concentration, and PMS-5003 plantower sensor [17] to measure PM concentrations. Although, PMS-5003 is capable of recoding different PM concentrations based on the size of the dust particles, we used only PM_{2.5} and PM₁₀ to measure the concentrations of dust particles of diameter up to 2.5 μm and 10 μm , respectively. To collect location information, GPS Neo6m Module [12] was used. SIM800L GSM module [13] was used at the portable node to transmit the data SMS from the sensor node. To ensure the portable and robust hardware, a three-layer PCB design was conceived and fabricated as illustrated in Figure 3.

The top-layer serves as the main control and monitoring layer as it hosts the micro-controller, GPS module and OLED display module. The mounting of these components

on the top layer supports, reliable GPS positioning, easy visualization, effective heat dissipation, and easy microcontroller access for programming and debugging.

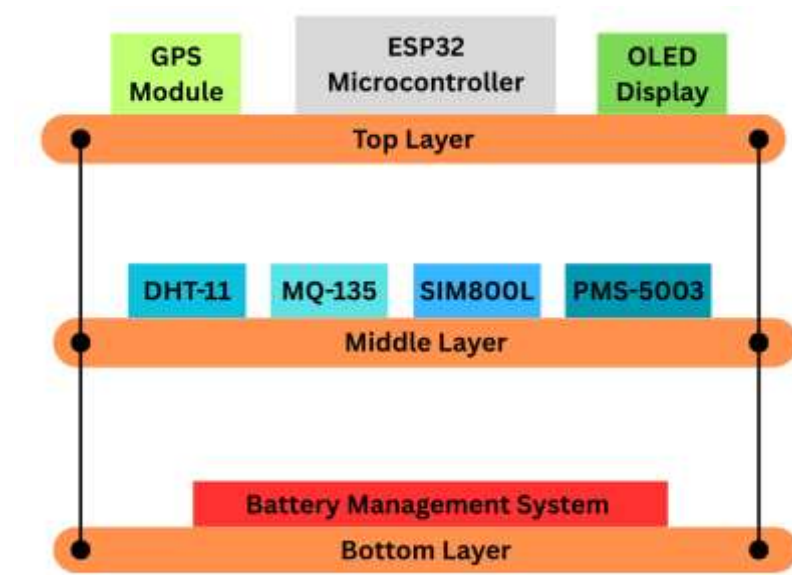


Figure 3. Illustration of three-layer design of the developed sensor node.

The middle layer serves as the sensor core of the system, which hosts the sensors and GSM module. Though the interface was provided through the middle layer of the system, all the air quality sensors were positioned in such a way that they are fully exposed to air for accurate measurement. The bottom layer of the system holds a battery management system to ensure all components get the required voltage and power for proper functioning. Each layer was designed on a 4×4 inch board. For PCB designing, we used EasyEDA tool [18] and then fabricated using conventional ironing and etching methods. Additionally, standoffs were used to ensure a consistent separation between the three vertically stacked PCB layers. The separation was approximately 4 cm in measurement. This enables a clear path for the air to flow between the layers to overcome the risk of heating up, improving the performance of the sensors, controller and power regulation circuits. The structure was then made rigid using some screws as spacers between the PCBs prevent electrical shorts and ensure structural integrity under harsh outdoor conditions and it also attached an acrylic base to the hardware for easier handling and portability. Figure 4 depicts the picture of the developed sensor node.

The gateway design was very simple as it required only interfacing of GSM module with the microcontroller. For the gateway, we used ESP32 D1 Mini microcontroller and SIM900A GSM module [14].

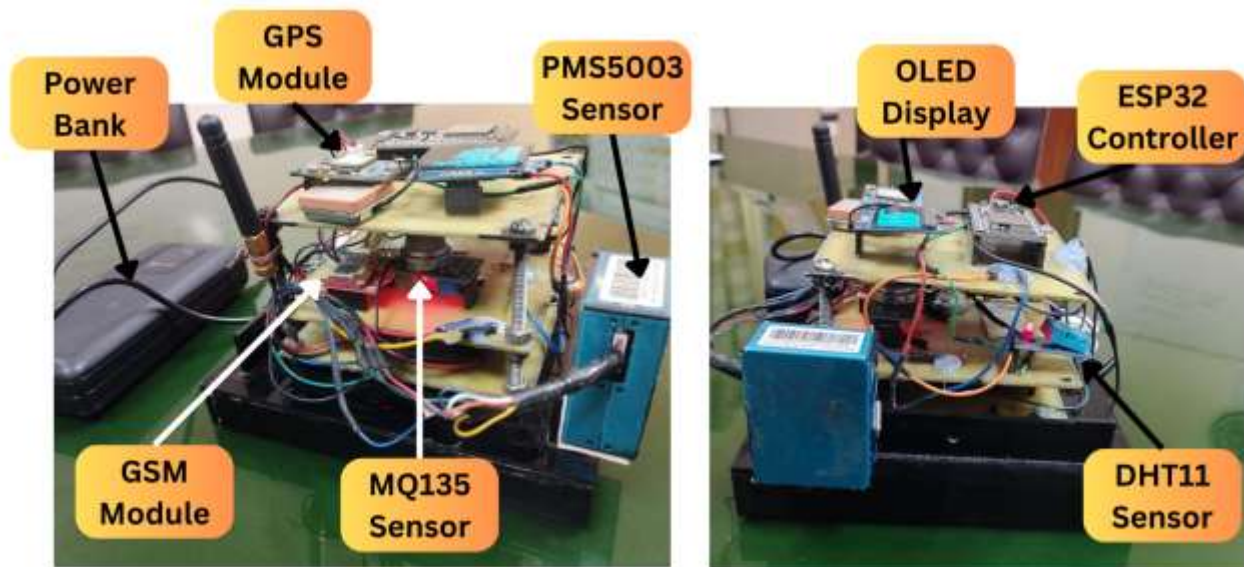


Figure 4. Two views of the developed sensor node indicating different components arranged in a three-layer design.

4. AQMS Data Visualization

In this section, we have presented the real-time, interactive dashboard developed to provide data visualization platform for our developed AQMS. We have used Google Firebase Firestore [19]. Firestore is a flexible, scalable database for mobile, web, and server development from Firebase and Google Cloud, allowing data to sync across client apps in real-time. Using Firebase, we have developed a custom real-time web dashboard to display the parameters used in monitoring, which include CO₂, PM_{2.5}, PM₁₀, temperature, and humidity. Moreover, using the dashboard, historical data of the mentioned parameters can also be seen allowing for users to understand the trend of sensor readings. The system also utilizes the location provided using GPS module to map location of the sensor node on the map. The dashboard is also customized for mobile-friendly view to facilitate monitoring for users on-the-go.

Figure 5 shows the dashboard GUI developed using Firebase for AQMS data visualization. Each air quality parameter can also visualized as a trend curve, displaying current and historical data. Figure 6. depicts an example of such plot, displaying PM_{2.5} levels recorded over an extended period of time. Similar graphs can be obtained for other parameters as well. Using the live map option, the GPS location of the node can be visualized in real-time as depicted in Figure 7.

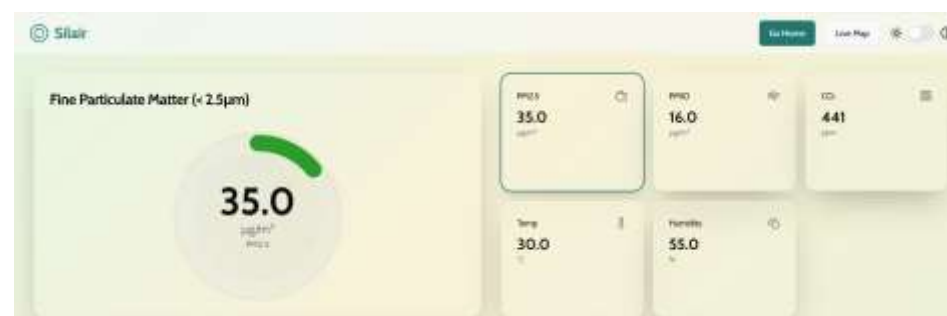


Figure 5. Portable AQMS Dashboard showing real-time PM_{2.5}, PM₁₀, CO₂, Temperature, and Humidity levels.

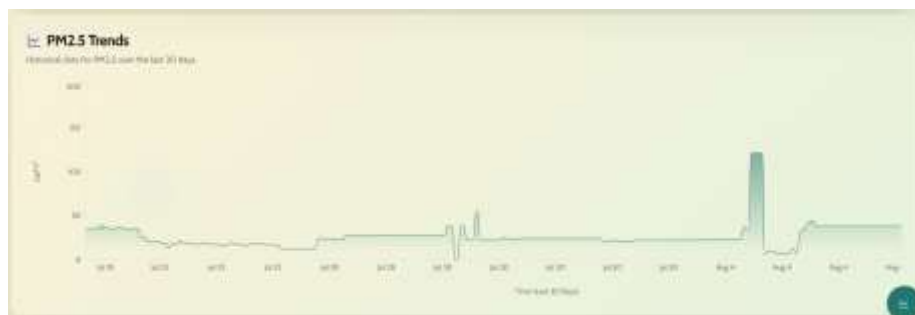


Figure 6. Dashboard showing real-time PM_{2.5} levels in ppm. Other sensor readings can also be accessed using the dashboard.



Figure 7. Map view showing GPS location of sensor node.

5. Results and Discussion

In this section, we have presented the details of results obtained through a sample drive test conducted over a travel distance of 6.18 km and a covered area of 1.936 km². The region covered through this drive test is a part of Gulshan-e-Iqbal town (East district) of Karachi Pakistan, a heavily populated, urban region with a population density of 33,776/km² [20]. Moreover, this region houses schools, colleges, universities, and several commercial buildings attracting hundreds of thousands of vehicles (bikes, buses, cars, rickshaws) every day.

For effective visualization, we have integrated the firebase with Google My Maps tool [21]. Using this tool, we have established a visualization system for the air quality data collected using the mobile AQMS sensor node. Figure 8. shows the visualization of the distance and route covered during the sample drive test generated via Google Maps. During the drive test, we measured several air quality parameters on 10 critical locations on the defined route. These locations were short-listed because of the nature of vehicular and passenger traffic experienced on these locations. Figure 9a depicts the sequence of air quality data collection where point 1 represents the first data collection point at the beginning of the drive test and point 10 represents the last data collection point where the drive test concluded. As evident from the figure, we have targeted data collection over intersections and locations where vehicular traffic aggregates (choke points). Figure 9b shows a sample of air quality data being visualized using the My Maps application. User of this platform can observe latitude, longitude position, temperature, humidity, CO₂, PM_{2.5}, and PM₁₀ concentrations.

Figure 10a depicts temperature levels measured in degree centigrade observed at the selected data collection points over the route. An interesting observation is that only in a region of 1.936 km², there is significant variation in temperature observed with highest temperature recorded is 36.3 degrees and minimum temperature recorded was 26.7 degrees (difference of 9 degrees). Overall average temperature recorded was 31.5 degrees. Figure 10b presents humidity levels measured in percentage recorded at selected locations on the route. Unlike temperature, the humidity levels recorded over the route show consistency with most of the data points showing same humidity levels.

Figure 11a,b shows the PM_{2.5} and PM₁₀ levels in ppm respectively, as recorded at selected locations on the route. Both figures depict consistent trend of PM levels as well as variation in said levels. Higher PM levels were observed around Block-6 of Gulshan-e-Iqbal. Figure 12. depicts CO₂ levels measured in ppm recorded at selected locations on the route. The levels recorded over the route are at acceptable levels (between 300 and 400 ppm). The variation in the CO₂ concentrations can be observed in the figure with minimum and maximum levels of 355 and 397 respectively.

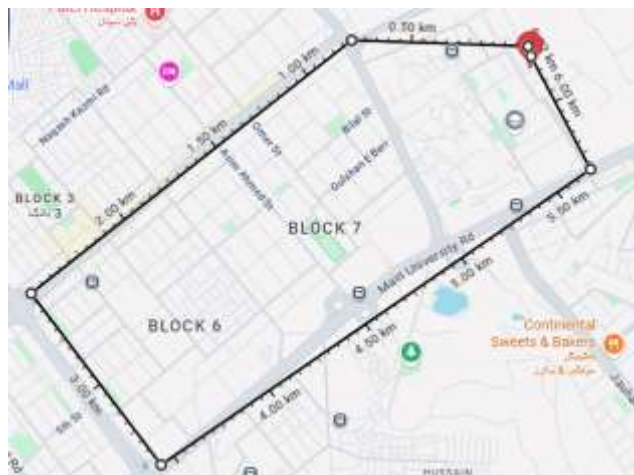


Figure 8. Distance covered during the sample drive test conducted to collect air quality data in outdoor environment.

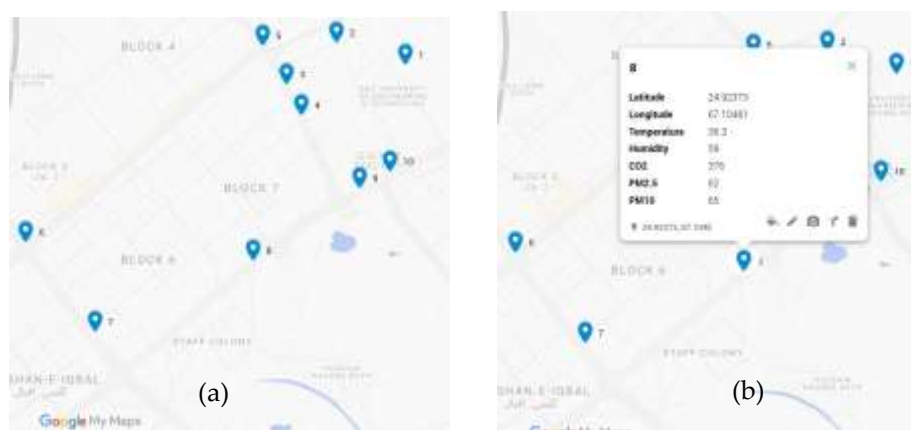


Figure 9. (a) Sequence of air quality data collection showing the road route taken for drive testing and (b) Sample of collected air quality data for one location.

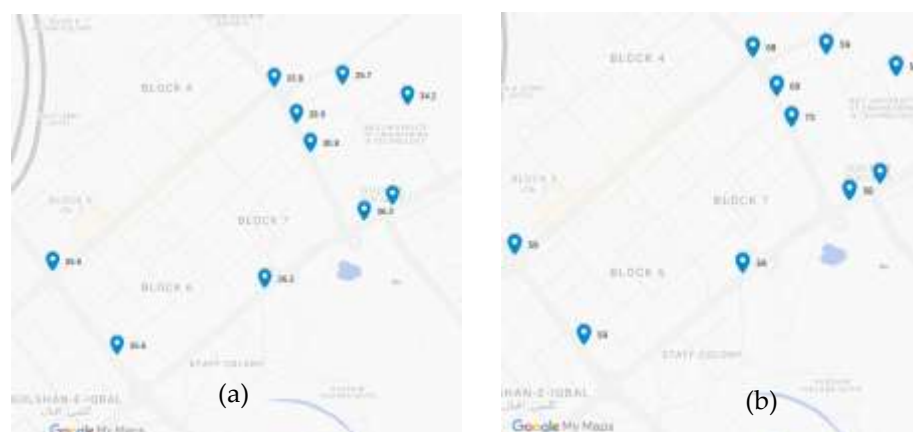


Figure 10. (a) Temperature levels (in °C) and (b) Humidity levels (in %) recorded at selected locations on the route.

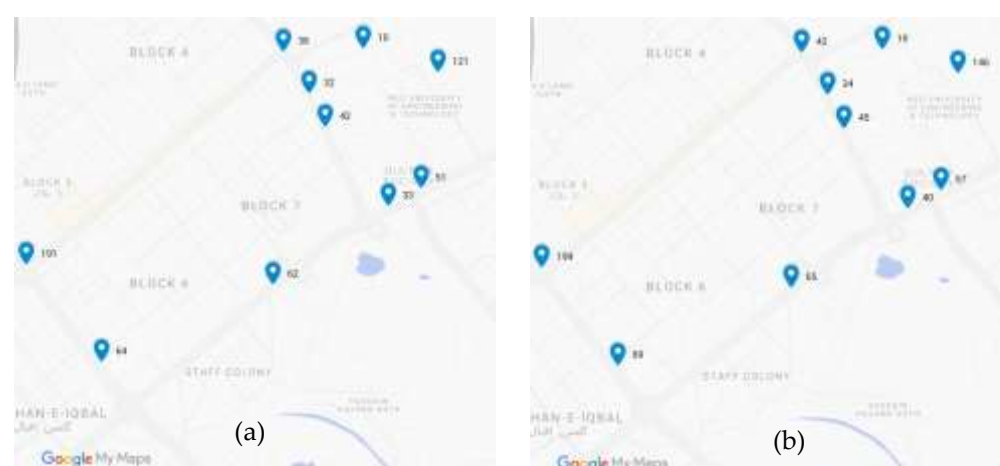


Figure 11. (a) PM_{2.5} levels (µg/m³) and (b) PM₁₀ levels (µg/m³) recorded at selected locations on the route.



Figure 12. CO₂ levels (ppm) recorded at selected locations on the route.

6. Conclusions

In this paper, we have presented the three layer design and development of the C-IoT based AQMS system. The system is designed to ensure complete mobility and collection of air quality parameters while moving around roads. Unlike conventional Wi-Fi

based IoT system, the developed system utilizes exiting cellular infrastructure to transmit collected data using SMS service. The developed AQMS is capable of collected temperature, relative humidity, CO₂ concentrating, PM_{2.5}, PM₁₀ values. Furthermore, the system also records the position in terms of latitude and longitude of the sensor node using GPS. A live dashboard is also developed for visualization of the recorded data. We have also presented the results of test drive using the developed system by recording air quality parameters in an area.

Author Contributions: Conceptualization, M.I.A. and S.A.; methodology, M.A. and I.A.; software, G.N.; validation, S.A., I.A. and M.I.A.; formal analysis, G.N.; investigation, M.A.; resources, M.I.A.; data curation, I.A. and S.A.; writing—original draft preparation, M.A. and G.N.; writing—review and editing, M.I.A. and S.A.; visualization, G.N.; supervision, S.A.; project administration, I.A. All authors have read and agreed to the published version of the manuscript.

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