Development of a Real-Time, Indoor Air Quality Monitoring System for Public Utility Buses With Wi-Fi-Based Occupancy Counting

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***Abstract*—As of 2016, 80% of the Philippines' air pollution is from motor vehicles, posing risks to drivers and passengers in Public Utility Vehicles (PUVs). Current AQM systems in the Philippines are limited to outdoor AQM stations in select areas. In other countries, studies have developed AQM systems for Public Utility Buses (PUBs) mainly for assessing outdoor air quality. However, analysis regarding Indoor Air Quality (IAQ) was not in-depth in most studies. There is a need to assess IAQ, especially in the Philippines where overcrowding is frequent which leads to increased air pollutant exposure. This study developed an IAQ monitoring system for PUBs with occupancy tracking. The system includes three IAQ nodes connected via a mesh network, linked to a gateway node, and an internet-connected web dashboard. Occupancy is tracked using a Wi-Fi module that scans for mobile phone MAC addresses. The dashboard displays cabin air quality, pollutant distribution, and occupancy count. Field tests showed that higher occupancy increased carbon dioxide (CO2) and volatile organic compounds, while particulate matter levels rose when doors were opened. CO2 levels were notably higher in crowded sections but dropped when doors were opened.**

***Index Terms*—indoor air quality, Internet of Things, public utility buses, Zigbee, Thread, BLE-MESH, passenger counting**

I. Introduction

In recent years, it was estimated that 11.65% of global deaths was attributed to air pollution [2]. The cause of air pollution is commonly associated with the combustion of fuels, motor engines, and industrial factories [3]. As of 2016, 80% of the Philippine's total air pollution comes from motor vehicles in traffic, posing high risks to drivers and passengers [4]. To address air pollution, Air Quality Monitoring (AQM) systems measure pollutants and alert users when dangerous levels are detected. AQM systems are important because the information they provide allows users to mitigate their risk of exposure [5]. This mitigation can be done using methods such as filters, exhaust fans, masks, or by avoiding the area itself. However, the Philippines lacks solutions that addresses air pollution in the transportation sector.

The study will focus on Public Utility Buses (PUBs) as it poses a high risk to air pollution exposure due to the nature of its operating conditions such as high passenger capacities, long travel times, and enclosed spaces. In other countries, mobile AQM systems have been developed and attached onto PUBs for monitoring outdoor air quality, ma. Although some studies include indoor air quality monitoring, they lack passenger interaction or attention to passenger health. Thus, in this study, the researchers aim to develop an AQM system that addresses the needs of the public transportation sector of the Philippines. This study focuses both on the passengers and environmental monitoring of air pollution. The factors that will affect air quality is passenger occupancy, air pollution concentration inside the bus cabin, and comparison with outdoor and indoor environments.

II. Bus Air Quality Monitoring Systems

A. Air Quality Monitoring Systems

Existing AQM system studies on bus primarily focus on outdoor air quality for pollution mapping along the bus route [8] [9] [10]. Additionally, the presence of multiple nodes and alert systems are only present on room AQM systems. Passengers of public transportation who are at risk of exposure to unhealthy air pollution should be informed when they are exposed to air pollution hazards. Some studies used a multiple sensor node implementation interconnected together through a wireless sensor network to cover a large area for better data accuracy [11] and [12]. In the Philippines, a survey conducted found that IAQ studies for PUBs have been limited to chemical and pollutant investigations, while real-time or IoT-based systems are not implemented yet [16].

B. Occupancy and Air Quality

Poor air quality may be directly correlated to the number of people in a room, especially without sufficient ventilation [6]. Dangerous pollutants such as carbon dioxide may accumulate and lead to health risks [7]. A study conducted in Tokyo University of Science developed a method for measuring the number of people in a PUB, where a packet sniffer device detects all nearby mobile devices by recording their unique MAC Address [14]. This approach may be implemented in an AQM system to estimate passenger occupancy and correlate it to air quality.

III. Methodology

A. System Overview

The overall system measures different metrics including air quality (AQ) metrics, supporting AQ metrics, and miscellaneous metrics. AQ metrics include carbon monoxide (CO), carbon dioxide (CO2), Particulate Matter (PM2.5 and PM10), Nitrogen Dioxide (NO2), and Volatile Organic Compounds (VOCs). Metrics supporting AQ include temperature and relative humidity. Lastly, other metrics such as occupancy estimate, bus speed, and location are also included in the system.

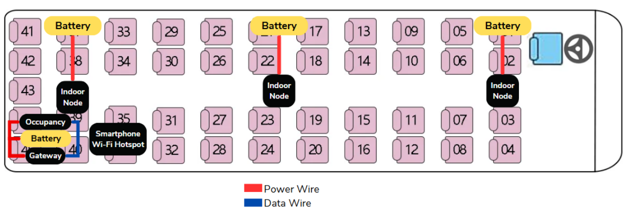

Fig. 1. System Setup and Sensor Node Locations

Figure 1 shows the sensor nodes' placements in the PUB. Three indoor nodes are employed to ensure the entire coverage of the PUB cabin. The gateway receives the node data through the mesh network, and uploads it to the website via Wi-Fi hotspot, provided by the nearest researcher at the rear of the PUB.

For this study, 3 different mesh networks were implemented and compared. These are the Zigbee, Thread, and Bluetooth mesh network.

B. Sensor Nodes

The respective components of the sensor nodes may be seen at Table I.

TABLE I
AQ Sensor Node Components

Component	Role / Measurements	Remarks
ESP32-H2 DevKit	Microcontroller	
SEN55	PM2.5, PM10, Temp., Rel. Humidity	
SGP30	eCO2, TVOC	
MiCS-4514	CO, NO2	Not in Back Node

The chosen microcontroller unit (MCU) for the sensor nodes in this project is the ESP32-H2-DevKitM-1-N4 for its low power consumption and IEEE 802.15.4 support [13]. To add, the front sensor node contains LED lights for the AQI alert system while the middle sensor node contains the GY-NEO6MV2 GPS module.

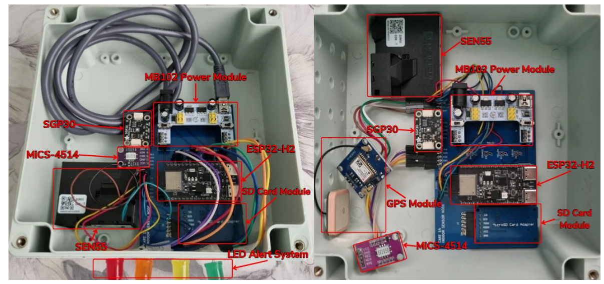

Fig. 2. Sensor Node 1 and Sensor Node 2

Seen in Figure 2 are the implementations of the front and middle sensor nodes with their respective components. To note, the powerbanks of nodes 1 and 2 are placed on the cover of the enclosure.

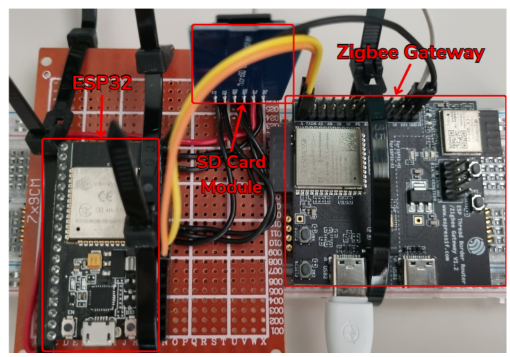

Fig. 3. Gateway Node with the Occupancy Sensor

For the gateway node, the MCU used is the ESP Zigbee Gateway board. It is a combination of an ESP32-H2 and ESP32-C3 chips connected through a Universal Asynchronous Receiver-Transmitter (UART) channel in a single board. It is also connected to the occupancy sensor through its second UART channel. The node can be seen in Figure 3.

The occupancy counter was developed using an ESP32 microcontroller as a Wi-Fi packet sniffing device. The algorithm estimates the number of people on the PUB by counting the number of nearby Wi-Fi devices such as smartphones, tablets, and laptops. The maximum count was set to 200 because PUBs cannot realistically fit people that will reach this count.

C. Information Display for Passengers

An onboard LED alert system is included in the AQM System implementation for passenger use. Meanwhile, data from the AQM system will be displayed through a publicly available Grafana web dashboard. An overview of how the AQM system interacts with the passengers is seen in Figure 4 below.

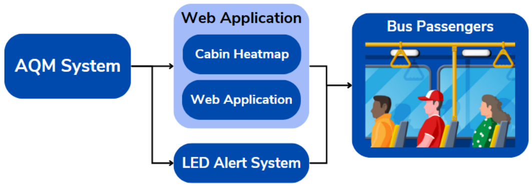

Fig. 4. AQM System and Passenger Interaction Overview

Fig. 5. Grafana Dashboard

Shown in Figure 5 is the Grafana web dashboard of the AQM system. The dashboard is divided into four parts: overview, front interior node, middle interior node, back interior node, and other metrics. The overview shows the overall AQI route map of the bus, AQI from each sensor node, and other bus information such as speed and estimated occupancy. For each sensor node, raw values and AQI of each pollutant along with temperature and relative humidity readings are also displayed.

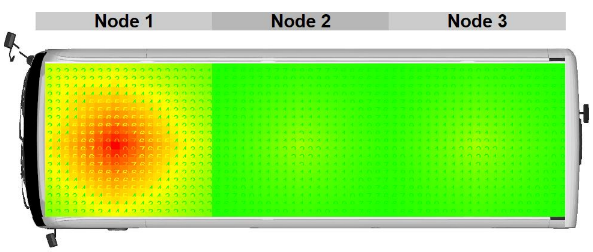

Fig. 6. Indoor Heat Map

To visualize the air quality inside the bus, an indoor heat map was created based on the AQI of each sensor node placed in different parts of the bus interior. Node-RED, a browser-based programming flow editor, was used to fetch data from the system via an MQTT broker and connect to the heat map created in Google Sheets.

D. Sensor Calibration

The AirGradient Open Air, as seen in Figure 7, was used as a reference to calibrate the SEN55 sensors. It can measure different air quality parameters such as temperature, relative humidity, PM2.5, and PM10 [15]. Calibration was done for at least one whole day and a simple linear regression model was created to adjust the SEN55's measurements in relation to the reference sensor's measurements.

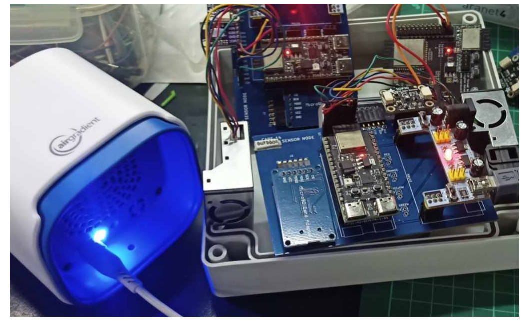

Fig. 7. Sensor Calibration with AirGradient Open Air Sensor

E. Field Testing

Test deployment was done at the EDSA Bus Carousel, having a dedicated bus lane and bus stops along the Epifanio de los Santos Avenue (EDSA) in Metro Manila. It is considered the most congested roadway in the metro. Field testing was done for at least two hours, with the stops being Main Avenue Station, Monumento Station, and Buendia Station.

During field testing, three separate researchers carried the nodes into position as seen in Figure 1. They then took note of the following significant information. The operation of the bus doors, changes in weather or temperature, and the manual counting of passengers on the bus.

F. System Characterization

System Reliability. The reliability of the AQM nodes were characterized using the criteria of upload success rate and upload delay. Upload success rate is characterized by counting the number of successful uploads as seen in 1. The researchers also determine the exact timestamps where upload failure occurs.

$$SuccessRate = \frac{\sum \text{Successful Uploads}}{\text{Total Upload}} \times 100\% \qquad (1)$$

Upload delay was characterized by measuring the difference of the website upload time against the offline data time. The average and median delay of all time stamps are calculated. Both the upload success rate and upload delay will be compared between Zigbee, Thread, and BLE network.

Network Performance. The performance of the Zigbee mesh network was analyzed through range and latency tests. Conditions for range testing include a free line-of-sight which simulates the conditions inside the PUB. Latency testing of Zigbee was performed by measuring the time it takes to receive sample data from another Zigbee node upon request.

Occupancy Counter Accuracy. The occupancy counter was compared to manual researcher counting. The accuracy is first tested in controlled environments with a constant number of people using the formula 2. In the PUB field test, its accuracy is calculated using linear regression in comparison to dynamic change in passengers. The data will also be analyzed by observing patterns or significant events in the time chart of the field test.

$$\text{Accuracy} = \left(1 - \frac{|\text{Device Counter} - \text{Actual Count}|}{\text{Actual Count}}\right) \quad (2)$$

IV. Results and Discussion

A. Air Quality Results

The field test was conducted where the northbound route from Buendia to Monumento was the first to be traversed from 4:32PM to 5:39PM, while the southbound route from Monumento to Buendia was traversed from 5:42PM to 6:35PM.

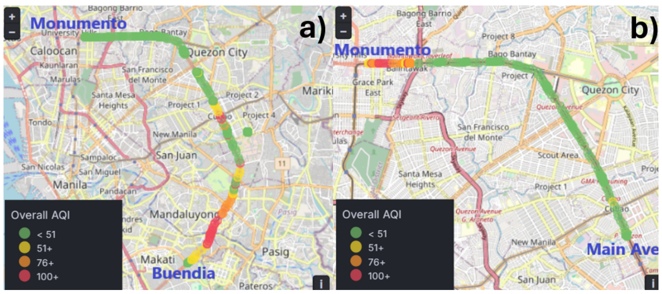

Fig. 8. AQI Maps of Northbound (a) and Southbound(b)

Based on the overall AQI values seen in Figure 8, Buendia stop and Main Avenue stop resulted in worse AQ compared to other stops along the northbound route. For the southbound trip, only in the initial station at Monumento indicated a high AQI.

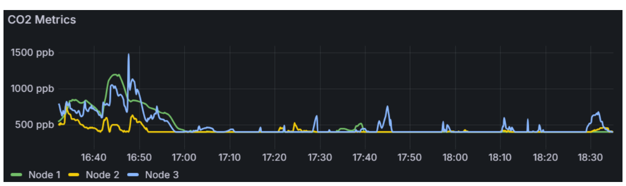

Fig. 9. Carbon Dioxide Readings

Carbon Dioxide. Figure 9 shows the CO2 readings from the field test, with nodes 1, 2, and 3 measuring the front, middle, and rear section of the bus cabin, respectively. Higher CO2 levels were measured from 4:40 to 4:50PM which may have been due to the increase in passenger occupancy inside the bus in Ortigas station. Afterwards, CO2 settled to lower levels as the bus traversed along the route. It was also observed that front and back sections have higher CO2 levels compared to the middle section. This may be attributed because the front interior of the bus is usually crowded the most while the section of node 3 is more cramped, leading to accumulation of CO2. Especially around 4:40 to 4:50PM, more commuters boarded the bus exceeding the seating capacity which led to spikes in CO2 levels. While the middle interior can be crowded at times, CO2 levels were generally lower due to bigger space and presence of large doors on both sides of the bus, which may helped lessened the accumulation of CO2 in the middle section.

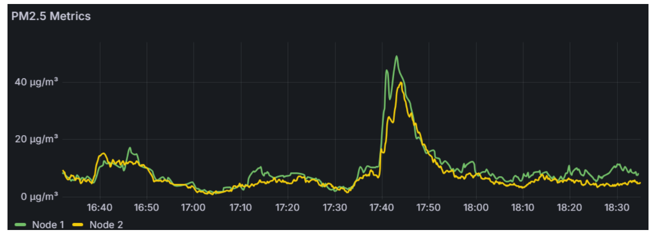

Fig. 10. Particulate Matter 2.5μm Readings

Particulate Matter. Figure 10 shows the PM2.5 readings on the field test. One notable observation is that from 4:40PM to 4:50PM, a notable increase in PM2.5 levels may be seen which may have been due to the frequent operation of the PUB doors located in both the front and middle of the PUB. In addition, the stop located at Quezon Avenue was where the bus experienced heavy traffic in both the bus lane and the other lanes in EDSA. Then on 5:40PM, the researchers exited the PUB to change routes and boarded the southbound PUB which indicated worse PM2.5 levels in the outdoor which may have been due to heavy vehicle traffic in the area. At 5:42PM, the significant rise in PM2.5 levels may be attributed to the observed cigarette smell upon boarding the bus on the southbound trip. The front node had a slightly higher reading compared to the middle node, suggesting that the source of the pollutant was closer to the front of the bus.

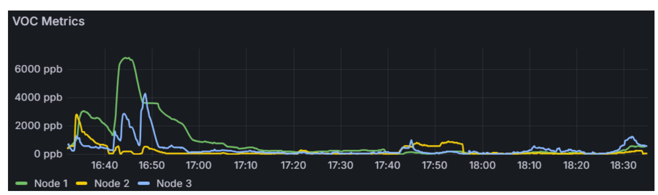

Fig. 11. Volatile Organic Compound Readings

Volatile Organic Compounds. Observing the VOC readings in Figure 11, it can be seen that VOC and CO2 correlate with each other and that similar to the trends seen in the CO2 readings, both the front and rear nodes share a higher level of VOC readings due to the more crowded nature in that area of the PUB. In addition, the VOC readings were also highly correlated with the presence of perfumes, alcohol sprays, etc. From 4:32 to 5:00PM, different scents mixed in the air as the PUB was crowded. However, just past 4:50PM, readings from the back and rear nodes steadily decreased while the front node stayed relatively the same. This was because from past 4:50 to 5:00PM people were still relatively crowded at the front of the PUB.

B. System Reliability

Upload Success Rate. The success rate was calculated by measuring the number of uploads from the mesh network to the online website. Furthermore, the uploading rate was varied between 5 seconds, 10 seconds, and 30 seconds. The Zigbee, Thread, and Bluetooth mesh network was calculated as seen in Table II. Thread and Bluetooth performed reliably, especially at 30 seconds where both have a 100% success rate. Zigbee performed poorly. The trend for all networks is that as the sending rate is increased, the success rate also increases.

TABLE II
UPLOAD SUCCESS RATE NETWORK ANALYSIS

Mesh Network	Upload Period	5 sec	10 sec	30 sec
Zigbee	Node 1	26%	74%	91%
	Node 2	27%	87%	87%
	Node 3	26%	76%	91%
	Average Success (%)	**26%**	**79%**	**90%**
Thread	Node 1	91%	99%	100%
	Node 2	91%	93%	100%
	Node 3	90%	99%	100%
	Average Success (%)	**91%**	**97%**	**100%**
Bluetooth	Node 1	98%	100%	100%
	Node 2	99%	100%	100%
	Node 3	97%	100%	100%
	Average Success (%)	**98%**	**100%**	**100%**

Upload Delay Analysis. The delay of of the system was calculated by measuring the difference between the local data time and the online website arrival time. The Zigbee, Thread, and Bluetooth mesh network was calculated as seen in Table III. The Thread network had the shortest delay of 1.95 seconds during the 30 second upload rate.

TABLE III
UPLOAD DELAY NETWORK ANALYSIS

Mesh Network	Upload Period	5 sec	10 sec	30 sec
Zigbee	Node 1	11.58	13.35	6.47
	Node 2	11.07	9.24	25.10
	Node 3	12.25	14.60	19.11
	Average Delay (s)	**11.63**	**12.39**	**16.89**
Thread	Node 1	9.91	1.62	2.21
	Node 2	10.05	1.96	1.82
	Node 3	10.07	1.75	1.81
	Average Delay (s)	**10.01**	**1.78**	**1.95**
Bluetooth	Node 1	6.95	4.68	5.13
	Node 2	6.94	5.29	5.08
	Node 3	7.69	6.00	5.90
	Average Delay (s)	**7.20**	**5.32**	**5.37**

C. Occupancy Counter

In initial tests, the occupancy counter succeeded in detecting control devices owned by the researcher. The device names would appear on screen whenever their Wi-Fi was turned on as seen in Figure 12.

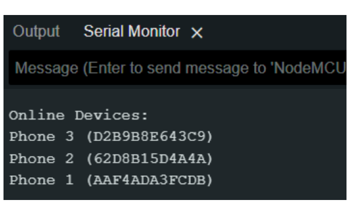

Fig. 12. Detection of Researcher Wi-Fi Devices

Accuracy was tested in isolated locations with clear line of sight to all phone users. The results are as follows in Table IV.

TABLE IV
CONTROLLED ENVIRONMENT ACCURACY TEST

Setting	Accuracy
Outdoor Gazebo	88%
Outdoor Parking Lot	80%
Large Lecture Classroom	74%

In the PUB Field Test, the occupancy sensor performed poorly. In Figure 13, there is almost no relation between the occupancy counter and actual passengers. From 4:32PM to 5:22PM, the passenger count was around 50. Meanwhile, the device counter would fluctuate between 200 and 0 passengers. The linear regression score for this data is -0.2852.

Based on the map data, it was found that the counter would spike near malls or train stations. It would drop to near 0 in areas with no buildings. The possible reason for this is that almost all passengers on the bus are using mobile data instead of Wi-Fi. Philippine PUBs do not provide free Wi-Fi access, so the context of Wi-Fi scanning was ineffective for the field test.

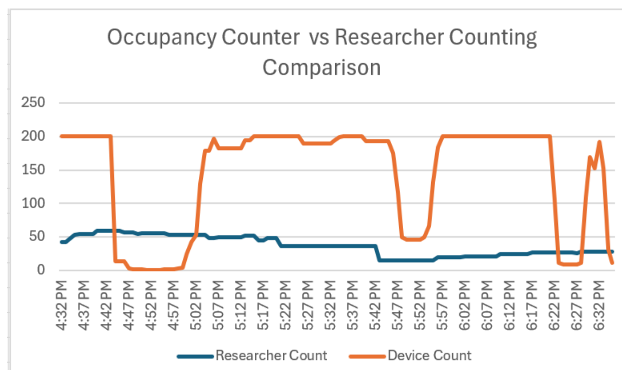

Fig. 13. Occupancy Counter vs Manual Researcher Counting

V. CONCLUSIONS AND RECOMMENDATIONS

The Indoor Air Quality Monitoring System was able to acquire and display air quality and occupancy information on the website through the use of the MQTT protocol. Passengers who use the website are informed about the air quality status in all sections of the PUB. They may expect delays of up to 30 seconds, but will still be updated at least once every minute regarding the status of the PUB. The wireless mesh network allows for seamless data transfer across multiple nodes.

Trends in air pollutant concentrations inside the PUB may be attributed to numerous factors such as bus capacity and opening of doors. PM2.5 levels may be attributed to opening of doors at bus stops and heavy traffic which led to prolonged exposure to dust and smoke. CO2 and VOC levels were also observed to spike with increased passenger capacity and tighter spaces. Also, VOC levels were also observed to increase with the presence of perfumes and alcohol sprays.

The Wi-Fi based occupancy counter is not a reliable method of measuring and estimating the number of people on the PUB. It was able to perform well in a controlled environment with accessible Wi-Fi, proving that it is capable of counting devices. However, in a public transportation setting, the concept of Wi-Fi is inapplicable to the current culture of technology where users primarily use mobile data to access the internet. It was found that the interference from approaching populated buildings resulted in overcounting. On the other hand, locations without interference lead to a count of nearly 0. This could mean that everyone on the PUB keeps their Wi-Fi off in favor of mobile data.

This may be the first real-time measurement campaign done to assess indoor air quality in PUBs in Metro Manila and the Philippines. The information from the website will help them make decisions beneficial to their health. This includes choosing where to sit for minimal exposure, or choosing whether to leave the PUB if air pollutants become too high. The proposed system also allows to gather air quality and other relevant data to urge the government for better policy-making to push for a better transportation system.

For future works, an implementation of an outdoor node for environmental monitoring would be ideal for comparison with indoor readings for the driver to conduct measures such as switching the air conditioning mode and opening of windows. A partnership or agreement with a bus company or the government to deploy is recommended for more secure installation and longer deployment period.

Acknowledgment

We would like to acknowledge the Department of Science and Technology (DOST) for funding for the UP Center for Air Research and Environment (CARE) Program. Also, we would like to give thanks to the J. Amado Araneta Foundation for providing financial assistance for this capstone project. Finally, we would like to thank the College of Engineering Office of the Associate Dean for Student Affairs for giving us the opportunity to be supported by sponsor organizations.

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