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Temperature, Humidity, and Light Intensity Monitoring System using Internet of Things on Mesh Network

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Abstract: This research discusses the use of the Internet of Things in monitoring the humidity, temperature, and light intensity conditions in a room that is connected in a mesh network. The objective of this research is to build a system that can monitor room conditions based on microcontrollers and interconnected in a mesh network. The data is then displayed on a dashboard and categorized as either a comfortable or uncomfortable room based on existing standards. To ensure the accuracy of the system's values, it is compared with commercial tools, and accuracy and precision are calculated. System's standard deviation for temperature is 0.12-0.19% while its RMSE is 0,16-0,48%, and for humidity the RMSE is 0,54-1,77%, with the standard deviation of 0.33-0.69%. For light intensity with the outlier is removed the RMSE is 1.1% - 4.90% and standard deviation 0.79-2.76%. All this value is still comparable to the commercial tools' accuracy on specification sheets. For packets loss the system is run continuously for 9 days and at the end the total data sent, and data receive at the server is calculated to count the differences. The packets loss after 9 day and 777.600 data is 0.00103%-0.00193%. from all 6 sensors used in the system.

Keywords: Internet of Things, mesh network, humidity, temperature, light intensity, dashboard, comfortable, accurate, precise

1. Introduction

The Industrial Revolution, a period marked by rapid technological advancements and mass production, significantly increased the demand for energy [1]. Initially, humans relied on natural resources like firewood and waterpower. However, the rise of mass production necessitated more efficient and powerful energy sources. The invention of the steam engine and the utilization of coal as fuel fulfilled this need.

The widespread adoption of fossil fuels like coal and oil enabled mass production at lower costs and in larger quantities[1]. However, this reliance on fossil fuels also contributed to global climate change, primarily in the form of global warming. Burning fossil fuels releases greenhouse gases like carbon dioxide, which trap heat in the atmosphere, leading to rising global temperatures. This intensifies effect on environment and human in many different ways, rise of ocean temperatures, rise of ocean surface level, intensifying of natural disaster from storm, flood to drought [2], [3]

Awareness of the detrimental effects of fossil fuels on the environment and human health has grown considerably. Consequently, the development of more environmentally friendly alternative energy sources like solar, wind, hydro, and biomass power has become increasingly important. Technological advancements like lithium-ion batteries and electric vehicles are also gaining popularity.

While alternative energy sources are becoming more prevalent and affordable, they are still generally more expensive than conventional fossil fuels. The initial investment costs associated with new infrastructure and technologies make them less accessible to many consumers and countries [4], [5]. Therefore, significant challenges remain in effectively replacing fossil fuels with alternative energy sources.

In the short term, fossil fuels will continue to be necessary to meet global energy demands. However, to reduce greenhouse gas emissions and mitigate the impacts of climate change, adopting more efficient energy conservation practices is crucial. This can be achieved through improvements in building designs, the development of more efficient appliances and vehicles, and the promotion of energy-conscious consumer behavior.

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Heating Ventilation and Air Conditioning or HVAC is one of the main contributors of energy usage in daily building operation. Another contributor is lighting, HVAC take up to around 30% and lighting take up to around 20% [6], [7].

The Internet of Things (IoT) offers a promising approach to optimizing energy consumption and improving efficiency in buildings. By connecting devices and sensors to the internet, real-time data on energy usage can be collected and analyzed. This data can then be used to automate and optimize HVAC and lighting systems based on occupancy, weather conditions, and user preferences. This can lead to conservation of energy and energy cost, at the same time reduce the negative effect of fossil fuel to the environment [8], [9].

IoT-enabled HVAC systems can utilize sensors to monitor temperature, humidity, and occupancy levels. Based on this data, the system can automatically adjust settings to maintain comfortable conditions while minimizing energy consumption [10]. Additionally, smart thermostats can be programmed to learn user preferences and optimize energy usage accordingly.

IoT-based lighting systems can employ light sensors and occupancy detectors to adjust lighting levels based on ambient light conditions and occupancy. This dynamic control can significantly reduce energy consumption without compromising lighting quality.

In older buildings with decentralized HVAC systems, mesh networking offers a viable solution for IoT implementation [11]. Mesh networks consist of interconnected devices that communicate directly with each other, eliminating the need for a central router or server. This decentralized architecture allows for flexible deployment and adaptability to varying building configurations. Mesh network also increase reliability with each node is looking for other nodes, this mean if one node is removed or off the other can take it place as relay and the network is not affected [12].

The Industrial Revolution revolutionized energy consumption patterns, leading to a heavy reliance on fossil fuels. While alternative energy sources are gaining traction, energy conservation measures and IoT-based optimization strategies are essential to mitigate the environmental impact of energy production and consumption. By embracing these approaches, we can transition towards a more sustainable and environmentally responsible energy future.

2. Related Work

The utilization of IoT (Internet of Things) for surveillance purposes has gained significant traction, particularly in industrial settings. However, prior research has primarily focused on industrial applications rather than domestic or indoor use cases. For instance, IoT has been employed in Industry 4.0 for predictive maintenance [13] and in the construction industry using proprietary platforms and machine learning [14], [15]. These approaches often result in expensive and inflexible systems, hindering their widespread adoption and limiting their potential to address climate change.

In the healthcare industry, IoT applications also face challenges, particularly in connecting devices to the internet. The most common solution involves GSM (Global System for Mobile Communications) for data transmission [16], [17]. However, employing GSM for building monitoring can lead to inflated costs and inefficiencies, rendering it unsuitable for this purpose.

Previous research has explored the use of multiple sensors, often employing MODBUS for inter-sensor communication [18]. This approach complicates network expansion and sensor addition, as it introduces additional costs. Other studies have utilized UART for inter-sensor communication and connected a microcontroller to the internet via existing Wi-Fi networks [19]. This method, however, is limited by the availability of Wi-Fi networks and requires an internet connection for operation.

LoRa (Long Range) has also been employed for inter-sensor communication before connecting to the internet via GSM [20]. This approach is constrained by LoRa's limited Line of Sight (LOS) range, necessitating minimal obstructions between sensors. Additionally, Zigbee, a closed-source protocol requiring costly licenses, has been used [21]. However, Zigbee is outdated and possesses security vulnerabilities. Mesh networks based on Wi-Fi protocols can address these issues.

Regarding controllers, some previous studies have replaced microcontrollers with Raspberry Pi [22]. While this significantly enhances computational capabilities, these capabilities remain largely untapped, as Raspberry Pi is primarily used for sensor data acquisition and relay control. This approach also limits further network expansion due to Raspberry Pi's higher cost compared to microcontrollers like ESP8266 or ESP32.

Other research has employed Arduino Mega and the AT&T M2X protocol [23]. This microcontroller falls between Raspberry Pi and ESP32 in terms of capabilities. However, Arduino Mega 2560 lacks networking capabilities, necessitating an Ethernet HAT to connect sensors to the network before using the M2X protocol for internet access. This method introduces cabling complexities and limits scalability. The AT&T M2X protocol is also closed-source, proprietary, and relies on a third party (AT&T) for operation. Additionally, DHT11 is commonly used as a temperature and humidity sensor [24]. This sensor employs one-wire protocol, which is known for its unreliability. Based on the author's experience, DHT11 sensors often fail to transmit data when used in systems with complex algorithms.

For light sensing, some previous studies have utilized LDRs (Light Dependent Resistors) [25], [26], [27]. These sensors rely on resistance to detect light intensity, necessitating pre-calibration before use. While less expensive than BH1750 sensors, LDRs are unreliable due to temperature sensitivity and slow response times caused by light-induced chemical reactions.

To address the limitations of existing IoT monitoring systems, this research proposes a novel system utilizing ESP32 microcontrollers, AHT10 temperature and humidity sensors, and BH1750 light intensity sensors. The proposed system offers several advantages from the previous works, one of the is reliability of new sensor run on I2C communication, and mesh network on Wi-Fi.

3. METHODOLOGY

A. Device design and implementation

The device is built using an ESP32 as the control unit. The ESP32 was chosen because the ESP8266 was not designed with mesh networking in mind. The mesh networking implementation and data transmission follow the research of [28] and are adapted to the sensors used. The sensors used in this research are an AHT10, and BH1750. The AHT10 is used to measure temperature and humidity. The BH1750 is used to measure light intensity. These sensors are then read and used as a reference for whether the device should turn the air conditioner or lights on or off. The IR receiver is used to record commands sent from the air conditioner remote control and then send them back if the device is going to turn the air conditioner on or off.

The device is designed to fit inside a standard electrical switch box, which is 100mm x 100mm x 61.2mm. The device will use SSRs and IR LEDs to control the air conditioner and lights. The SSRs will switch the power to the lights on and off. The IR LEDs will be used to turn the air conditioner on and off.

In addition to the sensors, an additional button is provided to turn the lights on or off outside of the schedule for a specified time. This is added for use cases such as room cleaning.

The testing environment for temperature and humidity was created in the form of a cube made of multiplex with dimensions of 30cm on each edge. The cube will be connected to a 300W thermoelectric cooler. The cube will be equipped with a 3w LED light as a light source.

B. Data acquisition

1) Temperature and Humidity

Data collection for humidity and temperature was done simultaneously. 6 devices will be placed at the bottom of the cube. The commercial device used as a reference was placed in the middle. 6 devices will be spread evenly around the commercial device.

Data collection was done for a cycle of 5 minutes on and 5 minutes off. When on for 5 minutes, the thermoelectric cooler will turn on and blow cold air into the sensor. When off for 5 minutes, the polarity of the thermoelectric cooler will be switched to blow hot air to the sensor.

Data was collected every second. Data from the devices will be sent via MQTT to a Raspberry Pi, received by the Mosquitto broker, and sent to Node-Red for display and sent to a database for logging. Data was collected for 100 cycles.

2) Light intensity

Data collection for light intensity was done simultaneously with temperature and humidity. The setup used was the same as for humidity and temperature data collection. The devices were placed inside the cube around the commercial device that was placed in the center of the cube. The light intensity was controlled by an application from the light manufacturer that sets the light intensity in 256 levels that change every second up to the highest position and down again in a 10-minute cycle.

Data was collected every second. Data from the devices will be sent via MQTT to a Raspberry Pi, received by the Mosquitto broker, and sent to Node-Red for display and sent to a database for logging. Data was collected for 100 cycles.

3) Data loss

Data transmission testing was done by sending data every 1 second, from 1 device to the Raspberry Pi. This was done for 9 days and the average data loss was observed. Data was sent by the device farthest from the Raspberry Pi. It was recorded in the database and the number of received data packets was counted.

Data transmission testing was done in a gypsum-walled room. 6 devices will be spread out on the left with a spacing of 6m between rows and columns. The device distribution will be in 3 columns and 2 rows.

C. System Evaluation

1) Accuracy

The accuracy of the data will be evaluated by calculating the root mean square error (RMSE) compared to a commercial device. RMSE is a statistical measure of the average difference between the predicted values and the actual values. A lower RMSE value indicates a more accurate system.

In the case of the temperature and humidity data, the RMSE will be calculated by comparing the temperature and humidity readings from the system's sensors to the readings from the commercial device. The RMSE will be calculated for each time step (every second) and then averaged over the entire 100-cycle test period.

For the light intensity data, the RMSE will be calculated by comparing the light intensity readings from the system's sensors to the light intensity readings from the commercial device. The RMSE will be calculated for each time step (every second) and then averaged over the entire 100-cycle test period.

2) Precision

The precision of the data will be evaluated by calculating the standard deviation compared to a commercial device. Standard deviation is a statistical measure of the dispersion of data points from the mean. A lower standard deviation value indicates a more precise system.

In the case of the temperature and humidity data, the standard deviation will be calculated for the temperature and humidity readings from the system's sensors. The standard deviation will be calculated for each time step (every second) and then averaged over the entire 100-cycle test period.

For the light intensity data, the standard deviation will be calculated for the light intensity readings from the system's sensors. The standard deviation will be calculated for each time step (every second) and then averaged over the entire 100-cycle test period.

3) Data loss

Data loss will be calculated by counting the number of data packets that are not received by the Raspberry Pi. The data loss will be expressed as a percentage of the total number of data packets that were sent.

A lower data loss percentage indicates a more reliable system. The data loss will be calculated from 9 days data consisting of almost 800.000 data for each node.

4. RESULT AND DISCUSSION

A. Testing medium

1) Temperature and Humidity

Before the experiment began, a 30x30x30cm cardboard box was prepared as the testing medium. Two types of testing media were created: one for temperature and humidity testing, and the other for light intensity testing.

For temperature and humidity testing, the first type was made with holes on the left and right sides for water to enter and exit, and another hole for the power cable to exit. Inside the testing media box, a Peltier cooler was placed with the cold side in contact with a heatsink that was given a fan, while the hot side was in contact with a water block that was circulated with water by a pump. Both the pump and the Peltier cooler were connected to a power supply that was set with a timer to cool for 5 minutes and heat for 5 minutes.

This testing medium can be seen in Figure 1. In the upper left part, the position of the commercial device and sensors can be seen during the preparation for measurement. In the upper right part, the placement of the Peltier cooler can be seen, and in the lower part, it can be seen when the testing media box is closed, the power supply and timer are on top of the box, and the pump is on the side.

2) Light intensity

For light intensity testing, an 8x8 LED matrix was attached to the top of the testing media box. The LED matrix was connected to an ESP8266 microcontroller that controlled the lighting level from 256 brightness levels, changing from 0 to 255 over 5 minutes and from 255 to 0 over 5 minutes.

Figure 1. Temperatur and Humidity measuring medium

This testing medium can be seen in Figure 2. On the left, the light source, sensors, and commercial device can be seen placed for testing. Once arranged, the testing media box is closed and measurements are taken. On the upper right, the sensors are seen placed on a 3D-printed bracket that ensures the sensors are at the same distance from each other. On the lower right, the light source from the LED matrix controlled by the ESP8266 can be seen.

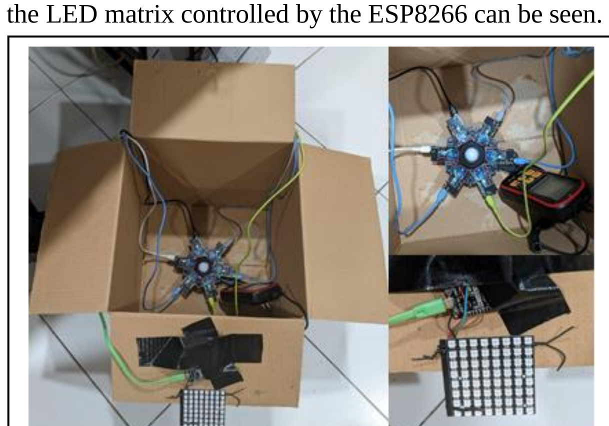

Figure 2. Light intensiy measuring medium

B. Ground truth

Ground truth used in this experiment is Benetech GM1030 for light intensity and Benetech GM1360A for temperature and humidity. The sensor is compared to this two commercial tools to assess it this sensor comparable to commercially available tools and can replace it.

C. Data storage

A Node-Red dashboard was created to log the data sent by the sensors into a CSV file. The function after the data is received from the MQTT broker contains code to add two columns, namely the time and date columns, to the data before it is saved to the CSV file. The CSV file is then saved to the Raspberry Pi for further analysis. This data flow translated to Flow on Node-Red shown on Figure 3.

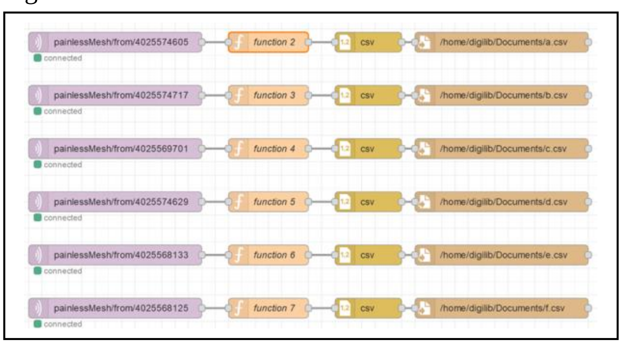

Figure 3. Flow on Node-Red for storing sensor data

D. Testing sensor for light intensity

Unlike temperature and humidity, for light, the light source is used is centralized in a relatively small area compared to the measurement room. The light intensity value will vary depending on the distance from the source to the measuring sensor. The high light intensity value will decrease quadratically with the distance from the light source.

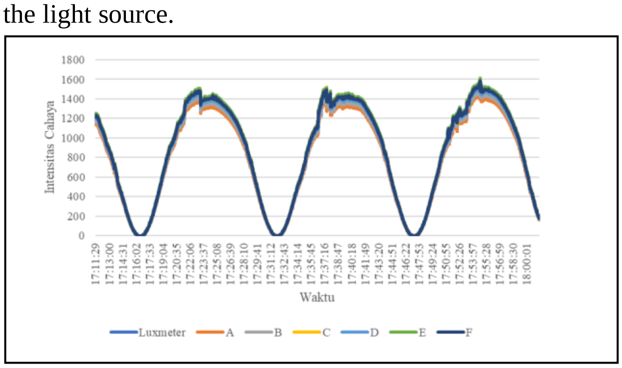

Figure 4. The first 3000 data of light intensity against time from all 6 sensors

This results in the sensor placement not being the same for each sensor and leads to differences in intensity on each sensor. This can be seen in Figure 4, which shows that overall, the sensors follow the trend of the reference sensor, but at high intensity there is a more noticeable difference in measurement due to the different sensor placements. Figure 4 below shows the first 3000 data from all 6 sensors.

When the light source is observed to undergo irregular changes, each sensor measures the change with the same trend direction. If the Pearson correlation is calculated between the commercial reference lux meter and each sensor, the values in Table 4.1 are obtained.

Table 1 shows that the values of each sensor are highly correlated with the values of the reference. To see the error value, the RMSE value of each sensor is calculated. Percentages are used because the values are quite large, ranging from a minimum of 0 to a maximum of over 1,600 lux. This is done so that the error value can show the accuracy of the sensor at all measurement values used in the experiment.

TABLE I. TABLE R VALUE FROM LIGHT INTENSITY DATA

	Nilai R
Sensor A	0.998696
Sensor B	0.999435
Sensor C	0.999717
Sensor D	0.999907
Sensor E	0.999115
Sensor F	0.999770

Table 2 shows that the error values are quite varied. This is because the light source uses a PWM mechanism to dim and turn on the light source. In very dark conditions, even a small change in the sensor reading can result in a very large error. Each sensor takes a value at a slightly different time from each other, but for ease of comparison, it is made into 1 data input per second. Both of these things, PWM and simplified data input to 1, cause some sensor readings to have a very large error percentage. This results in a lot of outliers. These outliers can be seen if we create a boxplot for all 100,000 data points.

TABLE II. RMSE AND STANDARD DEVIAITON OF LIGHT INTENSITY COMPARED TO COMERCIAL TOOLS

	RMSE	Standard deviation
Sensor A	4.59%	3.97%
Sensor B	6.31%	4.44%
Sensor C	3.91%	2.76%
Sensor D	2.34%	2.18%
Sensor E	4.78%	4.78%
Sensor F	1.77%	1.70%

From Tabel II the standard deviation and RMSE is quite big. The data is then visualized in Figure 5 as box plot on the left. This shows that the data has a quite a spread and need to be tidy up a bit. the outlier from each sensor then being removed according to each inter quartile range. The data later being visualized again is shown in the left side of Figure 5.

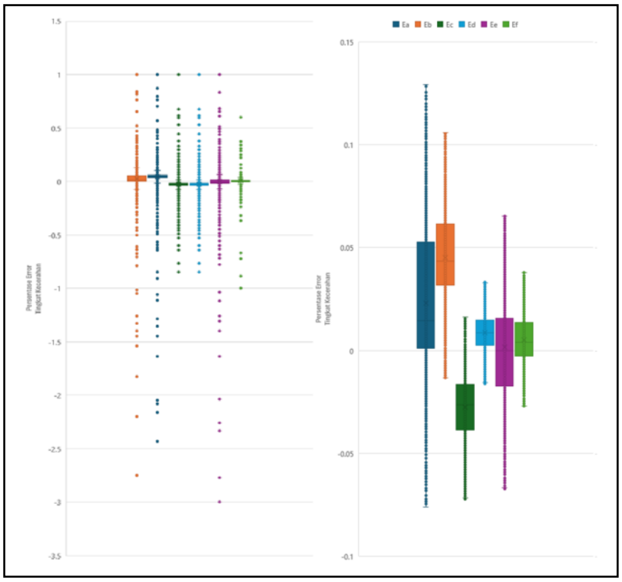

Figure 5. Data of llight intensity before removing outlier and after.

Both RMSE and standard deviation are much better than before the outliers were removed, but for sensor B, RMSE still exceeds the reference value of ±4% error. This value would be much better if the light source intensity were controlled using voltage or current.

TABLE III. RMSE AND STANDARD DEVIAITON OF LIGHT INTENSITY AFTER OUTLIER REMOVED

	RMSE	Standard Deviation
Sensor A	3.59%	2.76%
Sensor B	4.90%	1.95%
Sensor C	3.12%	1.47%
Sensor D	1.17%	0.79%
Sensor E	2.25%	2.25%
Sensor F	1.25%	1.14%

LEDs were chosen because they are relatively inexpensive and easier to set up than using current and voltage. LEDs can also be controlled more precisely for voltages or currents outside the working voltage or current.

In addition to the light source, the placement of the sensors also greatly affects the values read by each sensor. As can be seen from Figure 4, there is always a deviation from each sensor. If the sensor placement is exactly the same, this deviation can be reduced.

However, according to [29], the change in light that can be perceived by humans is 7.4%. The error value and standard deviation are still below this, which shows that the BH1750 sensor can still be used for everyday indoor applications.

E. Testing sensor for temperature

Out of the 100,000 data points that were taken, 1,000 data points were visualized in Figure 6 to see the difference between each sensor and the reference temperature. It can be seen that the difference in the values read is not far off. To clarify the difference in the values read, a boxplot was then created for the entire 100,000 data points that were taken.

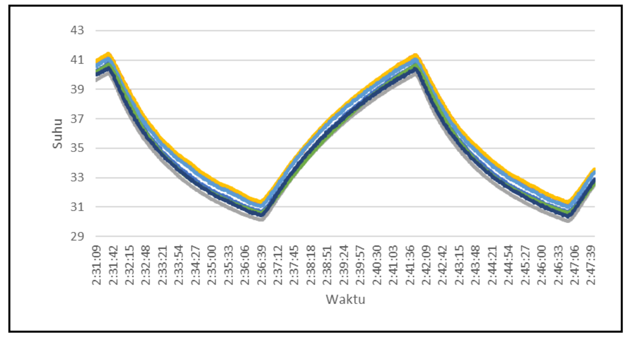

Figure 6. The first 1000 data of temperatur against time from all 6 sensors

Figure 7 shows the difference in sensor values compared to the reference. Since this boxplot was created with all 100,000 data, the values displayed represent the entire population of data measured by the 6 sensors. From this boxplot, it can be seen that the data distribution of each sensor is quite small, which is represented by the standard deviation value of less than 1%. The calculation of the standard deviation for each sensor is shown in the Table IV.

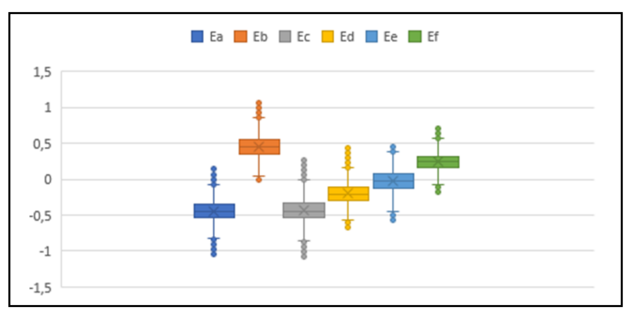

Figure 7. Boxplot of all 100.000 of temperature data from all 6 sensor

TABLE IV. RMSE AND STANDARD DEVIAITON OF TEMPERATURE

	RMSE	Standard Deviation
Sensor A	0.47%	0.15%
Sensor B	0.48%	0.14%
Sensor C	0.47%	0.19%
Sensor D	0.26%	0.16%
Sensor E	0.16%	0.16%
Sensor F	0.27%	0.12%

Referring to the boxplot in Figure 7, which shows the temperature distribution, it can be seen that the distribution value is still below ±1°C, with some outliers of -1.03°C, 1.06°C, and 1.07°C in sensors A, B, and C, respectively. In addition, all of these are still comparable to the commercial reference device used.

The RMSE of each sensor is not worse than that of the reference device, which is a maximum of ±1°C. With a standard deviation of less than 0.2°C and an RMSE of less than 0.5°C, the AHT10 sensor is considered sufficient for measuring room temperature. This refers to [30] where a temperature change of 0.92°C (±0.05°C) can be perceived by humans with 95% accuracy.

F. Testing sensor for humidity

Temperature and humidity are highly dependent on each other. The relative humidity value depends on the current temperature because the ability of air to bind water vapor depends on the air temperature. The higher the air temperature, the greater the capacity of air to bind water vapor. If the amount of water vapor in the air is constant, the relative humidity value will decrease if the temperature rises, and vice versa.

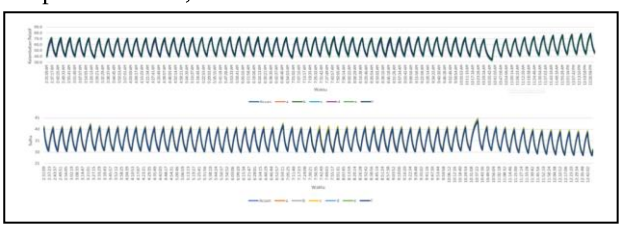

Figure 8. Value of termperature and humidity at the same time

The top portion of Figure 8 shows the humidity values read by the 6 sensors over time. The graph shows 10 hours or 36,000 data points so that the trend of the relationship between temperature and humidity can be seen. The humidity value is change with the changes in the temperature value in the opposite direction.

After ensuring that the sensors are functioning, the accuracy and precision of the sensors are then determined by calculating the RMSE and standard deviation of the sensors. The RMSE and standard deviation are calculated from the data that has been collected and written down in Table 4.6.

TABLE V. RMSE AND STANDARD DEVIAITON OF HUMIDITY

	RMSE	Standard deviation
Sensor A	1.260886	0.334768
Sensor B	1.773866	0.470935
Sensor C	1.223893	0.403527
Sensor D	0.544912	0.342023
Sensor E	0.693869	0.689724
Sensor F	1.062222	0.330923

Table V shows that Sensor D, with an RMSE of 0.545%, has the best value among all sensors. However, all sensors still have values below 3%. Three percent is used as a reference because the Benetech GM1360A reference device has an accuracy of ±3%.

To see the level of precision of this humidity measurement, a boxplot is created, as shown in Figure 9.

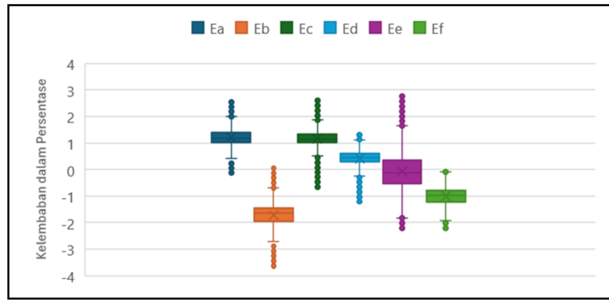

Figure 9. Boxplot of all 100.000 of temperature data from all 6 sensor

Figure 9 shows the distribution of the error for each sensor, with sensor E having the largest spread. This is consistent with the previous standard deviation calculation, which showed that sensor E has the largest standard deviation value.

G. Testing for data loss

To avoid disrupting the daily opearion at the university where the data was collected, data collection was conducted between December 23, 2023 and January 2, 2024. Data collection was carried out for 9 days or almost 780,000 samples.

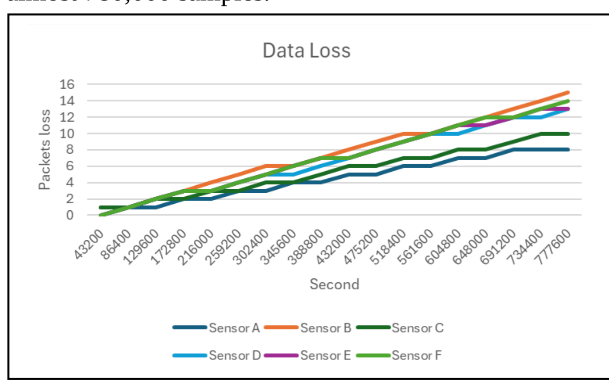

Figure 10. Number of packets loss sample every 12 hours for all 6 sensors

The data was sampled every 12 hours to see the recorded time at the time of transmission. This time was then compared to the reference time. If the recorded time was faster than the reference time, it meant that there were lost packets and data entries were missed. Each missed second meant that there was one lost packet. From Table 4.7, it can be seen that the lost packets do not have a fixed pattern but have a final value of 0.00103% or about 1 packet lost for every 100,000 transmissions.

For sensor B, as shown in Table VI, at the end of day 9 there were 0.00193% lost packets. This value is different from sensor A at 0.00103%. This difference in value may be due to the difference in the field between the sensors. For sensor C, as shown in Table VI, the value of lost packets is 0.00129%, which is between sensor A and B. Sensor A has a percentage of lost packets of 0.00103%, and sensor B has a percentage of lost packets of 0.00193%. Sensor D, as shown in Table VI, the value of lost packets is not far from the other three sensors at 0.00167%. Sensor D's percentage of lost packets is still between Sensor A, which has the smallest value, and Sensor B, which has the largest value.

TABLE VI. PACKETS LOSS AFTER 777.600 DATA SENT

	Percentage Packets Loss
Sensor A	0.00103%
Sensor B	0.00193%
Sensor C	0.00129%
Sensor D	0.00167%
Sensor E	0.00167%
Sensor F	0.00180%

The data from sensor E is shown in Table VI. Sensor E has the same percentage of lost packets as Sensor D, although Sensor E reached this value first at data point 734,400 shown in Figure 10.

The data from sensor F in Figure 10 has a trend that is almost the same as sensor E. However, in the last 12 hours there was one additional lost packet, making the percentage of lost packets for sensor F slightly worse than sensor E, or 0.00180% lost packets.

This packet loss value is far below the 1% benchmark used for acceptable values in Voice over Internet Protocol (VoIP) [31]. Unlike VoIP, temperature and humidity data collection does not require continuous data. Therefore, the packet loss value of this monitoring system can be used to monitor temperature and humidity.

H. Presenting live data on dashboard.

Data for each room is displayed on a dashboard in one sheet. Data received from the MQTT node is split into 6 outputs. Three outputs are in the form of gauges, and three are in the form of text. For text, ISO CIE 8995 - 2002 and OSHA 1910.1000 room standards are used. A workspace is considered comfortable if it has a light level above 200 lux, a temperature between 19.5-27.8°C, and a humidity below 65%. Figure 12 shows the flow of the dashboard, while Figure 12 shows the dashboard itself.

If the sensor reading is not up to standard each text on top of the gauge for every room will notify user about the condition. The color of the gauge itself will change according to value of the reading compared to the standard used.

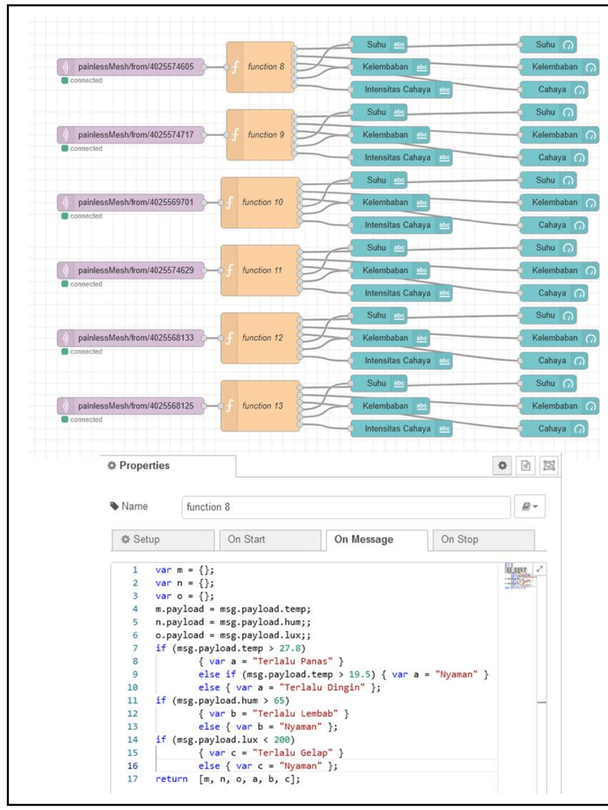

Figure 11. Flow of the Node-Red Dashboard

Figure 12. Appereance of the dashboard

5. Conclusion and Future work

From experiment above monitoring system for light intensity, temperature, and humidity could be made using ESP32, AHT10 and BH1750. This system is not dependent on existing wireless networks because of mesh networks that being used. The packets loss after 9 day and 777.600 data is 0.00103%-0.00193%.

For sensor that used in this experiment is comparable to commercial tools. Sensor AHT10 for temperature the RMSE is 0,16-0,48%, and the standard deviation is 0.12-0.19%, and for humidity the RMSE is 0,54-1,77%, and the standard deviation is 0.33-0.69%.

For light intensity because of the nature of the experiment using PWM the value sometimes erratic. So the outlier is need to be removed first. With the outlier is removed the RMSE is 1.1% - 4.90% and standard deviation 0.79-2.76%.All this value is still under the tolerance of the commercial tools' accuracy and precision.

The promising results of this study highlight the potential of the proposed HVAC and lighting monitoring system. However, further investigations are warranted to fully assess its robustness and applicability in real-world scenarios. To this end, the authors recommend the following areas for future research:

1. Impact of Obstructions on Packet Transmission:
2. Battery Life Evaluation
3. Network Reliability under Sensor Failures

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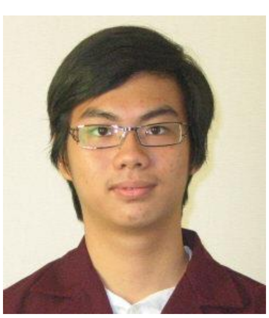

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