

Article

Design and Experimental Results of an AIoT-Enabled, Energy-Efficient Ceiling Fan System

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Abstract: With technological advancements, domestic appliances are leveraging smart technologies for getting smarter through learning from their past usage to enhance user comfort and energy efficiency. Among these, ceiling fans, though widely used in Lower- and Middle-Income Countries (LMICs) in temperate regions, still lack a cohesive system integrating all necessary sensors with a machine learning-based system to optimize their operation for comfort and energy saving and to experimentally verify the performance under different usage scenarios that could transform a high-power-consuming device into an energy-efficient system. Therefore, the present research proposes an experimentally verified and energy-efficient Artificial Intelligence of Things (AIoT)-based system that could be retrofitted with regular DC ceiling fans. An Internet of Things (IoTs) circuit, equipped with an ESP8266 microcontroller, temperature, humidity, and motion sensors, was designed to communicate with a developed Android application and an online dashboard. A total of 123 ceiling fans with the designed IoTs circuit were deployed at various household locations for two years, with manual operations for the first year. In the next year, an auto mode based on the predictions of the machine learning model was introduced. The experimental outcomes showed that the fan with added smart features reduced the energy loss by almost 50% as compared to conventional AC ceiling fans. Consequently, the carbon footprint of the appliances is reduced significantly. A high user-rated acceptability of the system, examined through a standard measure, was also achieved.

Keywords: artificial intelligence of things; ESP8266; system usability; user comfort; CO₂ emission; motion sensors; temperature and humidity; machine learning; BLDC fans; home automation



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1. Introduction

Over the past three decades, energy efficiency has gained special attention in most industries. From energy-saving system design to energy harvesting technologies, a wide range of strategies have been adopted to attain an overall high efficiency resulting in lower energy costs and reducing the carbon footprint. On one hand, energy harvesting from the environment using electromechanical phenomena such as the triboelectric effect provides the opportunity to embed energy harvesting in the building infrastructure; for example, in smart floors [1,2]. This effectively reduces the energy bills of a premises. On the other hand, domestic appliance industries have developed energy-efficient solutions for all applications [3,4]. From air conditioning to lighting, from televisions to washing machines, all modern domestic appliances are focused towards greater energy efficiency [5–7]. Energy efficiency can be increased and energy savings in lighting of up to 90% are possible when

controlling light intensity in a building corridor through an IoT system and Machine Learning (ML) algorithm [8]. With the increase in energy efficiency of domestic appliances, modern buildings are also becoming energy efficient by taking care of HVAC (heating, ventilation, and air conditioning) systems using IoT devices for data collection and energy monitoring. Using LSTM (Long Short-Term Memory) machine learning models, an improvement of 17.4% in energy efficiency in the building is achieved [9]. Apart from smart HVAC systems in buildings for energy efficiency, an IoT-based Plug Load Management system can be used in a commercial building which can automate the load using different control strategies resulting in a 7.5% improvement in energy expenses of the building [10].

In domestic appliances, air conditioners are the major equipment in developed countries for temperature control or comfort [11–15], and they are always in focus to be energy efficient due to their high energy consumption. On the contrary, ceiling fans are usually preferred for ventilation and comfort in developing countries in temperate regions. Consequently, energy efficiency in electric fans has largely been neglected in developed economies [16], and, therefore, there is a potential to increase energy efficiency in fans by 50% using commercially available technologies. Thus, the development of energy-efficient fans for domestic appliances can lead to considerable potential savings at the consumer level in Lower- and Middle-Income Countries (LMICs) as well as improve the quality of life.

Recently, a practical implementation of BLDC fan motors reported that the energy saving is even higher in BLDC motor-based ceiling fans compared to AC induction motor ceiling fans when operated at lower speeds than at high speed. The power consumption of BLDC ceiling fans is reduced to 20% at low speeds compared with AC induction ceiling fans [17]. Meanwhile, in another study, replacing induction motors with BLDC motors in fans reduced the power consumption of the fan by up to 35% [18]. Through the measurement of the power consumption of the DC ceiling fans developed locally and commercially available in the market it is found that BLDC ceiling fans also consume 35% less power than the conventional AC induction fans. Since BLDC motors are inherently energy efficient compared to AC induction motors, the BLDC technology-based fans cause low losses as compared to AC fans [19]. In addition, there is an opportunity for energy efficiency improvement by employing modern and low-cost technologies in BLDC ceiling fans.

Recent technological developments like the Internet of Things (IoT) and Artificial Intelligence (AI) could be great sources of opportunity for energy-efficient solutions in domestic applications. These technological methods are data-driven and make decisions based on past experiences. In terms of a ceiling fan, there is an opportunity to make it energy efficient through the integration of smart controls. In a study, an IoT-based system is used to automate the fan and lights in a house using a PIR (Passive Infrared Sensor) motion sensor to switch 'ON' and 'OFF' the fan, enhancing ease of use [20]. However, this approach is limited to fan switching only and does not allow fan speed adjustment. An article presented the precise human presence detection achieved through computer vision techniques using a camera integrated with a microprocessor [21]. A prototype using MATLAB was developed with a temperature sensor, a camera, and a PIR sensor with a microcontroller for human detection and fan speed control based on ambient temperature [22]. These systems detect humans to turn ON or OFF the fan but lead to an invasion of privacy. Also, the method used a conventional conditional statement for setting the speed of the fan and lacks in learning the usage pattern which may disturb the user's comfort. The speed control issue is addressed in another work where a mobile application was integrated with a cloud server and temperature sensor. The microcontroller was used to operate the fan along with live monitoring of the environmental condition [23]. However, the system for fan operation was limited to the local network and did not leverage the possibility of true IoT capabilities. An IoT-based fan is proposed in another study where a framework for IoT-based home automation through vocal commands was proposed that used cloud-deployed serverless functions along with an MQTT (Message Queuing Telemetry Transport) protocol for data

transmission [24]. In a similar work, the proposed framework of Narrow-Band IoT (NB IoT) was tested on a home-based kitchen fan and the latency in communication delay was 0.477 s [25]. However, IoT backend technologies such as NB-IoT, Sigfox, and Lora WAN devices are not commercially available in many developing countries and require relatively expensive hardware that may not be viable for use in low-cost, high-volume applications such as fans. Room occupancy detection for fan operation is addressed with a relatively simpler technique of using motion sensors to switch ON/OFF and to adjust the speed of the fan as a function of temperature and humidity sensors in [26]. Besides the ability to capture environmental conditions, the system does not train machine learning model utilizing past usage experience for predictive operation, which could achieve enhanced energy efficiency.

The available literature related to ceiling fan automation reveals the opportunity to integrate modern digital technologies in fans to achieve higher efficiency and comfort levels. Presently, no fan has been reported that leverages humidity, temperature, and occupancy detection simultaneously with machine learning (ML) algorithms to establish a user-centric comfort profile of the fan learning from the past usage while minimizing energy consumption. Furthermore, no widespread technology deployment in fans, user feedback, and performance have been reported so far to establish the acceptance and efficacy of the proposed solution in a variety of environments and use cases. Thus, this work is focused on incorporating humidity, temperature, and motion sensor data into the ML algorithm to tune the user operation profile that is used by the fan controller for its operation effectively, making the fan operation follow the user's preference while minimizing the energy consumption. The resulting solution comprising multiple sensors and an IoT circuit is targeted to be retrofitted in a large installed base of BLDC ceiling fans, thereby integrating AIoT controls, facilitating data harvesting with a streamlined approach, and opening up the possibility of visualization of energy consumed and saved, and the means to assess the user acceptability of the system determined through standard measures. The efficiency enhancement over a period across different usage patterns will be quantified while improving the comfort level of the users.

2. Materials and Method

2.1. System Description

This research highlights an energy-efficient ceiling fan solution with user comfort. This study presents an IoT circuit that commands the driver circuit of a BLDC motor for room fan operation. The IoT circuit uses multiple sensors to acquire room environmental conditions, including temperature, humidity, human motion, and time of operation, and transfer them to the cloud server through the MQTT protocol. The ML algorithm is fine-tuned weekly using the obtained dataset and generates a lookup table. The table is generated through the conversion of the updated weights; this table is transferred to the controller in the IoT circuit which is then used to update the fan operation profile present in the controller memory which the fan follows in the autonomous mode. A mobile application and web-based dashboard are also part of this research project that offers different modes of fan operation and the visualization of fan usage patterns, energy consumption, and environmental conditions. There are two modes of fan operation which include a manual mode and an auto mode. In the manual mode, the mobile application allows the user to either switch ON/OFF the fan or adjust the speed of the fan between five levels from 1 being the minimum to 5 being the maximum. On the contrary, the auto mode offers two sub-modes of fan operation that include economy and sleep mode. The fan automatically turns OFF during the economy mode if there has been no human motion in the room for the last two minutes. In the case of movement detection implying human presence, the fan will remain in an ON state with an adjusted speed determined by a machine learning model based on environmental conditions according to the fan profile in the controller, which is constantly updated with weights determined from past usage data. In the sleep mode of operation, the fan operates similar to the economy mode, with the only difference

being that it does not turn off the fan when it recognizes no motion in the room. The aforementioned modes of fan operations are set through a mobile application that first communicates with the cloud server and then the cloud server requests the IoT circuit for the required fan operation as shown in Figure 1. A MySQL database, which stores all environmental data along with the corresponding fan usage configuration, is deployed on the digital ocean cloud server. The machine model is also deployed on the same cloud server that gets fine-tuned weekly using newly acquired data.

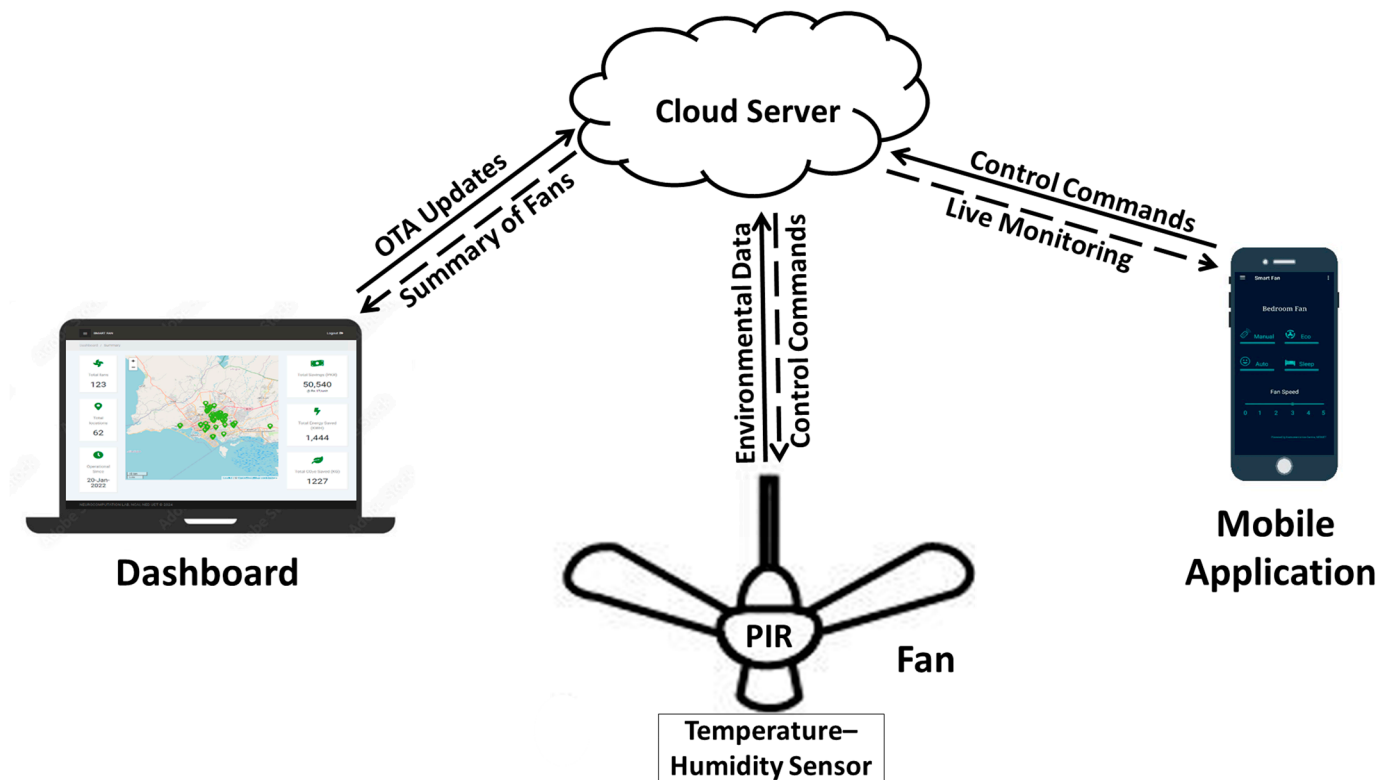


Figure 1. System components and the flow of data and commands.

2.2. Methodology

Regular DC ceiling fans utilize a BLDC motor that runs through a driver circuit. A manual remote containing an infrared (IR) transmitter communicates with the IR receiver incorporated within the driver circuit and is used to operate and control the fan. These IR signals were decoded first to obtain the binary codes that the driver circuit receives from the remote to operate the fan. The IoT circuit, proposed in this research, replaced the IR sensor of the driver circuit and used the decoded binary codes to operate and control the fan. This IoT circuit contains an IR sensor, temperature and humidity sensor, motion sensor, and a microcontroller that allows the user to operate and control the fan through either a mobile application or a manual remote. The description and work of this IoT framework are outlined in the following sections.

2.3. Hardware

a. Microcontroller

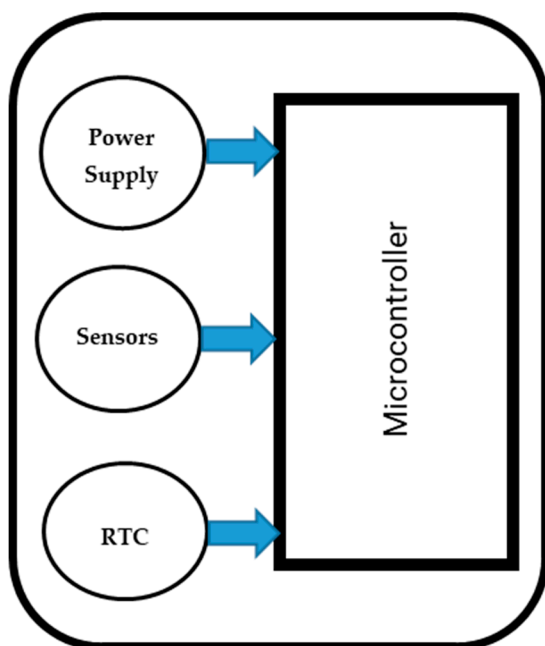
The Wemos D1 Mini development board built on a 32-bit ESP8266 microcontroller was used in this research. The Wemos D1 Mini is a Wi-Fi (System on Chip) SoC that is powered at 3.3 Volts through the microcontroller and runs at 80 MHz. This Wi-Fi-enabled microcontroller development board served as the brain of the proposed system that interfaced with the incorporated sensors, communicated with the cloud server for data transmission, and controlled the BLDC motor driver circuit to operate the fan.

b. Sensors

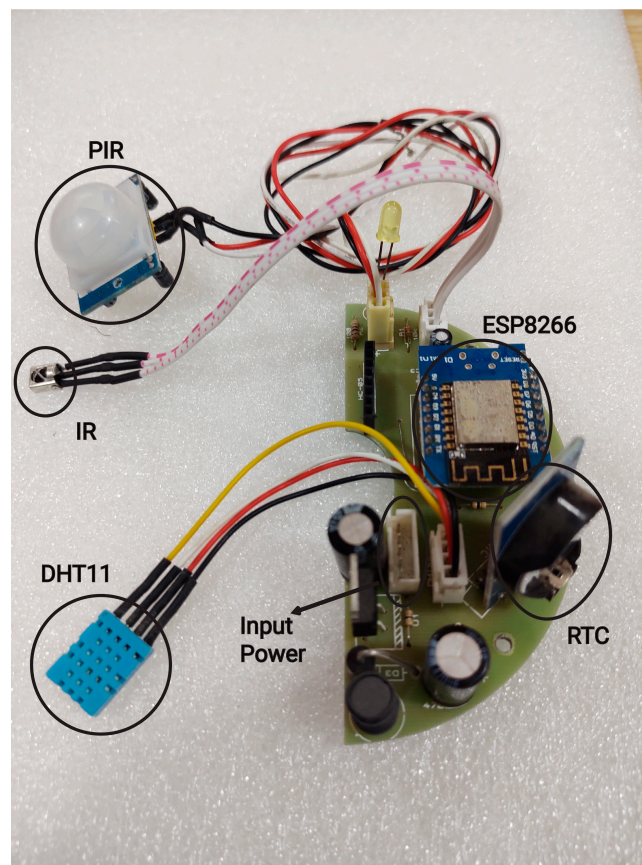
The proposed system utilizes three sensors making sure there is user comfort and efficient control of the fan. These sensors include the temperature–humidity sensor, motion sensor, and IR sensor. DHT11 is a low-cost temperature humidity sensor used to measure the relative humidity in the range of 20 to 90% RH and temperature between 0 to 50 °C, with an accuracy of $\pm 5\%$ RH and ± 2 °C, respectively [1]. The motion sensor used in the circuit is a PIR sensor, which detects human motion by receiving the infrared radiation emitting from the human body, and the IR sensor is used to receive signals from the transmitter.

c. IoT Circuit Design

The proposed IoT circuit comprises four blocks, namely, the power supply, microcontroller, sensors, and Real-Time Clock (RTC), as shown in Figure 2. The power supply block takes 15 volts DC from the BLDC motor driver circuit and feeds it into a buck converter which steps it down to 5 volts DC to operate the microcontroller. Along with the RTC module, all three sensors including DHT11, PIR, and IR were interfaced with the microcontroller through its input/output (I/O) pins. The RTC module has a coin cell as its own power supply and is used to obtain time stamps to keep track of the hour (in 24 h format) of the day at which the fan is operating along with the time whenever the microcontroller starts or gets into low power mode.



(a)



(b)

Figure 2. (a) Block diagram and (b) on-board setup of developed IoT circuit.

2.4. Firmware

ESP8266 was programmed using Arduino IDE (Integrated Development Environment) and the script was written in C Language. The ESP8266 was programmed for the various roles and operations discussed below.

a. Internet Connectivity Setup

ESP8266 was programmed to remain in access point (AP) mode in order to connect to the internet. During AP mode, the ESP8266 behaves like a Wi-Fi router as an open network. When a user connects with this open network, it redirects the user to a web portal page to input the credentials of a Wi-Fi network that holds active internet connectivity. Successful verification of the entered credentials establishes the connection of the ESP8266 to the internet, as shown in Figure 3.

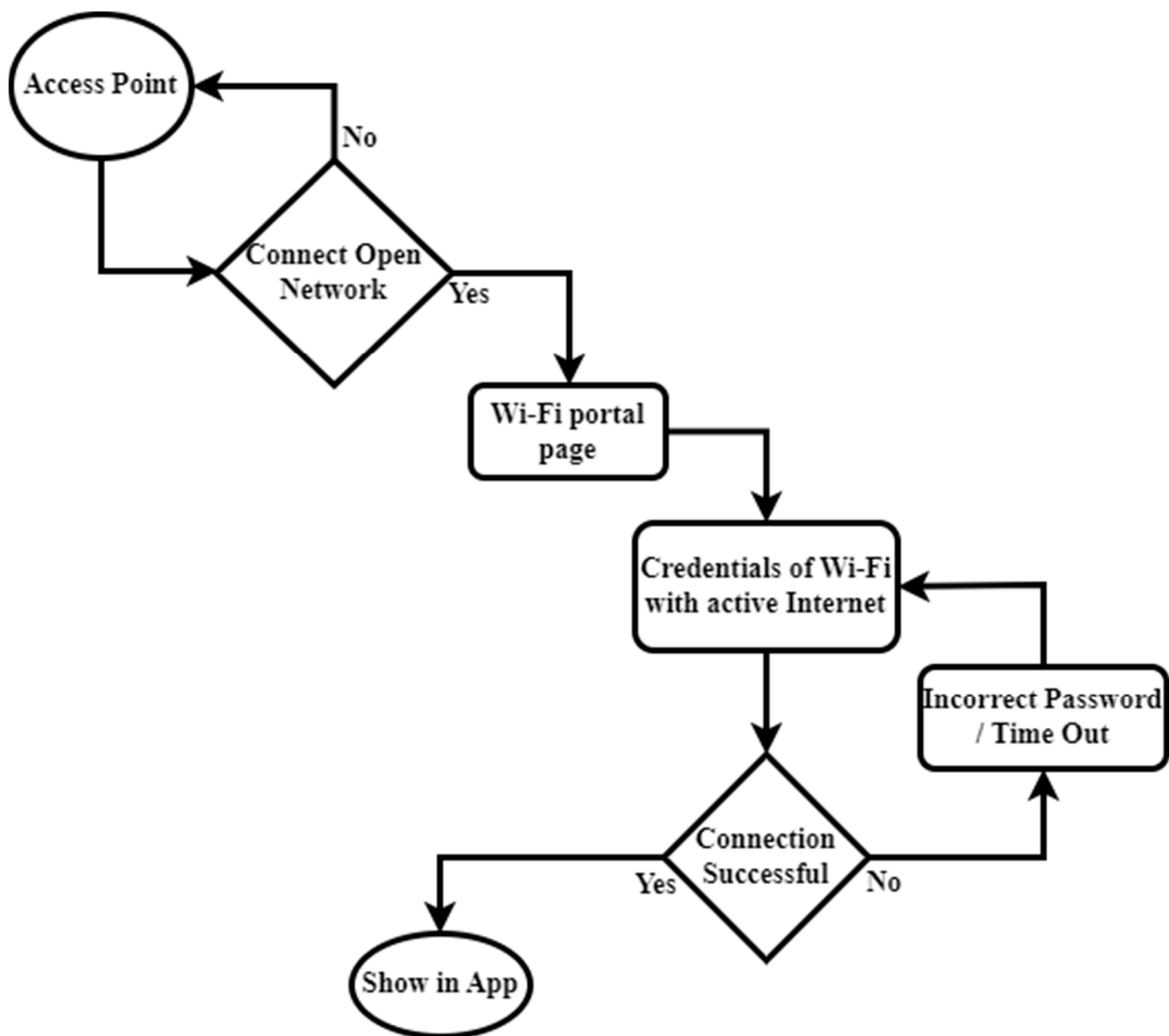


Figure 3. Internet connectivity flow chart.

b. Fan Operation

The proposed system was deployed in two phases with continuous environmental data logging from the integrated sensors during each phase of the deployment. There are two modes, i.e., *manual* mode and *auto* mode, at which the microcontroller works to control the BLDC motor driver circuit in order to operate the fan as shown in Figure 4. The first phase of the deployment only offered a manual control of the fan composed of two options: (a) a user-based manual remote control that communicates with the microcontroller through an IR, and (b) a user-based mobile application that communicates the control commands to the microcontroller via a cloud server. Moreover, during the second phase of the deployment, the proposed system offered both modes of fan controlling, i.e., manual mode and auto

mode. There are two sub-categories in auto mode which include economy and sleep mode. During economy mode, the microcontroller turns OFF the fan automatically if the PIR sensor does not recognize any human motion in the room for two minutes. In case of motion detection, the microcontroller keeps the fan in an ON state and adjusts the fan's speed based on fan usage patterns in different environmental conditions learned by the machine learning model. The fan operates on 5 increasing levels of speed with 'Level 0' and 'Level 5' as the minimum and maximum speed of the fan, respectively.

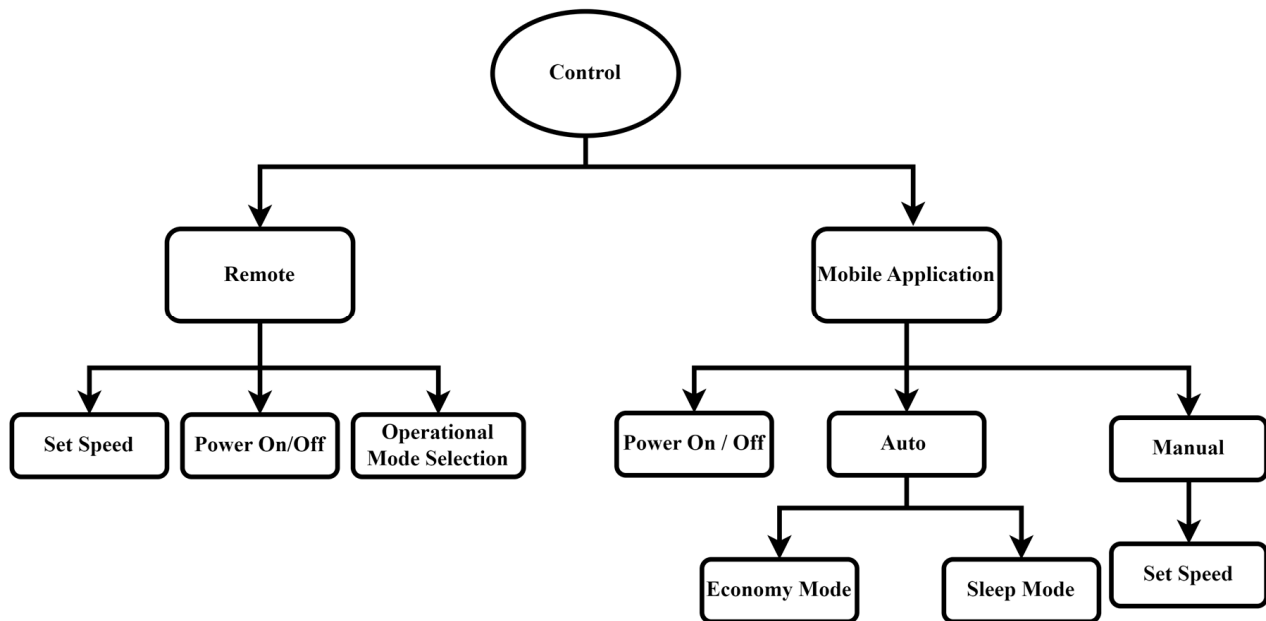


Figure 4. Fan operation modes.

c. Data Logging

The data logging was performed simultaneously in both a cache-based local storage topology as well as a cloud storage topology. An onboard flash chip, with an adequate cache memory of 2 MB to 4 MB integrated into the ESP8266 development board, was used that supports lightweight file system versions called SPI Flash File System (SPIFFS). The adapted methodology in this research enabled the data packet comprising fan speed, sensory data, and time stamps from RTC to be added in an empty text file in JSON format. The microcontroller was programmed to continuously monitor the sensory data and logged the data packet into the JSON file only when any of the following three conditions were met,

$$\begin{aligned}
 -1\text{ }^{\circ}\text{C} &\geq (\text{Temperature}_{(t)} - \text{Temperature}_{(t-1)}) \geq 1\text{ }^{\circ}\text{C} \\
 -5\% \text{ RH} &\geq (\text{Humidity}_{(t)} - \text{Humidity}_{(t-1)}) \geq 5\% \text{ RH} \\
 \text{PIR}_{(t)} &\neq \text{PIR}_{(t-1)}
 \end{aligned}$$

where,

t = present timestamp.

The generated JSON data file gets transferred to the cloud server through HTTP protocol when the microcontroller establishes a successful internet connection, as shown in Figure 5. However, in the case of unavailability of the internet, the JSON file remains saved locally in cache memory. In order to manage and transmit the data file efficiently, we acquired a three-file approach. The microcontroller logs data in the first file and on successful internet connection, it tries to transmit the first file to the cloud server when it reaches its defined size limit; meanwhile, the system begins to store real-time data in the second file. When the second file reaches its limit, the data begins to get logged into the third file, and the system attempts to transmit the second file to the cloud server after

the successful transmission of first file to the cloud. As the file transmission to the server is completed, it gets removed from local storage. This cyclic process, in which one of the files stores data while another file gets transmitted to the cloud server in parallel, runs continuously in a loop. In the case of unavailability of the internet for the time period in which all three files get filled, the microcontroller discards the first file and starts the same cycle.

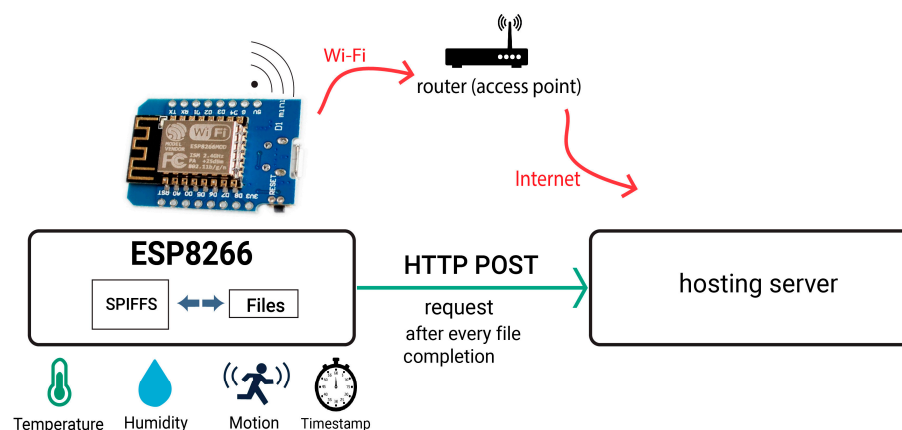


Figure 5. ESP8266 communication with cloud server.

d. MQTT Client Setup

The ESP8266 microcontroller communicates with the mobile application through a cloud server using the MQTT communication protocol. MQTT is a lightweight transport protocol that works on transmission control protocol (TCP) and assures the message delivery from node to server protocol. Due to its message-oriented information and publish–subscribe protocol, the MQTT protocol is ideally suited for IoT circuits. The ESP8266 contains an MQTT client that establishes its connection with the cloud server comprising an MQTT broker called “Eclipse Mosquitto” in order to send sensory data and time stamps to the cloud server, as shown in Figure 5. This MQTT broker binds with the mobile application to acquire the operational commands, at the cloud server, set by the user to control the fan.

e. Firmware Update

The user-friendliness of the system was maintained through an additional feature of easy and accessible system updates. ESP8266 was programmed to update its firmware wirelessly Over the Air (OTA). ‘Local’ and ‘Remote’ modes were adapted for the wireless firmware update. The local mode enables the firmware update to be shared through the local web server when both ESP8266 and mobile applications are connected to the same network. Moreover, during the remote mode, the firmware gets updated through the cloud server using the HTTP protocol, as shown in Figure 6.

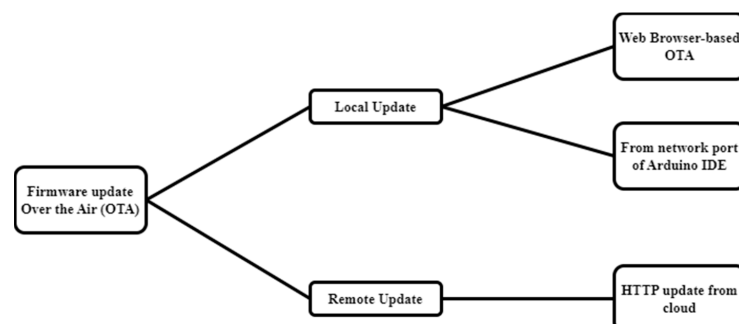


Figure 6. OTA firmware update.

2.5. Software

a. Cloud Server and Database

The cloud server was utilized to enhance the usability, robustness, and functionality of the proposed system. A digital ocean cloud server was integrated with the system to facilitate remote access through MQTT broker hosting, database management, and the deployment of machine learning models for smart controls, a web application, and a dashboard for live monitoring of the system. The digital ocean server was set up using a PHP script and serves on Apache whereas backend APIs were used to fetch the data from the sensors and transmit them to the cloud. A PHP script runs on the digital ocean server that receives incoming requests from ESP8266 and stores the data in a table in the MySQL database.

An Entity Relationship Diagram (ERD), as shown in Figure 7, depicts the structure and connections of the tables built in the MySQL database for the proposed application. The data flowing from the ESP8266 to the database and server are encrypted using an end-to-end TLS subscription, thereby following a robust security practice. A script for data cleaning and transformation is executed one time a day to preprocess the raw data received at the server for the whole day from ESP8266. The same script is also programmed to maintain an error log file to track if each of the sensors is operational and provide precise and consistent measurements. This error log file was maintained with the help of flags that were raised due to the occurrence of two events, i.e., (a) if any of the sensory data were missed in the consecutive receiving data packets and (b) if there was a high variance in any of the sensory data. The acquired and preprocessed data can be visualized and monitored from anywhere around the globe. Furthermore, machine learning models are also deployed on the digital ocean cloud server for personalized user fan usage pattern recognition in a variety of environmental conditions.

b. Mobile App

An Android application was built on JAVA using Android Studio. The primary objective of developing the Android application was to increase user-friendliness and accessibility of the proposed system through real-time monitoring and seamless control of the fan. The major features of the developed mobile application include a user registration portal, an operational panel to control and operate the ceiling fan, a device management page to monitor and control the installed devices in the household, auto mode selection, and displays of the present state of the fan operation, as shown in Figure 8a. The mobile application communicates with the ESP8266 through the MQTT protocol. The MQTT broker “Eclipse Mosquitto”, hosted at the digital ocean server, acted as a communication bridge between ESP8266 and mobile applications, as depicted in Figure 8b.

c. Dashboard

Data visualization and system monitoring were performed through the integration of an interactive and personalized user dashboard application. The full-stack, web-based dashboard was developed, comprising a backend architecture on a PHP framework that retrieves data from the MySQL database. In contrast, the front end of the dashboard was designed using HTML, CSS, Bootstrap, and JavaScript. The dashboard delivers a superior user experience offering a window into the operational dynamics of the fan. In terms of access and visualizations, the dashboard has two types of views, i.e., an individual user view and a super user view. The dashboard provides access and visualization of the following two features for individual users:

1. Visualization of individual fan information.
2. Visualization of the information from all the fans installed in a household.

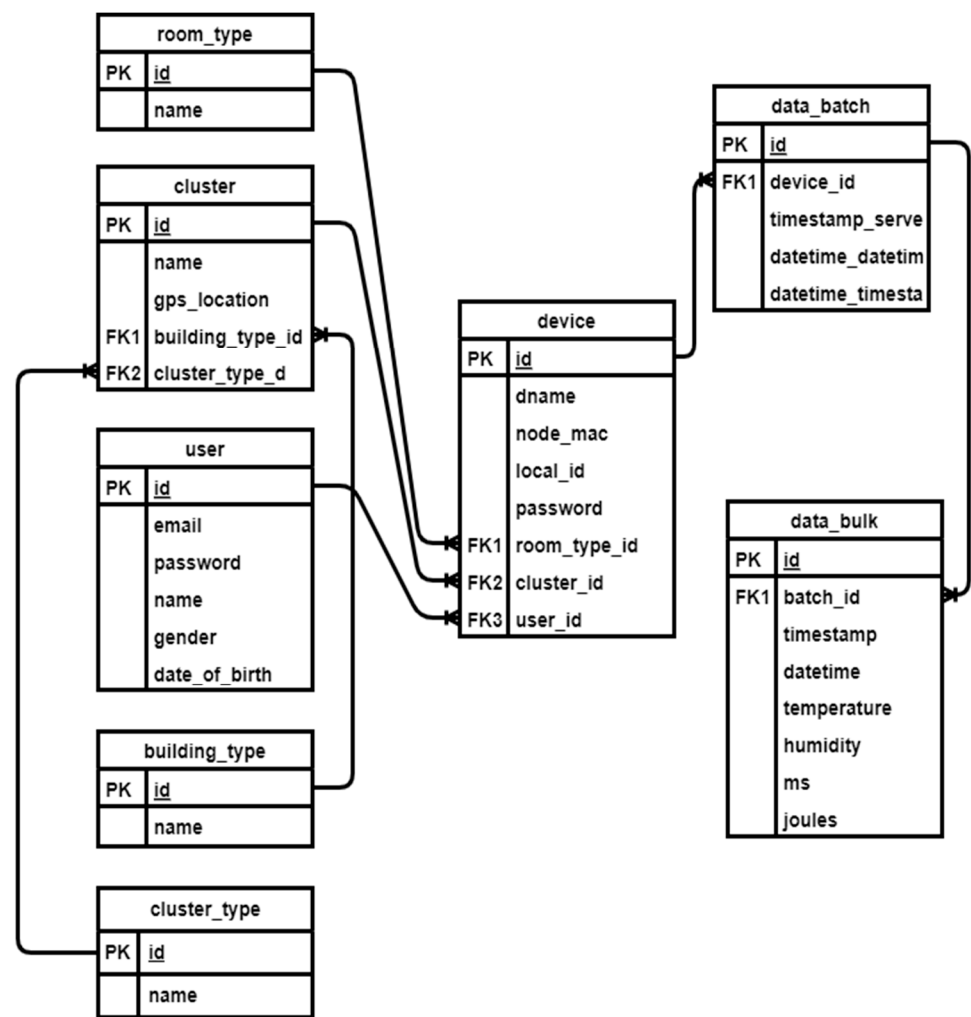


Figure 7. ERD diagram of the database deployed at cloud server.

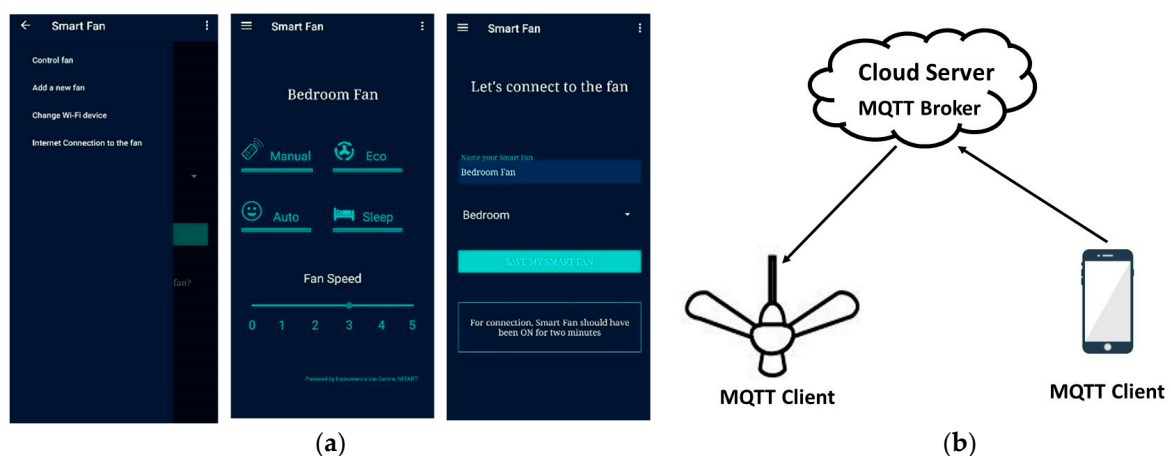


Figure 8. Developed mobile application's (a) user interface and (b) communication method with the cloud server.

Along with the aforementioned feature information, the superuser has access to the sensory and operational information from each of the deployed fans around the globe, geographical location (on Google map) of the deployed fans, total energy (in KWh) consumed by the fan as calculated in [27], and total cost (in Pakistan Rupee) saved due to smart

features and BLDC fans as compared to traditional AC induction fans. The dashboard also features the visualization of the reduction in carbon dioxide (CO₂) emissions (in Kg) calculated by the Mackay Carbon Calculator [28], as shown in Figure 9.

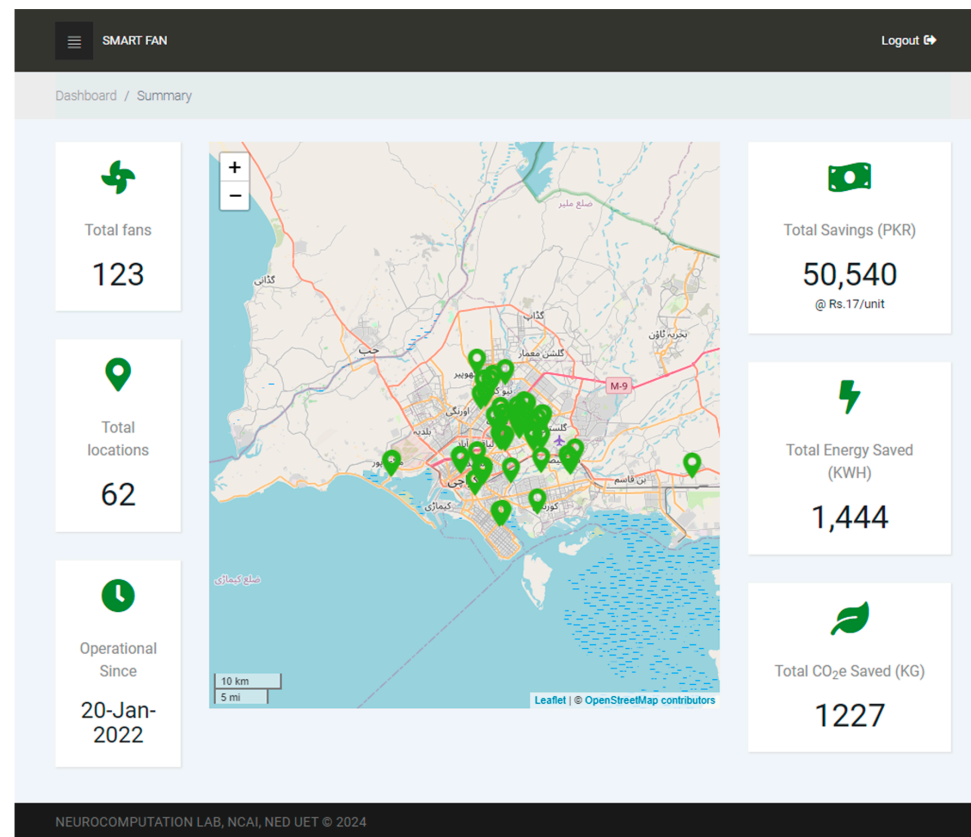


Figure 9. The user interface of the web-based dashboard.

2.6. Computation of Energy Saving and CO₂ Emission

Prior to this research, a preliminary study was conducted by the same authors to determine the energy consumption of AC as well as BLDC fans. During that study, a Fluke 43B/003 power analyzer was used to measure the current drawn by the fans over five different speed levels based on RPM (revolution per minute), as highlighted in Table 1. The amount of current drawn by each type of fan over each speed level was converted into energy in Watt-hour (WH) using Equation (1)

$$Energy = I \times V \times T \quad (1)$$

Table 1. Energy consumption at each speed level.

RPM	Speed Level	BLDC Fan Energy Consumption (Watt Hour)	Conventional AC Ceiling Fan (Watt Hour)
178	1	10	24
212	2	15	34
240	3	20	55
265	4	27	64
327	5	48	96

The difference in energy consumption between AC and BLDC fan operations was referred to as energy saved. Moreover, the saved energy, in kilo-Watt-hour (kWh), was converted into the reduction in carbon dioxide (CO₂) emissions, in kilogram (Kg), which was calculated from the quality of fuel saved through reduced energy consumption determined by the Mackay Carbon Calculator [28] using Equation (2).

$$\text{CO}_2 \text{ Emission} = \text{Energy Units} \times 0.707 \quad (2)$$

2.7. Experiment Design

A total of 123 fans were deployed at 62 different households for two years in Karachi, a city in Pakistan. There were more than one or two fans deployed at some of the households. The fans given to users were equipped with the designed IoT circuit composed of DHT11, PIR, and IR sensors, along with a remote and an Android application shared through the Google Play Store for fan control. The users were also given access to the web-based dashboard where they were allowed to visualize the usage pattern of their fans, the total energy consumption, and atmospheric conditions of the areas where they had installed their fans. Before the course of one year of initial deployment, operational training was provided to each user by the representatives of our research and development team and the respective team member was in correspondence with each user for user support during the entire experimental period. At the end of the first year of deployment, the firmware of the system was updated with the integration of the 'Auto' mode into the system, enabled through the deployed machine learning model. This second phase of the deployment lasted for another year, making the entire study two years. On the last day of the experiment, i.e., the 730th day, each user was asked to fill out a System Usability Scale (SUS) questionnaire to record their user experience and the usability of the integrated smart features in the regular BLDC ceiling fans.

2.8. Machine Learning

At the end of the first phase of the deployment, the acquired data, including timestamp, temperature, humidity, human motion, and fan speed set by the user, were analyzed through the methods of exploratory data analytics (EDA) in Python programming v3.6. During EDA, various heatmaps and boxplots were employed to examine the data distribution and outliers or irregularities. The EDA also aims to visualize the usage pattern of the fan along with the environmental conditions at the same time stamp in a household. To facilitate the user with smart operation and control of the fan based on its usage history, a supervised machine learning model was employed. The random forest classifier model, for the multiclass classification, was trained to classify fan speed. Random forest is a combination of several decision trees in such a way that each decision tree gets trained on a random subset of the dataset created through bootstrapping. An ensemble learning approach is adopted by the random forest classifier, whose predicted output depends on the majority voting of all decision trees. This method reduces the risk of overfitting and thereby increases the accuracy of the model. The timestamp, temperature, humidity, and human motion measurements included in the acquired dataset served as features for the model, whereas the speed level was used as a label for the machine learning model. The random forest classifier was built with the Scikit-learn package, which is available at <https://github.com/scikit-learn/scikit-learn> (accessed on 1 June 2024) and trained on the data points acquired during the first phase of the deployment. A total of 70% of the total of 5.5 million data points obtained from all fans were used for training a random forest classifier, while the remaining 30% of the data served as a test set to evaluate the model's performance. The overall performance of the trained random forest classifier was evaluated through a confusion matrix which determined the accuracy of the model using (3).

$$\text{Accuracy} = \frac{TP + TN}{(TP + TN + FP + FN)} \quad (3)$$

Feature importance can be defined as the contribution of each variable to the model, and it plays an important role in the model performance. Feature importance can be determined through a feature selection algorithm [29] or a statistical analysis of the data received from number of nodes [30]. In this study, a random forest classifier was used to compute the importance score of the features. The model uses impurity-based importance measure attributes, which compute as the mean and standard deviation of accumulation of the impurity decrease of each tree, acquired from the “feature_importances_” function of the random forest. It describes how useful each feature is in constructing the decision tree in the model. This random forest classifier-based machine learning model was deployed on the server and got fine-tuned weekly using the freshly acquired dataset in order to make the system more efficient. This updated model serves as a lookup table accessible through an API, which is accessed by the fan’s firmware. The lookup table is generated by converting the model predictions into entries for all possible combinations of input parameters. This table is stored locally on the controller’s memory, allowing for efficient and low-latency predictions directly within the fan’s hardware.

2.9. System Usability Scale (SUS)

The SUS is a standard measure of a system’s usability and user experience that comprises 10 items with its response on a 5-point Likert scale ranging from ‘0’ as ‘Strongly Disagree’ to ‘4’ as ‘Strongly Agree’. For the SUS score computation, the responses of the even number of items, i.e., 2, 4, 6, 8, and 10, were subtracted from 5, whereas 1 was subtracted from the response of each odd-numbered item, i.e., 1, 3, 5, 7, and 9. The subtracted responses of each item were summed and multiplied by 2.5 to compute the overall score of the SUS with a range of 0 to 100. A score of greater than 70 is considered acceptable, whereas a score of 50 to 70 and less than 50 is considered as marginal and not acceptable respectively.

3. Results

3.1. Machine Learning Model

The random forest classifier that was trained on the data points acquired during the first phase of the deployment was found to be 83% accurate in predicting the speed levels based on human presence and the room’s temperature and humidity, as demonstrated by the confusion matrix. Moreover, it is also evident from Figure 10, representing confusion matrix, that each of the predicted classes has an almost similar performance.

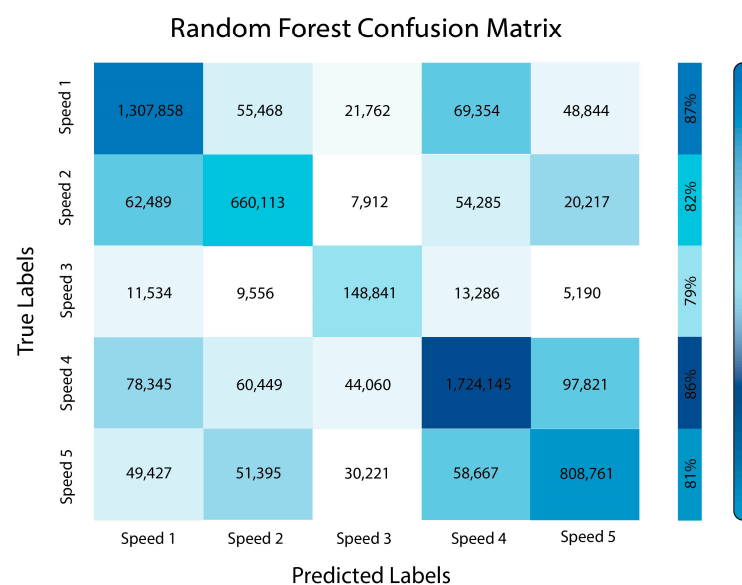


Figure 10. Random forest confusion matrix.

The variable importance of each training feature was also determined, as shown in Figure 11. The feature of humidity was found to have the most significant impact on the predicted outcome. The accuracy of the classifier will decrease by 40% if the feature variable of humidity does not get employed. Similarly, the removal of feature variables including temperature, the hour of the day, and human motion will cause a reduction in the accuracy of the classifier by 29%, 19%, and 12%, respectively. This variable importance highlights the significant role of humidity in the accurate prediction of the speed level of the fan.

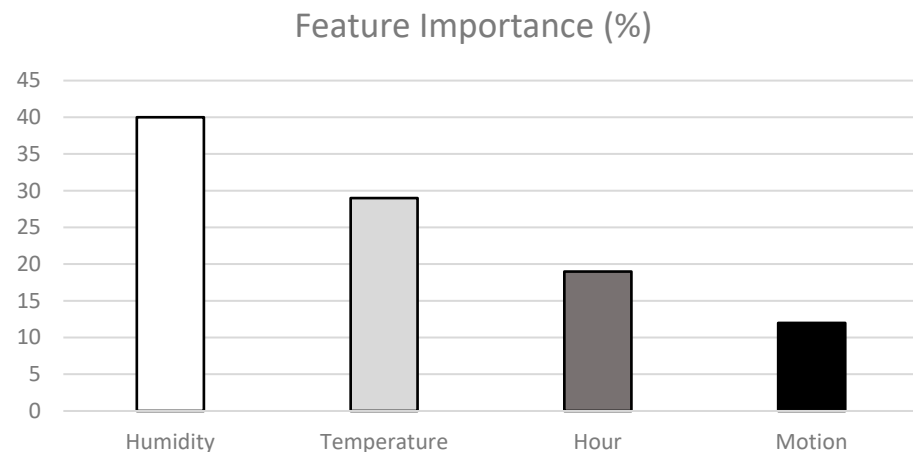


Figure 11. Importance of each of the feature variables used in the training of the random forest classifier.

3.2. Temperature and Humidity during Fan Operation

The average temperature and humidity in the household at each speed level, either set by the user or predicted by the machine learning model, during the entire experimental time period is shown in Figure 12. The measurements from temperature and humidity sensors were also statistically compared through a *t*-test for each level of speed. The temperatures during the two operational modes were found to be non-significantly different at any speed except level 2 ($t = 13.31$ and $p = 0.01$). Similarly, no significant difference in humidity at most of the speed levels was found except level 2 ($t = 10.08$ and $p = 0.01$) and level 4 ($t = 3.39$ and $p = 0.02$). It can be stated that the developed system does not compromise over user comfort as the user experienced the same thermal comfort during both modes of fan operation, i.e., manual and auto modes.

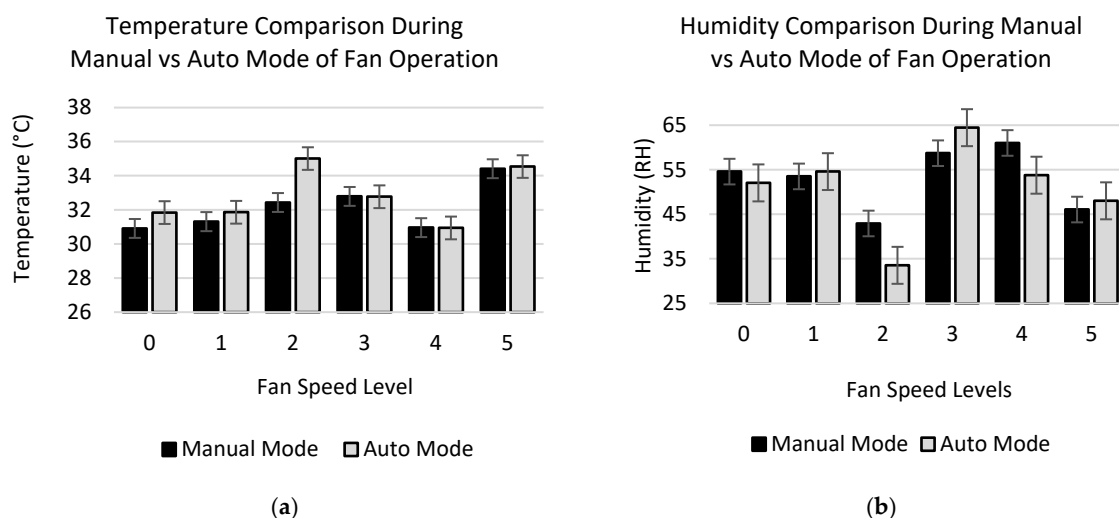


Figure 12. (a) Temperature and (b) humidity patterns during each speed level in manual and auto mode of operation.

3.3. Energy Efficiency

Figure 13 represents the average energy consumed by each of the deployed BLDC ceiling fans in manual and auto modes during the experimental years. On average, each BLDC fan during manual operating mode was found to consume 5.24 KWh (Kilo-Watt-Hour) more energy as compared to similar BLDC fans during the auto mode of operation. This reduced energy consumption during auto mode highlights the significant role of the AIoT system integrated with the fan. Therefore, this outcome supports/strengthens the proposed idea that the developed system enhances the energy efficiency of the BLDC ceiling fan without compromising user comfort.

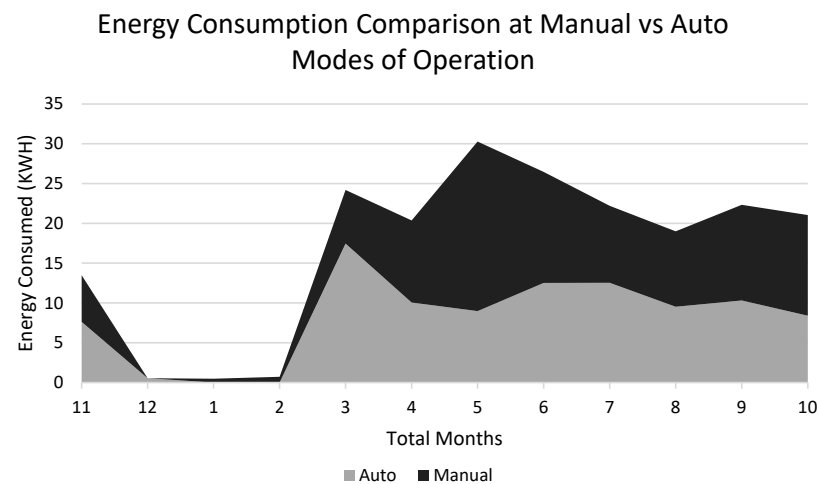


Figure 13. Speed occurrence frequency in manual and auto mode.

3.4. Saved Energy

Besides the improved energy efficiency of the BLDC ceiling fans through the integration of AIoT, the developed system also plays a vital role in environmental sustainability by reducing carbon footprints. Figure 14 represents the total energy consumed, saved, and the calculated CO₂ emissions prevented during the 2 years of experimental study in comparison with the conventional fans with AC induction motors. The total energy consumed by all 123 BLDC ceiling fans with either manual or auto mode of operation was found to be 1324.68 KWh, whereas the total energy saved, in comparison with AC fans, was found to be 1443.84 KWh. Additionally, 1227.2 kg of CO₂ emissions were observed to be saved, thereby creating a significantly positive value on climate change and sustainability.

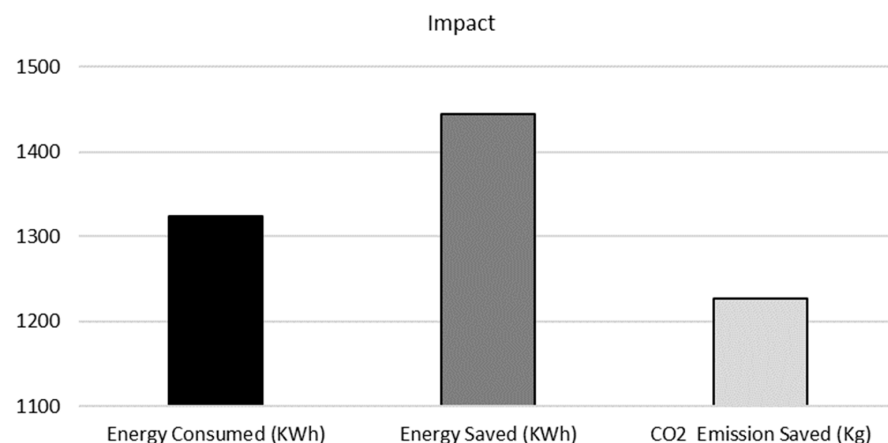


Figure 14. Impact of the deployed system in terms of energy consumed, saved, and CO₂ emissions saved.

3.5. SUS Results

The outcomes of the SUS highlight that 73% of the end users have shown acceptance of the developed and retrofitted IoT system with smart features, through the SUS score above the acceptable usability threshold of 68. Moreover, a score between 50 and 68, i.e., below average, was rated by 27% of the end users. The average score of each of the items asked, its ideal score, and absolute difference are listed in Table 2. Responses to each of the items lie in the range of a 0.8 to 1.7-point difference.

Table 2. Items of SUS and its averaged score.

#	Items of System Usability Scale	Mean Score	Ideal Score	Absolute Difference
1	I think that I would like to use the smart fan frequently.	4.06	5	0.93
2	The smart fan system is unnecessarily complex.	2.56	1	1.56
3	The smart fan system was easy to use.	4.06	5	0.93
4	I think that I would need the support of a technical person to be able to use this smart fan.	2.43	1	1.43
5	I found the various functions in this smart fan were well integrated.	4.12	5	0.87
6	I thought there was too much inconsistency in this smart fan.	2.75	1	1.75
7	I would imagine that most people would learn to use this smart fan very quickly.	3.87	5	1.12
8	I found this smart fan very cumbersome (awkward) to use.	2.31	1	1.31
9	I felt very confident using the smart fan system.	4.18	5	0.81
10	I needed to learn a lot of things before I could get going with this smart fan.	2.43	1	1.43

4. Limitations and Future Work

The present research study compared the performance and efficiency of ceiling fans with an AC induction motor and a BLDC motor with an integrated AIoT methodology. However, the comparison of the performance of BLDC fans with and without the AIoT system could be explored in future studies. Moreover, in addition to the present data acquisition, user information comprising gender and age group could also be obtained in future research. This user-related information could be used in machine learning model's training to achieve a personalized approach for fan operation.

5. Conclusions

In this research, an experimentally deployed and tested AIoT system retrofitted with a BLDC ceiling fan was proposed. The system covers a wide range of data acquisition methods for sensory information, followed through a streamlined pipeline, that can be obtained from a household's room environment so that the machine learning model can learn as much as it can to comfort the fan user. That is why a greater proportion of the users showed a high usability and acceptance of the system. Moreover, the energy efficiency of the system is up to 50% compared to the conventional AC induction ceiling fans, and that its high efficiency in energy saving leads to a reduced carbon footprint is the unique aspect of this research. There is a huge market for ceiling fans in countries where climate conditions usually remain warmer throughout the year [31]. In these countries, the system proposed in this research could be a great source of energy and cost savings that could lead to a reduction in CO₂ emissions, therefore contributing to a sustainable and clean environment. The addition of more smart features in the system could be a possible future direction of this research. The proposed methodology of the AIoT system could also be integrated with other high-power-rated home appliances to make them energy efficient and enhance user experience and comfort.

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manuscript writing. U.A. contributed to data visualization, processing, analysis, mobile application and dashboard development and deployment, and machine learning model training and testing. W.M. contributed to firmware development, sensor interfacing, circuit designing, and PCB development. S.A.Q. contributed to study conceptualization, project administration, resource identification, and manuscript review. K.A. (Kamran Arshad) and K.A. (Khaled Assaleh) contributed to funding acquisition and manuscript review. All authors have read and agreed to the published version of the manuscript.

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