Design and implementation of an IoT-Based air treatment Single-Room Ventilation System using ESP-NOW

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***Abstract*— Growing concerns about both indoor and outdoor air pollution have highlighted the vital importance of Indoor Air Quality (IAQ), an issue amplified by recent lifestyle changes, including those arising from the COVID-19 pandemic. Although traditional ventilation systems still widely used, they present several limitations including their maintenance and cost as well as their inability to fully eliminate pollutants.**

This paper presents the design approach of an IoT-based Single Room Ventilation System. This system is dedicated to operating autonomously or as part of a networked system alongside other ventilation units within the same building.

To ensure reliable communication between units, the ESP-NOW communication protocol was used. Moreover, a mobile application was developed and implemented using Dart and Flutter software enables users to monitor and control the system remotely. A database and IoT-based platform are used to collect and log real time parameters. This proposed solution aims to enhance IAQ management via user-friendly interface, accessible through both Android and iOS devices.

***Index Terms*—Single Room Ventilation system, IAQ, IoT, ESP-NOW, Mobile application.**

I. Introduction

Indoor air quality (IAQ) is crucial for people well-being, as the majority of them spend around 90% of their time even at home or at work [1], [2]. According to the World Health Organization (WHO), indoor air pollution (IAP), which caused 3,765 deaths in Canada and 4 million hospitalizations worldwide in 2019, has a significant impact on health [3]. Incidents at the Horne foundry in Quebec, which led to the move of 80 households to Rouyn-Noranda due to the IAP negative impacts, are clearly in evidence [4]. In June 2023, the smog spread produced by wildfires in both Montreal and Nova Scotia raised anxieties about long-term health impacts [5], [6].

To handle these problems, ventilation systems have emerged as promising solutions for improving IAQ. Contemporary buildings frequently feature mechanical ventilation systems that continuously replace stale indoor air with fresh outdoor air. With technological advancements, many ventilation systems have recently evolved into smart devices, leveraging the IoT potential. These devices offer sophisticated features such as remote-control, real-time monitoring and data transmission with other connected devices [7].

The integration of IoT technologies has greatly improved the performance of ventilation systems, supported by significant advancements in the affordability and availability of IAQ sensors. As reported by Saini et al [8] and Dai et al [9], IoT-based smart ventilation platforms used compact and energy-efficient sensors to monitor major pollutants such as Carbon dioxide (CO_2), carbon monoxide (CO), particulate matter (PM) and volatile organic compounds (VOCs). These platforms provide real-time data, enabling more effective IAQ management. Research findings revealed that the implementation of smart ventilation systems can improve IAQ while reducing energy consumption by up to 60%.

More recently, a study carried out by Joshi et al [10] proposed an IoT-based smart ventilation and energy management system that uses real-time data to dynamically adjust airflow and maintain optimal air quality and energy efficiency.

According to a systematic review conducted by [8], 40 research studies were analyzed, revealing that microcontrollers including Arduino (37.5%), Raspberry Pi (35%) and ESP32 (32.5%) are commonly used in IAQ system implementations. These platforms integrated a range of data access methods, including mobile applications, web interfaces, and LCD displays, which enhance the scalability and user-friendliness of the systems, enabling them to better meet diverse user needs.

In [11], the authors implemented an ESP8266 NodeMCU based system to monitor PM10, PM2.5, temperature, humidity and air pressure. The developed system transmits real-data to cloud platforms via Wi-Fi, enabling accurate and continuous monotoring for IAQ management.

While IoT applications have introduced sophisticated features for monitoring IAQ, the internal design of ventilation systems remains crucial for ensuring effective pollutant removal and air exchange. Two widely adopted approaches are Distributed mechanical ventilation (DMV) and Controlled Mechanical Ventilation (CMV) systems. Each offers specific advantages and limitations, depending on the building design, occupancy type and operational requirements.

Regarding the CMV systems, they use a single fan and a duct network in order to extract stale air and supply fresh air throughout the building. However, DMV systems use multiple fans, each installed in individual utility rooms, thereby avoiding the need for ductwork. The key advantages of these systems include lower costs and simplified maintenance, particularly beneficial in the context of retrofitting existing residential buildings [12]. Distributed ventilation systems, without ductwork, avoid many issues associated with improper duct installation and are generally easier to maintain. However, the choice of an appropriate ventilation system should consider many factors, including initial investment, construction constraints, operational costs and flexibility [13].

To optimize energy consumption, the communication protocol choice is important to enable efficient data exchange and coordination among the different ventilation system components. These protocols facilitate real-time communication, system responsiveness and dynamic parameter adjustment between interconnected devices.

In this context, several communication technologies have recently developed based on various parameters, such as energy efficiency, bandwidth and transmission range. For IoT applications, energy-efficient versions of IEEE 802.11 Wi-Fi, such as IEEE 802.11ah, are commonly adopted. Similarly, 6LoWPAN protocols enable IPv6 connectivity for lower-power devices, making them especially well-suited for IoT-based air quality monitoring systems. ZigBee and Z-Wave offer robust mesh networking capabilities, making them ideal for sensor-dense environments that require reliable communication. Meanwhile, LoRa technology provides an excellent solution for wide-area sensor networks, offering long-range communication with minimal power consumption [14].

The key characteristics of communication protocols commonly used in IoT applications are presented in TABLE I [15].

TABLE I
ESP-NOW, WI-FI AND BLUETOOTH CHARACTERISTICS [15].

Characteristics	***ESP-NOW***	***Bluetooth***	***Wi-Fi***
Maximum Range (m)	~220	60	100
Transmission Speed (Kbps)	588	938	2048
Latency (ms)	1	6	3.3
Power Usage (mW)	1042	441	538
Signal Resistance (RSSI)	-55 to -87 dBm (varies by barrier)	-28 to -46 dBm (fails at 10m with walls)	-54 to -74 dBm (best resistance)

In the present study , the ESP32 microcontroller and ESP-NOW communication protocol are used. It is worthy to note that the ESP-NOW is selected due to its ability to provide low latency, high transmission speed, excellent energy efficiency and its capability to provide a robust signal penetration through barriers, ensuring reliable communication even in complex environments. The proposed approach focuses on communication optimization to enhance system performance and scalability, making it particularly suitable for IoT-based ventilation systems.

II. ESP-NOW COMMUNICATION PROTOCOL

A. Communication protocol

ESP-NOW [16], [17] is a peer-to-peer communication protocol. It enables devices to establish a private wireless network using 2.4 GHz transmitters and receivers, without any need for routers or traditional connection states. This architecture facilitates quick set-up, low latency and reduced communication overhead while delivering significant gains in internal reach. This communication protocol supports flexible data transmission methods, such as multicast, unicast and broadcast, while using minimal CPU and flash memory resources. Its packet structure integrates functionalities from several layers of the OSI and TCP/IP models, using IEEE 802.11-1999 for the lower layer. Unlike conventional Wi-Fi communication, it requires no interconnection between receiver and sender. Each ESP-NOW packet includes essential fields such as MAC addresses, category codes and payloads, with a payload capacity of up to 250 bytes. This protocol offers an initial transmission rate of 1 Mbps and supports communication over distances of up to 400 meters under optimal conditions. Moreover, it allows for both unidirectional (half-duplex) or bidirectional (full duplex) communication, enabling mesh networks to be set up for information transfer between devices. Furthermore, devices which interact via separate MAC addresses can be manually adjusted.

B. Communication topologies

Two communications topology types: mesh and hierarchical are analyzed in this study. According to [18], mesh topology ensures robust and reliable communication by connecting each node directly with at least another one, thereby creating multiple transmission paths and increasing network resilience. However, this approach demand higher memory space, requiring approximately 253.8 KB of RAM and 816.3 KB of flash storage per node. On the other hand, hierarchical topology employs a coordinator and sub-nodes, allowing communication only between sub-nodes and the coordinator. This configuration is more memory-efficient, with the coordinator using around 225.3 KB of RAM and 854.6 KB of flash storage.

In ventilation systems applications, the ESP-NOW protocol, despite its 250-byte data limit, is considered as an effective solution to control and monitor ventilation units. It enables communication between units in order to optimize performance while maintaining low energy consumption. Overall, the combination of ESP-NOW and hierarchical topology presents a cost-effective and memory-efficient solution for controlling ventilation systems, thanks to its simple deployment, minimal maintenance requirements and high energy efficiency.

III. SYSTEM APPROACH ARCHITECTURE

In this study, an experimental platform was developed and installed in a room to assess the IAQ. This assessment takes into account variations in temperature, humidity and static pressure detected by other units already installed in the same environment. The measured parameters are used to analyze the evolution of IAQ under different scenarios. Based on this analysis, decisions are made to trigger specific actions for each unit, adapted to each situation.

When poor IAQ is detected, the system automatically activates the ventilation fan to purify the incoming air for a predetermined duration, which is further adjusted based on real-time measurements. Static pressure data is also leveraged to monitor the condition of air filters, enabling the system to detect when cleaning or replacement is required.

To enable coordination among multiple devices, a dedicated communication protocol and network topology were selected to ensure seamless remote communication. Each unit shares its own measurements with the others, facilitating collaborative decision-making to enhance IAQ. Fan operation is optimized based on real-time data, improving energy efficiency by minimizing unnecessary runtime.

The proposed approach is illustrated in Fig. 1 by the block diagram, which is divided into two main parts:

- A: Remote data transmission using the ESP-NOW communication protocol
- B: Real-time data storage and monitoring

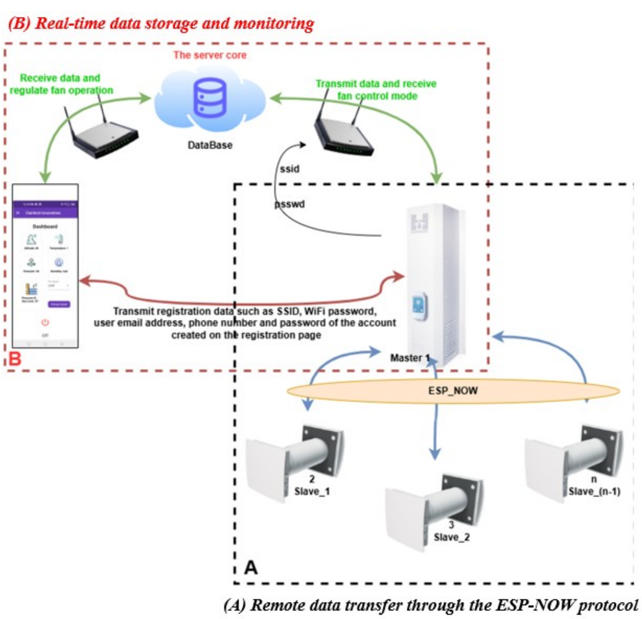

Fig. 1. System approach architecture: (A) Remote data using the ESP-NOW communication protocol / (B) Real-time data storage and monotoring.

The main objective of part (A) is to establish reliable bidirectional remote communication between connected modules and the master unit using the ESP-NOW communication protocol. For this purpose, the microcontroller ESP32 was integrated into the wall-mounted ventilation system. This open-source module was characterized by its high communication throughput, low power consumption and long range.

To simplify configuration between multiple ventilation systems, a push-button and LED indicator were incorporated into the unit, as shown Fig. 2.

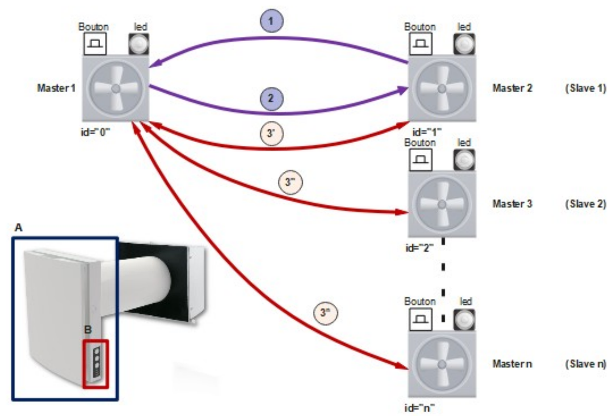

Fig. 2. Multi-unit ventilation system communication architecture.

Furthermore, the integrated LED serves as a status indicator to signal the proper system operation and alerting users to potential issues such as communication failures between units, sensor malfunctions or the need for filter replacement.

To validate the system's reliability and ensure it does not interfere with nearby systems, various test scenarios were conducted:

In the first scenario, master and single slave devices were used to evaluate the data transfer efficiency between the two units. The second scenario, similar to the first one, included an additional slave device, enable us to confirm the correct data transmission. In the third scenario, two master units and a single slave were tested to ensure that the master unit correctly manages the pairing process with the slave.

Regarding the second part (B) (i.e data storage monotoring), it plays an important role in the overall architecture.It ensures that collected data remains secure and readily accessible for analysis. In addition, the system must operate at a sufficient speed to allow real-time monitoring of IAQ and dynamic control. This monitoring can be performed either manually or autonomously depending on the measured parameters.

IV. IMPLEMENTATION

As depicted in Fig. 3, the developed single room ventilation system (SRV system) consists of a 6-inch DC fan, a metal fan guard for safety and a MERV8 filter for effective removal of particulate matter (PM10). Moreover, it incorporates a BEM680 sensor and a dual Button-LED that facilitate device pairing, factory reset and warning notifications. A custom printed circuit board (PCB), was designed based on the ESP32 microcontroller, to manage the core functionalities of the system, including sensor data acquisition, communication control and fan operation logic.

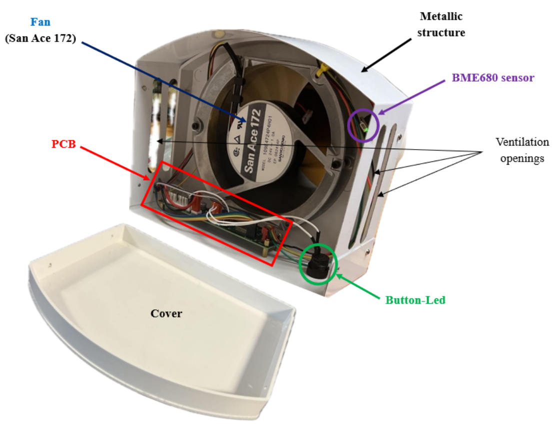

Fig. 3. System hardware architecture.

In this study, each ventilation unit operates autonomously based on data collected from BME680 sensor. Particulate matter (PM10) is filtered using MERV8 filter, while collaborative operation between units within the same building is ensured using the ESP-NOW communication protocol.

The system operation is represented by two main functions:

1. The setup function configures all essential components used in the main loop. It configures the BME680 sensor, checks the unit's status (slave or master) and ensures proper connection to a master unit. Additionally, it sets up the ESP-NOW protocol, establishes a Wi-Fi connection and prepares the database for measured data storage. The latter provides access to user-defined parameters, such as fan status and the desired humidity levels. Finally, the Input/Output pins are configured for the peer-to-peer (P2P) pairing button, signal LED and fan control pin.

2. The main loop continuously monitors system parameters. Every 30 minutes, it verifies the database for data sent by the BME680 sensor and reads the fan speed settings adjusted by the user via the mobile application, as shown in Fig. 4.

This proposed approach enables the system to control the fan based on both real-time measurements and user-defined target values. In addition, the master and slave units exchange parameters bidirectionally via the ESP-NOW communication protocol, enabling high-speed fan activation in case of extreme demand.

V. RESULTS

To validate the developed system functionality, an experimental setup was implemented and installed within laboratory environment at the University of Moncton, as shown in Fig 5.

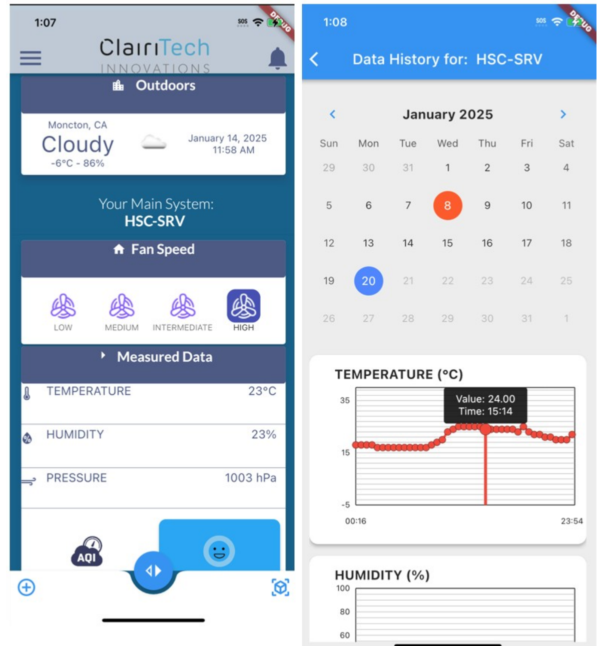

Fig. 4. Mobile Application Dashboard.

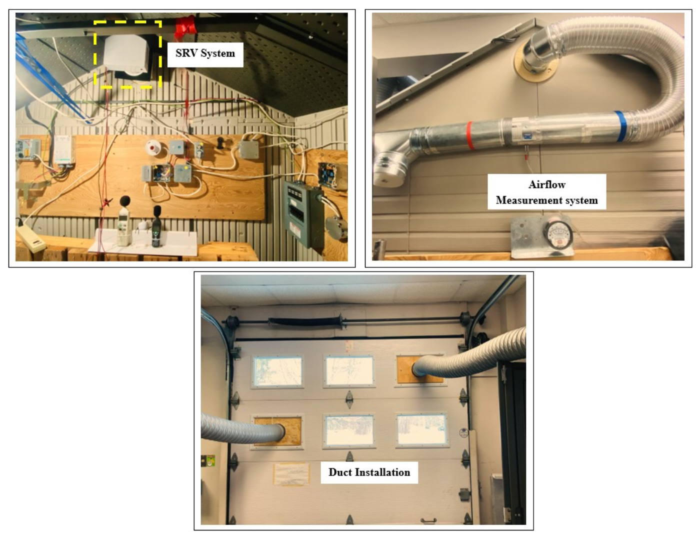

Fig. 5. Experimental setup.

A. System configuration

The initial system configuration involves several key steps to ensure proper functionality and communication. It includes components pin configuration (fan, Button-LED, BME680 sensor) and a quality control (QC) test via a dedicated Wi-Fi network. Key functions, such as reading sensor data and adjusting fan speed, are validated, and the collected data is stored in the database for future monitoring and analysis.

The unit's IP address is set to "10.0.10.10" to enable communication with the mobile application. Device-specific information, including unit ID, user ID and Wi-Fi credentials, is retrieved from EEPROM memory to ensure efficient and reliable remote communication.

Local communication via ESP-NOW is also configured with details such as the unit status (master or slave). A timer is activated to schedule the main tasks (i.e reading, saving, communication). During testing, two units were used: one operating in master mode and the other in slave mode.

The system was also evaluated for seamless transitions between the two aforementioned modes, as well as for manual and automatic pairing following a power failure or outage.

B. Communication through ESP-NOW protocol

In this section, three different scenarios are presented to evaluate and ensure optimal communication through the ESP-NOW protocol.

- Switching from master to slave mode: Three consecutive button presses switch the unit to slave mode. The unit retains its status in EEPROM. This ensures that even after a power failure, the unit remains in slave mode. If the user presses the button three times by mistake, no action will be triggered, preventing unintended mode changes.
- Pairing mode: Pairing is initiated by pressing the button five times on the master side, then on the slave one. If no connection is established within 5 minutes, pairing mode is disactivated to prevent accidental connection with another unit.
- Automatic pairing mode: Automatic pairing relies on two key parameters: the master unit's MAC address and a shared security code, both stored on the slave unit. The master unit (MAC D8:BC:38:75:22 , code 130691349) shares this code with a connected slave unit (MAC 10:06:1C:97:74). With two possible connections, the master unit is already linked to a slave unit (ID equal to 1), and the next one will receive ID equal to 2. Once paired, data flows securely between the two units.

C. Adding the unit via the mobile application

The unit receives a request containing Wi-Fi access point details, such as network name and password. This connection process may take a few moments, while the unit connects first to the Wi-Fi network, then to the database. One of the major issues encountered is the connection loss via the ESP-NOW protocol. To tackle this problem, it is essential that all units, both master and slave, belonging to the same user and located in the same home, are connected to the same Wi-Fi access point.

In this case, all units start interacting locally via the ESP-NOW protocol and storing data in the database. This enables data to be consulted via the mobile application while being shared locally via ESP-NOW, without any interruption or connection loss.

D. Communication between the HCS unit as master and our developed system as slave

The HCS system, developed by Clairitech Innovations Inc., is designed to regulate humidity levels, eliminate odors and detect carbon monoxide gas. It can be remotely controlled via a mobile application (iOS & Android), providing real-time monitoring and improved security. The developed system in this work is designed to be integrated with the HCS unit installed in the same home. Both systems will be interconnected, exchanging data to improve indoor air quality. To achieve this, master-slave communication is maintained with a few modifications. One significant change involves the pairing method between the developed system and the HCS unit.

Fig. 6, illustrates the communication block diagram, in which the developed system operates as a slave and the HCS unit is considered as the master.

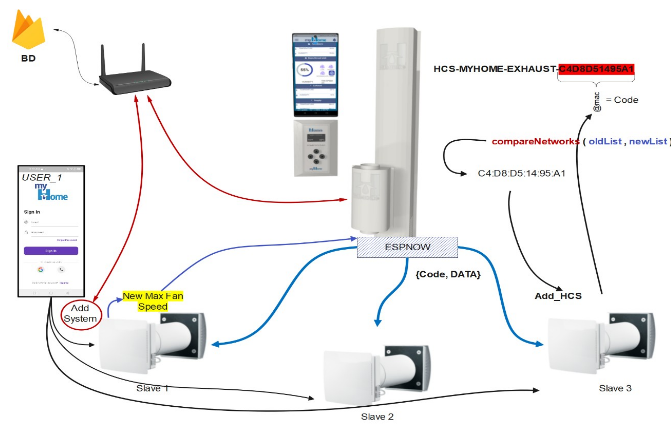

Fig. 6. Communication between the developed system and the HCS unit

The major difference is in how the pairing is carried out. There is no need to switch between master and slave modes. From the outset, the HCS system is considered as the master, while the new developed unit operates as the slave. The pairing process remains globally unchanged, requiring 5 push button presses. However, the unit must be unplugged, then 5 clicks should be performed while the LED is flashing, before plugging it back in. This procedure compares the two Wi-Fi network lists before and after powering up the unit as illustrated in Fig. 7.

Since the master unit's prefix is always «HCS-MYHOME-EXHAUST» followed by its MAC address, the master's MAC address is automatically detected, once the unit's SSID has been identified. It is then added to the peer list, establishing communication with the master as previously explained.

All relevant master unit information is transmitted to the slave, including fan speed, maximum speed, current speed, desired humidity, sensor measurements and data from other units connected to the master.

In the developed system, sensor measurements and data received via the HCS unit are used to control the fan operation across four modes: low, medium, intermediate and high.

E. SRV system control logic

The control logic of the developed single room ventilation system is illustrated in Fig. 8.

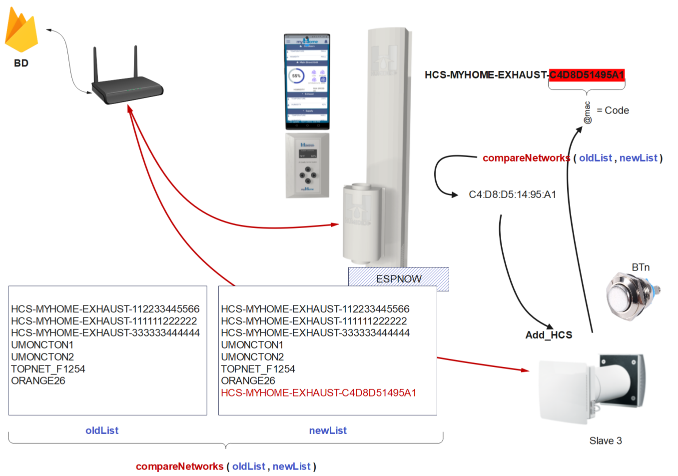

Fig. 7. New pairing method between master and slave units

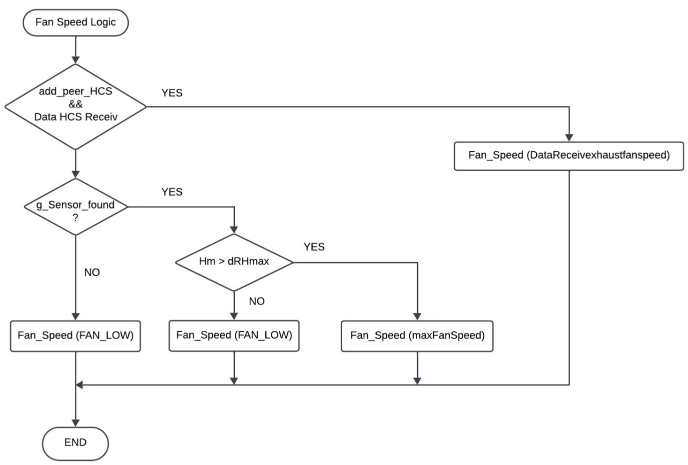

Fig. 8. SRV System Control Logic

The control logic is implemented in two modes:

- Master-slave mode: Check that the SRV unit is actively communicating with the HCS master unit and that there is no communication loss. This means that the SRV continuously receives information. In this case, the SRV fan follows the HCS instructions.
- Stand-alone mode: If the unit operates autonomously, without communication with the HCS, the fan speed is adjusted based on humidity levels. If humidity exceeds 50%, the fan runs at full speed. Otherwise, it operates in low-speed mode. In this mode, fan speed can also be adjusted remotely via the mobile application.

VI. CONCLUSION

In this present paper, the developed single room ventilation system (SRV) is dedicated to improving indoor air quality (IAQ) using IoT technologies and the ESP-NOW communication protocol. The system ensures stable communication between master and slave units, despite the presence of challenges like Wi-Fi loss connection. To address connectivity issues, solutions are developed in order to maintain communication even when only some units are connected to the network. By integrating a user-friendly interface and optimized energy management, the system aims to improve comfort, reduce energy consumption and meet the needs of vulnerable populations. While further testing is required to fine-tune the system's performance in complex environments, this initiative represents a significant step toward sustainable and efficient ventilation solutions.

Note: This research was conducted in collaboration with the University of Moncton and ClairiTech Innovation Inc, and was funded by the New Brunswick Innovation Foundation (NBIF). Furthermore, a trademark application has been filed to protect the intellectual property related to the developed system, including the patent and all information presented in this paper. This ensures that the unique technology and branding associated with the system are protected against unauthorized use, preserving both its originality and commercial potential.

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