APPLICATION OF BLUETOOTH MESH NETWORK IN MULTI-DEVICE SYSTEM MANAGEMENT

ỨNG DỤNG MẠNG BLUETOOTH MESH TRONG QUẢN LÝ HỆ THỐNG ĐA THIẾT BỊ

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Abstract - Currently, the application of the Internet of Things (IoT) in the industrial sector to improve the productivity and efficiency of industrial processes is no longer unfamiliar. However, for a wireless control system to operate reliably and stably even without the Internet, additional issues regarding energy and alternative control options need to be addressed. In this article, the authors have investigated the application of Bluetooth Mesh networks in industrial production systems. In a manufacturing facility, Bluetooth devices are installed on machinery and can exchange data with each other through a gateway device that serves as a data receiver for the Bluetooth devices. Additionally, the system can be remotely monitored and controlled through a Web server. Implementing this system in production enables industrial companies to digitize processes, transform business models, and enhance performance and productivity.

Key words - Bluetooth Mesh; IoT; wireless control; energy saving

Tóm tắt - Ngày nay, ứng dụng Internet vạn vật (IoT) trong công nghiệp để cải thiện năng suất và hiệu năng của các quy trình công nghiệp đã không còn xa lạ nữa. Tuy nhiên để một hệ thống điều khiển không dây hoạt động được lâu dài và ổn định ngay cả khi không có Internet thì chúng ta cần giải quyết thêm các vấn đề về năng lượng cũng như các phương án điều khiển khi không có Internet. Trong bài báo này, nhóm tác giả đã nghiên cứu ứng dụng mạng Bluetooth Mesh vào trong hệ thống sản xuất công nghiệp. Trong một khu sản xuất các máy móc sẽ được lắp đặt các thiết bị Bluetooth và có thể trao đổi dữ liệu cho nhau, thông qua một thiết bị Gateway đóng vai trò nhận dữ liệu từ các thiết bị Bluetooth. Ngoài ra, có thể giám sát, điều khiển hệ thống hoạt động từ xa thông qua một Webserver. Việc ứng hệ thống này trong sản xuất giúp các công ty công nghiệp có thể số hóa quy trình, chuyển đổi mô hình kinh doanh cũng như cải thiện hiệu suất và năng suất.

Từ khóa - Bluetooth Mesh; IoT; điều khiển không dây; tiết kiệm năng lượng

1. Introduction

Society is rapidly developing, and the daily essential needs of individuals for smart healthcare devices and smart homes are becoming a trend shortly. However, integrating these two needs into a seamless and unified system is not an easy task. In this context, wireless Bluetooth technology has emerged as a suitable solution, and a Bluetooth Mesh network has been created specifically to serve applications that require low power consumption while maintaining good interaction with traditional Bluetooth devices. While Bluetooth Mesh networks are widely used in IoT systems, their application in industrial production systems is still limited. However, in the near future, Bluetooth Mesh technology is expected to be widely applied in industrial production, enabling more automation and increased production efficiency. Bluetooth Mesh technology allows manufacturers to integrate machine data from factories, individual production lines, or networked locations to proactively improve performance by identifying gaps, errors, and potential obstacles in the production process [1], [2].

The inventory management system of TRooTech Business Solutions Pvt. Ltd. [3] facilitates the handling of inventory management activities, including transportation, receiving, picking, and packing (Figure 1). Different types of warehouses - controlled, private, automated, and on-demand - are available to meet the needs of the inventory management system. The efficient application of Bluetooth Mesh technology eliminates the need for barcode scanning to track and locate products within the warehouse.

Figure 1. *The application of Bluetooth Mesh in TRooTech Business's inventory management system Solutions Pvt. Ltd. [3]*

Solana and colleagues [4] have analyzed and evaluated the key features of the Bluetooth low energy (BLE) network as well as the challenges it poses in industrial systems, and they have proposed solutions for improvement. The application of BLE networks in IoT applications has also attracted significant research worldwide [5]-[9]. For instance, in a study conducted by Sergi and his researchers [5], the application of the BLE network in building automation was evaluated. In Vietnam, the BLE network was applied in operating security systems for smart homes [9]. Many studies on BLE networks have been conducted through numerous applications [10]-[19].

In this article, the authors have investigated the application of Bluetooth mesh networks in industrial production systems and tested them on respiratory machines. In a manufacturing facility, Bluetooth devices are installed on machinery and can exchange data with each other through a gateway device that serves as a data receiver from the Bluetooth devices.

2. Bluetooth Mesh

2.1. Structure of the Bluetooth Mesh

Figure 2 illustrates the structure of a Bluetooth Mesh system consisting of three main components: controller, host, and application. Each component includes one or more layers with specific functions. The controller consists of two layers, namely, the link layer and physical layer, which are responsible for determining hardware-specific parameters and abstracting logical links for communication. The host comprises multiple layers, such as Generic Access Profile, Generic Attribute Profile, Security Manager Protocol, Attribute Protocol, Logical Link Control, and Adaptation Protocol. These layers are responsible for providing higher-level abstractions based on logical links. The Bluetooth Mesh structure includes multiple layers, with each layer performing specific functions to facilitate communication between Bluetooth devices [20].

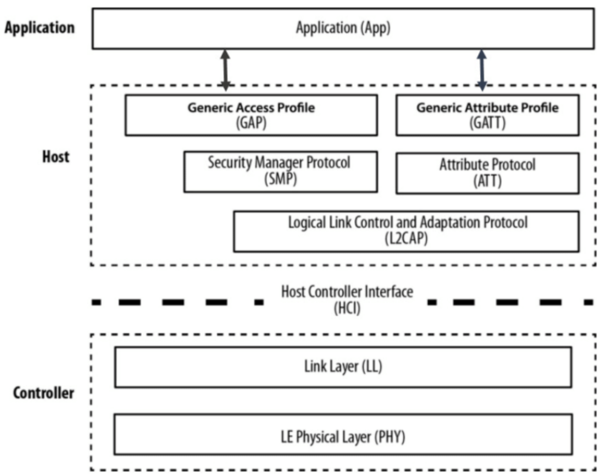

***Figure 2.** Structure of a BLE [20]*

2.2. Analysis of the Bluetooth MesH

Bluetooth Mesh is a network consisting of interconnected nodes. To become part of such a network, a device must undergo the provisioning process. This is a necessary five-stage process for security reasons. The stages are as follows:

- Beaconing: where the device broadcasts advertising packets to nearby devices.

- Invitation: a node sends a Provisioning Data Unit (PDU) invitation to a connecting node, which replies with a PDU indicating its provisioning capabilities.

- Public Key Exchange: where public keys are exchanged between the connecting nodes for encryption and decryption purposes.

- Authentication: the provisioning provider uses an appropriate authentication method to verify the connecting node.

- Provisioning Data Distribution: where the provisioning creates and sends provisioning data to the verified node

Once a device has been successfully provisioned, it can now send and receive messages to other nodes within the mesh network. However, four functions are limited to specific nodes assigned with these features, including relaying, proxying, friend, and low-power, as shown in Figure 3.

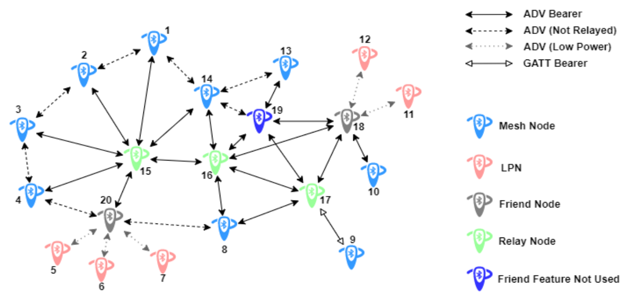

***Figure 3.** Elements in the Bluetooth Mesh (MATLAB.com)*

- Relay Devices: To avoid a sudden increase in the number of messages within the network, only a subset of devices in the network are configured to operate in relay mode. These devices, acting as relays, forward the messages they receive within the network. When a message passes through a relay device, the TTL value of the message decreases by one, and it is forwarded to neighboring devices. The message continues to reach other relays and is relayed until the TTL reaches zero.

- Proxy Devices: These devices allow the Bluetooth Mesh network to communicate with other Bluetooth-connected devices that do not support the Mesh standard. Proxy devices are configured to simultaneously operate on channels 0-36 to establish connections with devices such as smartphones and computers through Bluetooth connections. They act as intermediaries, facilitating communication between these devices and the devices within the mesh network.

- Friend Devices: These devices are designed to pair with low-power devices. Low-power devices spend most of their time in sleep mode to conserve energy, making them unable to listen to incoming messages while the network is active. Friend devices act as intermediaries for low-power devices, temporarily storing and relaying messages on their behalf until the low-power devices wake up and can receive the messages.

- Low-Power Devices: These devices have limited power resources and prioritize energy conservation. They are unable to receive mesh network messages most of the time and spend most of their time with their transmitters turned off to save energy.

2.3. System design

The system consists of two blocks: the Bluetooth Mesh block and the Internet block. The Bluetooth Mesh block includes a server, nodes, a provider device, and group addresses (see Figure 4).

- Server: The Bluetooth Mesh device operates as a central or peripheral device and is sometimes referred to as a server. The server registers to a group address to receive data from nodes and sends the data to a web server.

- Node: A device that has joined the Bluetooth mesh network. Devices that are not part of the network are referred to as unprovisioned devices. When an unprovisioned device joins the Bluetooth mesh network, it becomes a node.

- Group Address: An address used to identify a group of nodes. A group address can be thought of as a room where devices operate within a specific room, and each device is a Node.

- Provisioner: The provisioning process is one of the most important concepts in Bluetooth Mesh. It is used to add devices to the Mesh network. The devices added to the network are called nodes, and the device used to add nodes to the network is called a Provisioner (typically a tablet, smartphone, or laptop).

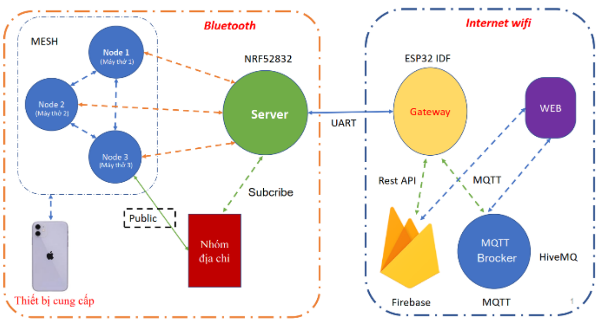

Figure 4. *Bluetooth Mesh description*

In a Mesh network, each node operates as an individual device, and the devices exchange data with each other in a star network topology. In this setup, a device can transmit data to other devices and vice versa. To add a device to the Mesh network, a provisioning device is used. When a device transmits data to a server device, it directly sends the data through other devices to reach the server.

To send data from the server device to the breathing devices, it is performed through group addresses within the mesh network. The server device sends data to a group address, and the breathing devices that want to receive the data register to that group address. The UART Gateway protocol is used to retrieve data from the server device containing the breathing device data, which is then stored in Firebase and pushed to the MQTT broker (HiveMQ). The Web server retrieves the data from MQTT and the broker to display it.

2.4. Circuit design

In the Bluetooth Mesh network system, there is a gateway circuit and multiple node circuits. The node circuits are interconnected, and the gateway receives data from the nodes. The circuit design and 3D modeling for the system are performed using Altium Designer software.

2.4.1. Design of Gateway circuit

The Gateway circuit consists of four main blocks: the power block, the Wi-Fi block, the Bluetooth block, and the power amplifier block. The Gateway circuit combines the NRF52832 chip and the ESP32-WROVER chip. The NRF52832 chip, developed by Nordic, is a wireless microcontroller system-on-chip that operates in the 2.4 GHz frequency range. It supports Bluetooth low-energy communication and offers excellent performance in terms of specifications, transmission range, and low power consumption.

The NRF52832 chip has notable features that make it suitable for low-power systems, including:

- Low Energy Consumption: The chip is designed to minimize power consumption, allowing for extended battery life in devices.

- Long Transmission Range: It provides a reliable wireless connection over a significant distance, enabling communication between devices even in large environments.

- Bluetooth Low Energy (BLE) Support: The chip supports the Bluetooth Low Energy protocol, which is optimized for low-power applications and enables efficient data transmission.

- High Performance: Despite its low power consumption, the NRF52832 chip offers excellent processing capabilities and can handle complex tasks efficiently.

- Integration: The chip combines various functionalities, including wireless communication, processing power, and peripheral interfaces, into a single integrated circuit, simplifying the overall system design.

Here, the NRF52832 chip serves as a server with the task of retrieving data from the nodes and transmitting the received data via the UART protocol to the ESP32-WROVER.

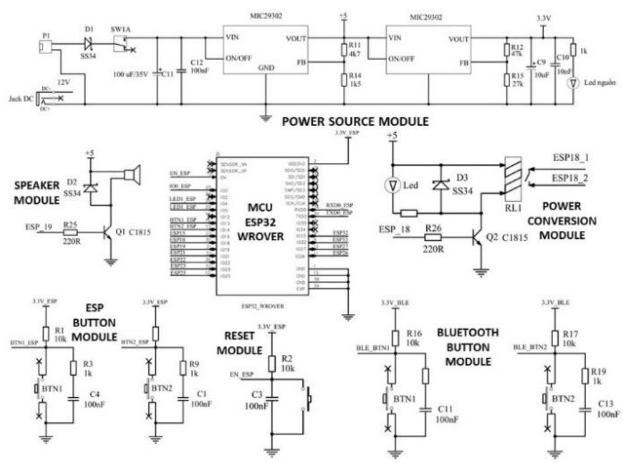

Figure 5. *Schematic of Gateway circuit*

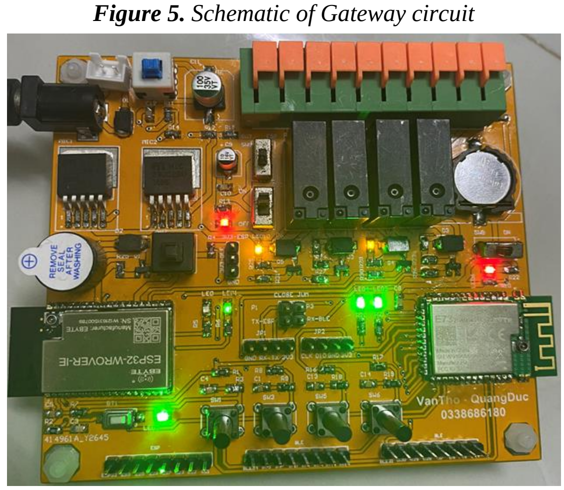

Figure 6. *Photo of Gateway circuit*

The ESP32-WROVER chip, developed by Espressif Systems, is designed for low-power Wi-Fi and Bluetooth applications. It is suitable for low-power sensor applications, such as voice encoding and MP3 encoding/decoding. It features two independently controlled CPUs, with adjustable frequencies ranging from 80 MHz to 240 MHz. Additionally, it supports various peripheral interfaces, such as I2C, SPI, and UART. It is equipped with an ARM Cortex-M4 32-bit 64 MHz core, making it capable of efficiently handling Bluetooth functions and connecting to smart devices. Figures 5 and 6 depict the primary section of the schematic design and the actual photograph of the Gateway circuit.

2.4.2. Design of Node circuit

The Node circuit follows a design similar to the Gateway circuit, comprising the power block, Bluetooth block, and switch block, excluding the Wi-Fi block. It acquires data from diverse devices, including temperature and humidity sensors. These data are then capable of transmission among nodes within the network. Figures 7 and 8 show visual depictions of the primary section in the schematic diagram and an actual photograph of the Node circuit.

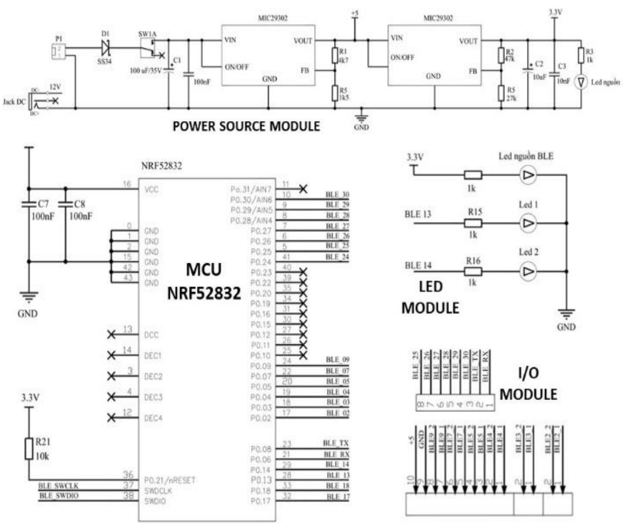

Figure 7. *Schematic of Node circuit*

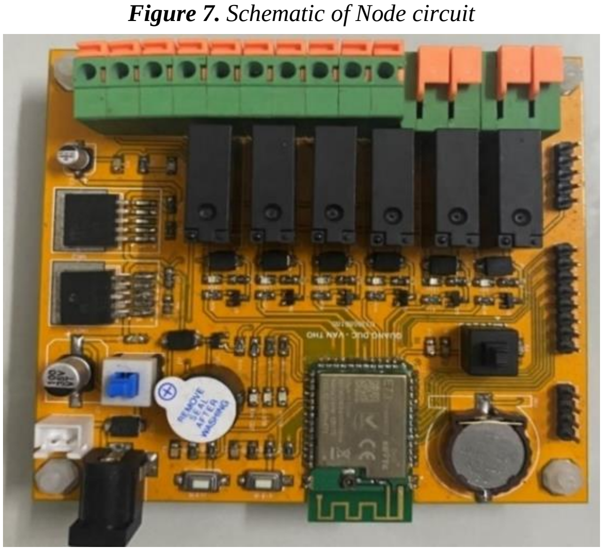

Figure 8. *Photo of Node circuit*

3. Results and discussion

3.1. Testing model

To test the Bluetooth Mesh system, the authors used breathing assistance machines as an illustrative example of communication in the industrial context (see Figure 9). By applying the Bluetooth Mesh system, it becomes possible to automate the patient care process and monitor the patient's condition through mobile health care solutions. Bluetooth Mesh-enabled breathing assistance machines collect important data such as the patient's condition, respiratory rate, and pressure. These data are transmitted to the doctor in real-time, providing information to relevant departments through a web server and connected devices. As a result, doctors can immediately check and monitor the patient's condition, even if they are not physically present.

Figure 9. *The patient is using a ventilator example [21]*

In a room with multiple breathing assistance machines operating, each machine is equipped with a Bluetooth Mesh device (specifically, a node circuit) to read sensors and control the machine's parameters while monitoring the patient's condition. The Mesh network is used to exchange information between the machines and transmit the machine's data through the ESP32-WROVER. The data are then sent to the cloud.

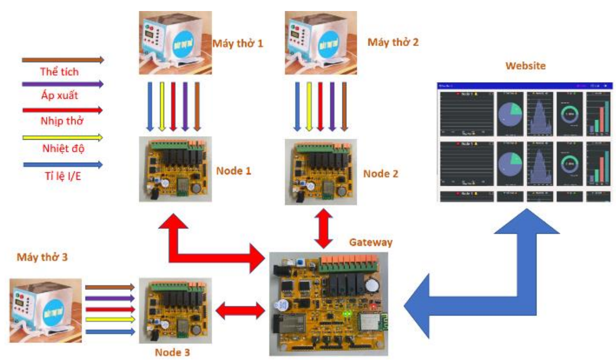

Figure 10. *System diagram*

A designed web server allows monitoring of the operating machines. With this system, nurses can increase the number of patients they can care for and reduce the need for physical check-ups. If a patient's condition deteriorates, nurses can quickly detect it instead of relying on patient reports or waiting for on-site checks. In a room with multiple breathing assistance machines, each machine is equipped with an internal Node circuit. This node circuit reads the machine's data, such as temperature, pressure, tidal volume, and respiratory rate. A gateway circuit is installed within the room to receive data from the node circuits. The gateway circuit is responsible for sending the data to the web server. The system does not use wired connections between the circuits, making the installation process easier (see Figure 10).

In full internet connectivity mode, the system can be controlled via a Webserver using both Wi-Fi and Bluetooth connections. When the Internet connection is lost, the Wi-Fi module will not function, and the circuit will be disconnected from the Webserver. However, it can still continue to be controlled using Bluetooth.

When controlling the circuit from a phone or web server (see Figure 11), the process of updating the status of the breathing machines on the Webserver depends on the speed of the Wi-Fi internet connection. Typically, the update process takes approximately 0.5 - 1 second. Once access to the Webserver is established, it will display two modes: a list view and a monitoring chart for tracking purposes.

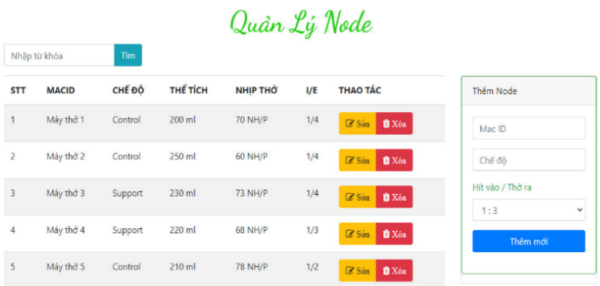

Figure 11. *Managing ventilators on a web server*

In the list mode, a list of connected nodes (breathing machines) will be displayed. This allows for easy management of patients on ventilators and monitoring of their conditions, such as ventilation mode, respiratory rate, and temperature. Nodes (breathing machines) can be easily added or removed from the system.

Figure 12. *Monitoring a specific node*

In the monitoring chart mode on the Webserver (Figure 12), the specific status of the patient on the ventilator will be displayed. This mode enables doctors and healthcare professionals to quickly monitor the patient's condition and remotely track their status. This allows for timely intervention in case of incidents and reduces the workload for nurses and doctors.

3.2. Experiment and evaluation

The authors conducted real-world testing to evaluate the communication capability between two devices in a room, both in the absence and presence of obstacles.

Table 1. *The transmission distance between two devices*

Without obstacles	30 m
With obstacles	18 m

Based on these results, the authors proceeded to install the devices within a hospital setting in a logical manner. The maximum number of nodes in the Bluetooth Mesh network is 32,767 nodes. The maximum number of hops that can be transmitted within the network is 127 hops. The use of Bluetooth Mesh does not limit spatial management by the number of devices. The scalability of the management depends on the number of devices and their positions within the network. Therefore, when deploying the system, the location and topology should be considered to determine the appropriate number of devices.

After the installation of the devices, the authors conducted a survey to assess the signal strength of the Bluetooth Mesh between the two devices, as follows:

Table 2. *Specifications of Bluetooth Mesh*

Device	*Signal amplitude*
Without obstacles	-56 dBm
With obstacles	-62 dBm

The Bluetooth protocol utilizes radio as the communication medium, similar to Wi-Fi, so it is important to optimize the signal strength in both transmission and reception. On Bluetooth devices, this is indicated by the Received Signal Strength Indicator (RSSI), which is represented by numerical values. The stability of the signal strength can vary depending on the situation or interference from other wireless signals. Based on the provided results table, the Bluetooth signal strength can be evaluated.

Table 3. *Evaluation of signal amplitude*

Signal amplitude	*Status*
0 to -60	Good
-60 to -70	Normal
below -90	Weak

Based on the two tables, it is evident that the devices operate with good signal strength without obstacles and within the needed range. When obstacles are present, the devices still function at a normal level.

After the research period, the author's design team completed the product and applied it to monitor the ventilator system. The system operates stably and can be monitored remotely. In the near future, Bluetooth Mesh networks will have wider coverage, and applications related to Bluetooth Mesh networks will become more prevalent. Additionally, the topic of "Applying Bluetooth Mesh networks in industrial production systems" will be implemented in various manufacturing systems in our country, contributing to increased productivity and quality. However, the system still has limitations, such as not achieving the maximum number of connections for each device and the need to add amplification circuits to the Bluetooth module to increase the transmission range.

4. Conclusion

This article presents research on the application of Bluetooth Mesh networks for monitoring ventilator systems. The system operates stably and can be remotely monitored. In the near future, Bluetooth Mesh networks are expected to have wider coverage, and applications related to Bluetooth Mesh networks will become more prevalent in industrial production. In the future, the research team plans to develop a more advanced system model with integrated features, including:

- Improving hardware quality optimization.

- Constructing a dedicated management system for facilitating communication between machines manufactured by various vendors, which are controlled not only by microprocessors but also by PLCs [18 – 23].

- Enhancing the stability of each device.

- Incorporating high-speed transmission capabilities for transmitting images or videos to serve additional functions such as surveillance cameras [24].

- Synchronizing existing Bluetooth-enabled devices (health trackers, Beacons) to easily manage and monitor them within the network.

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