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Design of Real-time Diaper Monitoring System Based on Message Queuing Telemetry Transport and Application Programming Interface

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In this paper, we aimed to address the problem of diaper dermatitis (DD) in newborns caused by delayed diaper changes. We designed a real-time diaper moisture monitoring system based on IoT technology. The perception layer utilizes a 433 MHz radio frequency (RF433) wireless transmission module and a moisture sensor to achieve low-power, real-time, and low-interference detection. When a diaper moisture threshold is reached, the system immediately notifies the caregiver via an alarm module and simultaneously transmits the data to a backend server via the protocol Message Queuing Telemetry Transport (MQTT) using a microprocessor at the transmission layer. The data processing layer utilizes an Application Programming Interface (API) and a database for storage and statistical analysis. The application layer includes Web and Application (APP) interfaces to simultaneously monitor the status of multiple patients across multiple platforms and provides real-time push notifications for alerts. Clinical trials have demonstrated that this system effectively reduces the incidence of DD and hospital stays, thereby improving overall care quality. In this research, we also showed that while MQTT offers real-time performance but exhibits significant latency, APIs provide greater stability and minimal latency, making them suitable for real-time display and management. Overall, this system demonstrates high scalability and practicality, and is poised for future expansion into long-term care and elderly care settings.

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1. Introduction

Because newborns are not yet physiologically mature and do not yet have the ability to control urination and defecation, the use of diapers is a necessary care measure. When newborns are in a medical environment, according to general ward care standards, regardless of whether the patient has wet their diaper or not, they will be checked and changed about every 2 h, which is about 12 to 15 times a day.(1)

Such an operating procedure can easily delay the best time to change the diaper. If the frequency of diaper wetting is high, the baby will have to endure the discomfort of diaper wetting before the medical staff's inspection period. In addition to urine, the feces of newborns are breast milk feces, which are mainly loose and sticky. The bacteria in the feces decompose to form urea. The skin of the baby's buttocks is delicate and sensitive.(2) When the buttocks are soaked in feces and urine for a long time, the skin is easily damaged and causes redness, swelling, pain and other discomforts, forming diaper dermatitis (DD).(3) The affected area includes the perineum, buttocks, lower abdomen, and both sides of the groin.(4) Figure 1 shows different degrees of DD.(5) When newborns have DD, they are relatively prone to crying and light sleep due to physical discomfort. Parents also have difficulty getting good sleep, which reduces the quality of life and work.(6)

According to statistics, the incidence of DD in newborns in the neonatal ward of Taiwan Medical Center is 19.9 to 53.6%. Clinically, newborns who have suffered from DD have a higher recurrence rate than those who have not suffered from DD.(7) Therefore, the "incidence of DD" has become an important indicator of medical quality. Factors that cause DD include the characteristics of neonatal skin, irritation from urine and feces, diaper materials, and chemical wet wipes.(8) The most ideal care methods to prevent DD include air circulation, barrier protection, cleaning methods, diaper use, and educating parents.(9)

With the rapid development of IoT technology, sensors and instant messaging modules have matured.(10) The moisture of diapers can be monitored in real time, and a message can be automatically transmitted to the caregiver. Newborns no longer need to wait until the next

Fig. 1. (Color online) Different degrees of DD.

checkup time to change their diapers. This effectively improves care efficiency and prevents newborns from getting DD.

Uddin *et al*. developed a smart diaper system using IoT technology.[11] Through a built-in moisture sensor and wireless microcontroller, the system can detect diaper moisture in real time and upload the data to the cloud. The mobile application then pushes notifications to users, improving care efficiency and immediate response capabilities. Khan developed a smart wearable device that can be attached to the surface of a diaper.[12] It uses temperature changes to detect infant urination and analyzes events through a hybrid classification algorithm. It pushes notifications to the caregiver's mobile phone immediately to improve care efficiency. The device is compact, low-energy, low-cost, and does not affect the diaper production process. Rahman *et al*. designed a low-cost smart urine moisture detection system that combines a smartphone with a low-power Bluetooth transmitter.[13] The system senses the moisture of the diaper through a flexible conductor and triggers an alarm module when the resistance drops below a preset value, thereby improving the care efficiency and skin health management of patients with severe intellectual disabilities or dementia.

While these devices provide basic moisture detection capabilities, most fail to address issues such as battery consumption, limited transmission distance, and limited scalability, making them difficult to implement in large-scale care facilities or multi-user environments. Table 1 shows the different methods. To address the aforementioned issues, in this research, we proposed a diaper moisture status alarm system with the following features:

(1) This system employs an ultralight, energy-efficient detection method at the diaper level, minimizing device intrusion and ensuring newborn comfort.
(2) When the sensor detects moisture, it immediately sends an alert to the nursing station, even in the absence of a network connection.

Table 1
Comparison of different methods.

Literature Number	Advantage	Defect
Uddin *et al.* (2021)[11]	1) Supports IoT cloud platform and App push notifications for real-time notifications 2) The sensor, MCU, cloud, and App architecture are complete. 3) Can be used for remote care	1) Requires a stable Internet connection 2) The system design is complex and power-consuming. 3) Operations must rely on cloud platform maintenance and data security.
Khan (2019)[12]	1) Non-invasive design does not affect diaper wearing. 2) Use KNN and decision trees to improve detection accuracy.	1) Accuracy may be affected by changes in ambient temperature. 2) Sensors and classification models need to be accurately calibrated and trained. 3) Battery maintenance burden
Rahman *et al.* (2017)[13]	1) Simple system design and low cost 2) Use common BLE modules and mobile apps. 3) Useful for patients who need simple care reminders	1) Conductors embedded in the diaper may affect comfort. 2) Humidity determination based solely on resistance changes may have poor sensitivity. 3) BLE still needs power supply with battery maintenance burden.

(3) When the alarm module at the nursing station is activated, the alert is simultaneously transmitted to mobile phones and computers. Caregivers can receive notifications through internet-connected devices, enabling immediate assistance and providing peace of mind for family members.
(4) The system can monitor the diaper moisture status of multiple care recipients simultaneously. User information, diaper alerts, timestamps, and alert frequencies are recorded in a database for subsequent tracking and statistical analysis.

To achieve these goals, in this research, we established a "Smart Diaper Real-Time Warning System" based on the Open Systems Interconnection model, as shown in Fig. 2. The detailed design is as follows:
(1) Perception layer: The contact part between the diaper and the patient is built with a 433 MHz radio frequency (RF433) wireless transmission module. This allows the diaper end to use the lightest and most energy-efficient equipment and minimizes interference to the newborn.

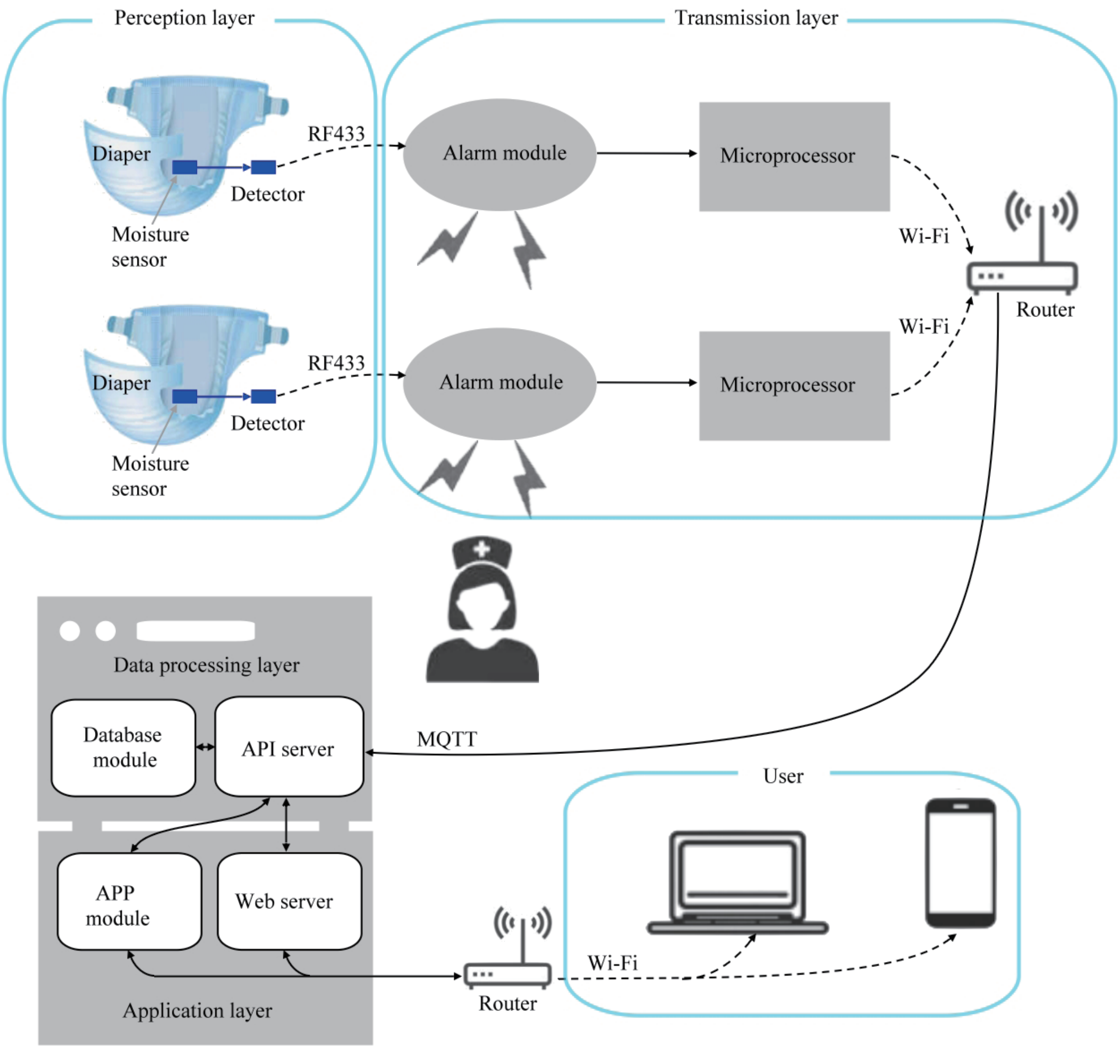


Fig. 2. (Color online) System architecture.

(2) Transmission layer: The transmission layer consists of an RF433 wireless receiving module integrated with a microprocessor. The RF433 receiving module functions as an alarm module, enabling the nursing station to be notified immediately when diaper moisture reaches the threshold. Data are transmitted to the server via the microprocessor using the protocol Message Queuing Telemetry Transport (MQTT), allowing the simultaneous processing of moisture status from multiple care recipients.[14]
(3) Data processing layer: The database stores basic user information, diaper alert records, timestamps, and alert counts for subsequent analysis.
(4) Application layer: An expandable system architecture is designed to support the simultaneous management and monitoring of multiple users and care recipients.

In this research, we developed a system that is more practical and has a greater implementation potential than existing approaches in terms of immediacy, scalability, and cross-platform applicability. Our work positively contributes to the development of smart care technologies.

2. System Architecture

The system architecture adopts a conceptual layered design based on the Open Systems Interconnection (OSI) model and is divided into four layers: perception layer, transmission layer, data processing layer, and application layer.

(1) Perception layer: The diaper serves as the sensing medium and is equipped with a moisture sensor and a detector. The moisture sensor is positioned appropriately on the diaper to measure moisture, whereas the detector is electrically connected to the sensor. When the detected moisture exceeds a predefined threshold, a signal is transmitted to the alarm module.
(2) Transmission layer: This layer includes an alarm module and a microprocessor, and its hardware is installed at the nursing station. When the alarm module receives the RF433 signal, it immediately generates an audible alert for caregivers and forwards the signal to the microprocessor. The microprocessor connects to the router via Wi-Fi and uploads the data to the backend Application Programming Interface (API) server using MQTT.[15]
(3) Data processing layer: This layer includes an API server and a database module. The API server receives alarm identifiers and status information uploaded by the microprocessor and forwards them to the database module. The database module stores historical records for subsequent querying and statistical analysis.
(4) Application layer: The application layer includes a web server and a mobile app module. Connected to the data processing layer, it receives moisture alerts in real time and displays them instantly on webpages or mobile devices. The system supports the simultaneous display of device status across multiple platforms.

2.1 Perception layer

The perception layer used in this study is a moisture sensor from I-ding Medical Equipment Co., Ltd., model UA433, which includes a moisture sensor, a detector, and an alarm module. This product has been certified by ISO 13485. As shown in Fig. 3, the moisture sensor consists of two

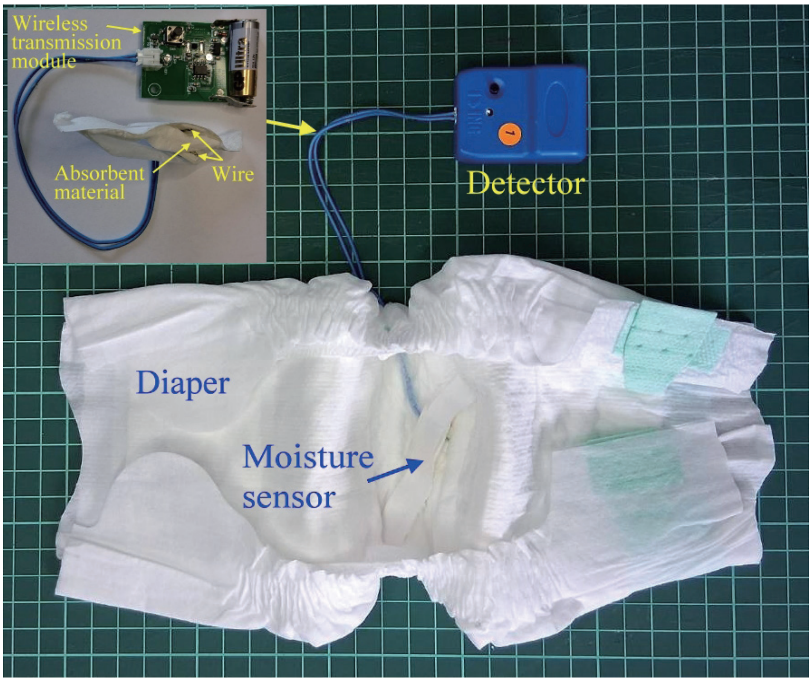


Fig. 3. (Color online) Appearance and circuit of the perception layer.

absorbent materials and sensing wires. It offers the advantages of low cost, disposable design, and simple structure. The cable is placed about 3–5 cm in front of the urethral opening, in the gap between the thighs, to avoid direct contact with the skin. This design ensures that the moisture sensor is unaffected by sweat, muscle contractions, or leakage, and only issues an alert when urine accumulates to approximately 40 ml. Resistance measurement determines the level of moisture in the system based on the resistance between the wires. Higher moisture results in lower resistance.

A 3 kg newborn baby has a daily urine output of approximately 90–180 ml and 5–8 bowel movements. The conductivity of newborn urine is approximately 2–10 mS/cm. This is primarily related to the electrolyte concentration. Higher conductivity indicates a higher concentration of dissolved ions in the urine. Conductivity is also affected by factors such as water intake, dehydration, fever, diarrhea, and diet. The detector in this system is set to a threshold of approximately 40 ml of urine or stool. When the resistance measurement module's detection value exceeds the set threshold, the detector transmits a signal to the alarm module via the RF433 module.

The detector circuit uses an RF433 transmitter. RF433 is a wireless radio frequency communication technology that operates in the 433 MHz frequency band. It is a common, low-power, short-range wireless communication method widely used in home automation devices. The communication range is approximately 10 m. It has the advantages of low power consumption, suitability for battery-powered devices, and low cost. The detector is powered by a 32 A, 12 V alkaline battery.

2.2 Transmission layer

The transmission layer consists of an alarm module, a microprocessor, and a router, as shown in Fig. 4. The alarm module is an RF433 wireless receiver module. When a signal from the detector is received, an alarm sounds to alert the caregiver. The microprocessor and alarm module are electrically connected. When the alarm module is triggered, its output signal is simultaneously input to the microprocessor's General Purpose Input/Output pins for simultaneous broadcasting to mobile phones and computers. This system uses ESP32 as the microprocessor. ESP32 offers several key features, including built-in Wi-Fi and Bluetooth connectivity, suitability for long-term operation. In addition, its transmission architecture enables communication with both website servers and API servers. These advantages make the ESP32 well suited for IoT applications. The microprocessor sends messages to the server using MQTT.

In IoT applications, sensor data need to be transmitted to backend servers or mobile devices via communication protocols. Common communication protocols include Hypertext Transfer Protocol (HTTP) and MQTT. To achieve lightweight and real-time performance, in this study, we used MQTT. MQTT has the following advantages: support for subscription/publishing mode, suitable for multi-device transmission, small packet size, and high security. This protocol is suitable for wireless transmission environments and compatible with common cloud platforms such as Mosquitto and HiveMQ. This system uses Broker to help manage data publishing and subscription for multiple devices, so as to meet the needs of the smart care environment. The current design can handle 15 diaper alarms, meeting the needs of a typical nursing station. The system also reserves space for expansion. The transmission layer is located at the nursing station and can be powered by mains electricity.

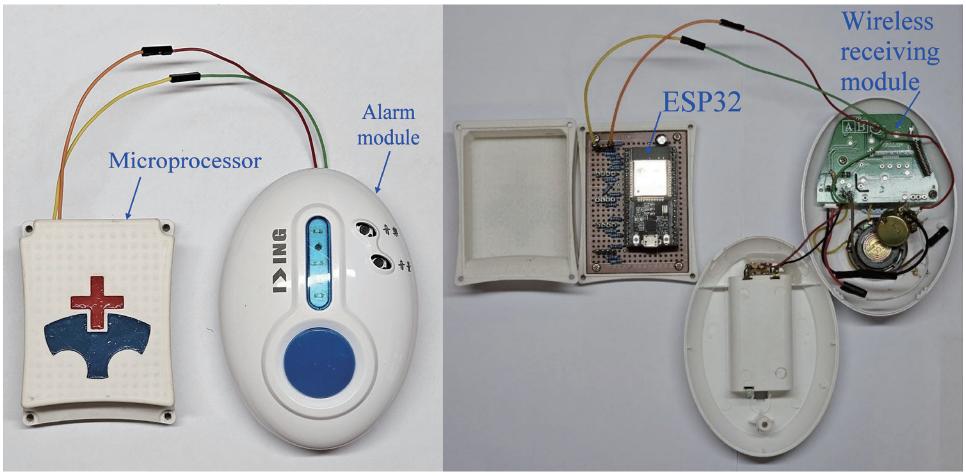


Fig. 4. (Color online) Transmission layer appearance and circuit.

2.3 Data processing layer

The data processing layer consists of an API server and a database module, responsible for data reception, analysis, configuration, and storage. Figure 5 shows the API server screen, and Fig. 6 shows the database module screen. The API server's primary function is to receive diaper numbers and alarm status data from the microprocessor and display the relevant information in real time on a Hypertext Markup Language webpage. Furthermore, the API server stores processed data in JavaScript Object Notation (JSON) format in the database module for subsequent querying, statistical analysis, and historical comparison. The database module is connected to the local API server. The database module is responsible for storing historical records and system parameter settings, supporting back-end data queries and real-time data display in the user interface. Overall, the data processing layer plays a core role in the system, enabling data conversion, logical analysis, and decision-making.

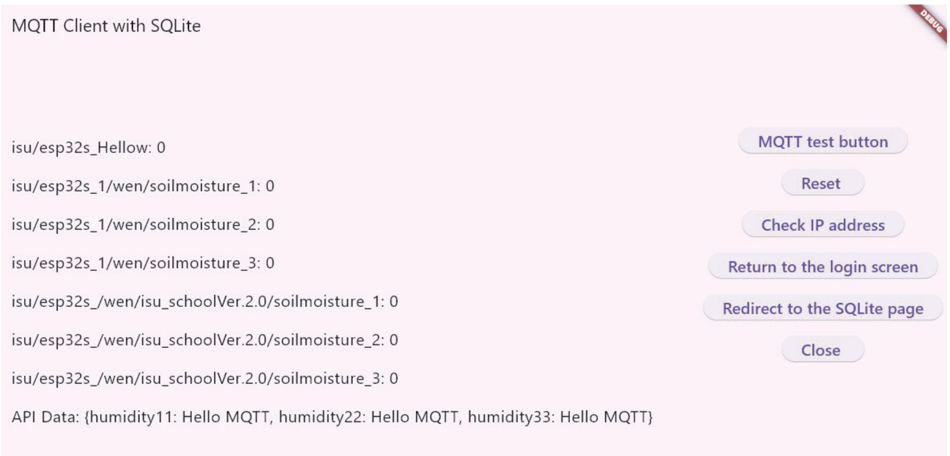
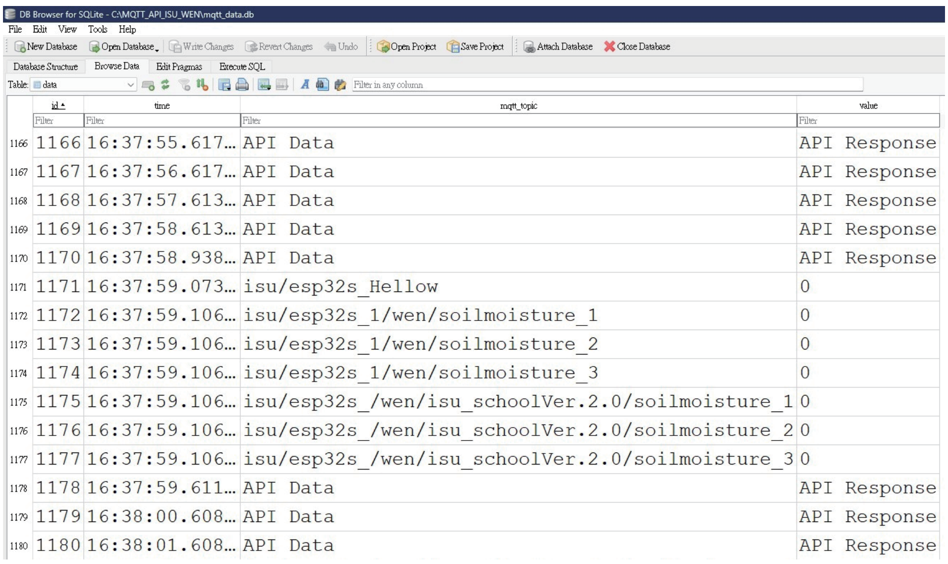


Fig. 5. (Color online) Transmission layer appearance and circuit.



	id	time	mqtt_topic	value
1166	1166	16:37:55.617...	API Data	API Response
1167	1167	16:37:56.617...	API Data	API Response
1168	1168	16:37:57.613...	API Data	API Response
1169	1169	16:37:58.613...	API Data	API Response
1170	1170	16:37:58.938...	API Data	API Response
1171	1171	16:37:59.073...	isu/esp32s_Hellow	0
1172	1172	16:37:59.106...	isu/esp32s_1/wen/soilmoisture_1	0
1173	1173	16:37:59.106...	isu/esp32s_1/wen/soilmoisture_2	0
1174	1174	16:37:59.106...	isu/esp32s_1/wen/soilmoisture_3	0
1175	1175	16:37:59.106...	isu/esp32s_/wen/isu_schoolVer.2.0/soilmoisture_1	0
1176	1176	16:37:59.106...	isu/esp32s_/wen/isu_schoolVer.2.0/soilmoisture_2	0
1177	1177	16:37:59.106...	isu/esp32s_/wen/isu_schoolVer.2.0/soilmoisture_3	0
1178	1178	16:37:59.611...	API Data	API Response
1179	1179	16:38:00.608...	API Data	API Response
1180	1180	16:38:01.608...	API Data	API Response

Fig. 6. (Color online) Database module screen.

2.4 Application layer

The application layer includes a Web server and an APP module. The server module transmits a warning message to the terminal device via the network. The system's application layer uses Flutter to develop the website and APP, providing a simple and intuitive interface. Figure 7 shows the APP module screen and Fig. 8 shows the Web server screen. This system supports multi-user detection, allowing multiple detection modules and wireless modules to be installed on the diapers of multiple caregivers for simultaneous monitoring. The server records the status of each device separately, allowing multiple caregivers to query or manage the system simultaneously. Users can instantly view the alarm status of all online diapers. When a diaper reaches a moisture threshold, the system instantly updates the event status on the front-end screen of their mobile phone or computer. It displays alarm time and diaper number. Different conditions are indicated by red or green colors. Caregivers can monitor the diaper's alarm status in real time via the webpage or mobile APP.

2.5 Software process and decision logic

Perception Layer Design Process:

(1) The moisture sensor is placed inside the diaper to detect moisture changes. The detector is placed next to the diaper.

(2) If the moisture exceeds the threshold, the detector wirelessly transmits an alert signal to the alarm module.

Transmission Layer Design Logic:

(1) The microprocessor reads the detector's alarm module data at regular intervals and classifies it as either normal or requiring replacement based on the alarm status. If the status differs from the previous one, it is considered a status change.

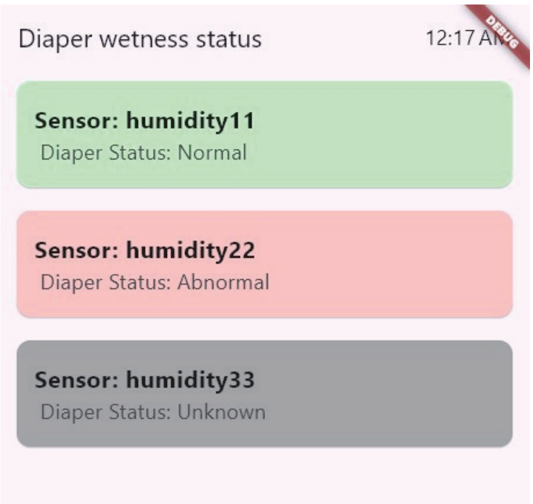


Fig. 7. (Color online) APP module screen.

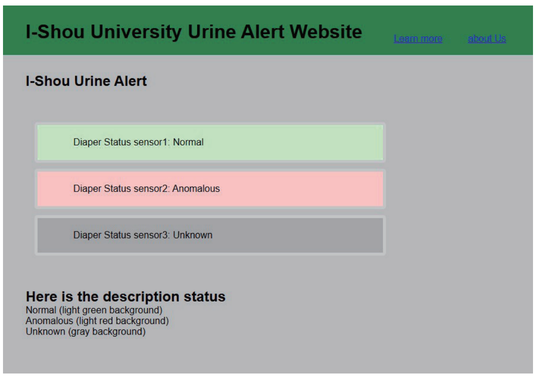


Fig. 8. (Color online) Web server screen.

(2) The microprocessor sends an MQTT message to a designated topic, containing a timestamp, diaper number, and alarm status.

The data processing layer design process is as follows: The backend server uses MQTT to subscribe to a specified topic to receive data, performs message parsing and data processing, stores the data, and provides data services to the App through the API.

The application layer design process is as follows: The APP requests the server to send the diaper status data and displays color information based on the severity of the alarm.

3. Results and Discussion

3.1 Delay analysis

In this article, we integrated commercial equipment with our self-developed system. This system had to ensure that the original alarms can be reliably and quickly transmitted to the mobile device. This reduces the time babies spend soaking in feces or urine, lowering the chance of DD. To evaluate the API server delay under long-term MQTT device operation, in this study, we used five MQTT devices to simultaneously transmit moisture data to the API server. One transaction was sent per second for 1000 s. The difference between the API server's timestamp and the MQTT device's timestamp represents the delay. Figure 9 shows the delay trends for this test. Overall, the delay for most devices remained stable below 0.7 s. This is ideal for instant diaper alert applications. However, at certain times, certain devices (such as #1) exhibited significantly shorter delay. This "delay discrepancy" and the resulting graph pattern are hypothesized to be related to the following factors: the incomplete synchronization of the sending and receiving timestamps; the momentary network congestion caused by simultaneous device transmissions; Wi-Fi bandwidth sharing and collision retransmissions; and MQTT server processing bottlenecks. These synchronization fluctuations indicate potential delay impacts, especially when multiple devices are transmitting simultaneously.

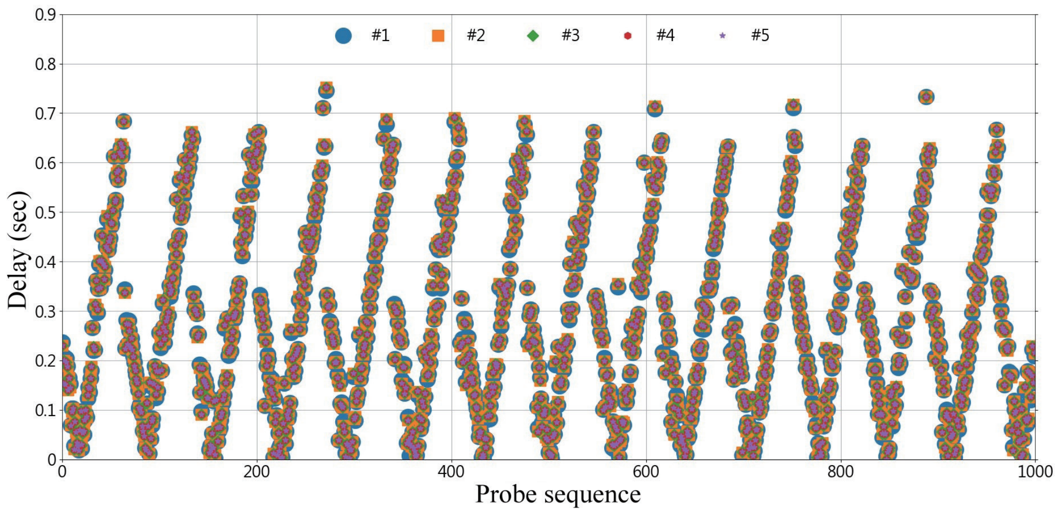


Fig. 9. (Color online) Trend of MQTT device delay.

3.2 Delay comparison

Figure 10 further shows the delay of an MQTT device and HTTP over multiple transmissions. For HTTP delay analysis, the Stopwatch() function was used to record the start and response time of each HTTP request to calculate HTTP processing delay. All data were stored in the SQLite database for subsequent statistical analysis. The results show that MQTT's average delay is significantly shorter than HTTP's, with an average delay of approximately 0.27 s for MQTT and approximately 1.23 s for HTTP. The delay fluctuation range for MQTT is also very narrow. This difference reflects the nature of the two transmissions. Although MQTT transmission involves multiple links, including devices, wireless networks, MQTT brokers, and API servers, its lightweight communication performance, small data packets, and relatively low system computation and bandwidth requirements ensure short delay across various devices and network environments, effectively reducing system resource consumption. In contrast, HTTP transmission is primarily used for data storage and processing within servers, typically employing a request/response model. Each transmission requires establishing a full connection and carries a significant amount of header information, resulting in relatively high system resource requirements and delay. Comparison results show that in multi-device data upload scenarios, the primary delay differences arise from the transmission protocol itself and the network environment, rather than the server's internal data processing speed.

3.3 Delay distribution

Figure 11 shows the delay distribution for MQTT and HTTP transmissions. MQTT's delay distribution ranged from 0.29 ± 0.20 s, with only a few instances exhibiting unusually long delays exceeding 0.7 s. This indicates that occasional delays can occur under certain conditions. In contrast, HTTP's delay was primarily concentrated within a range of 1.23 ± 0.29 s, with a

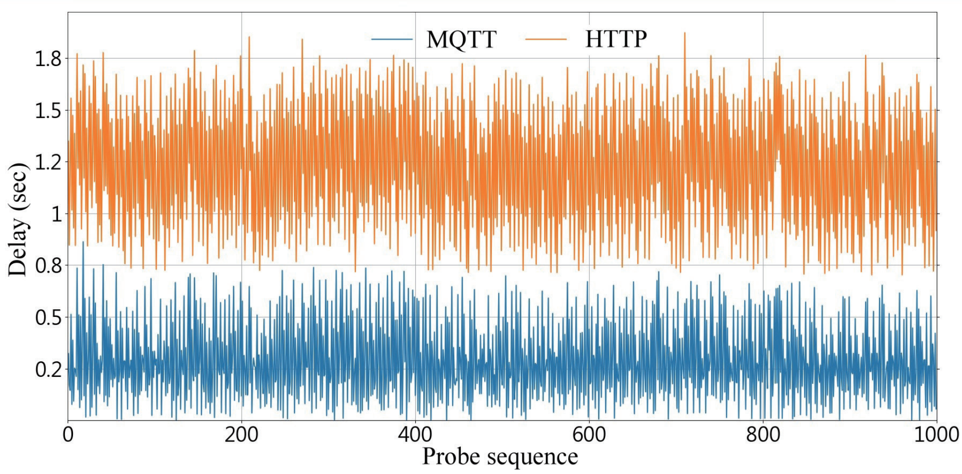


Fig. 10. (Color online) Delay time comparison between MQTT and HTTP.

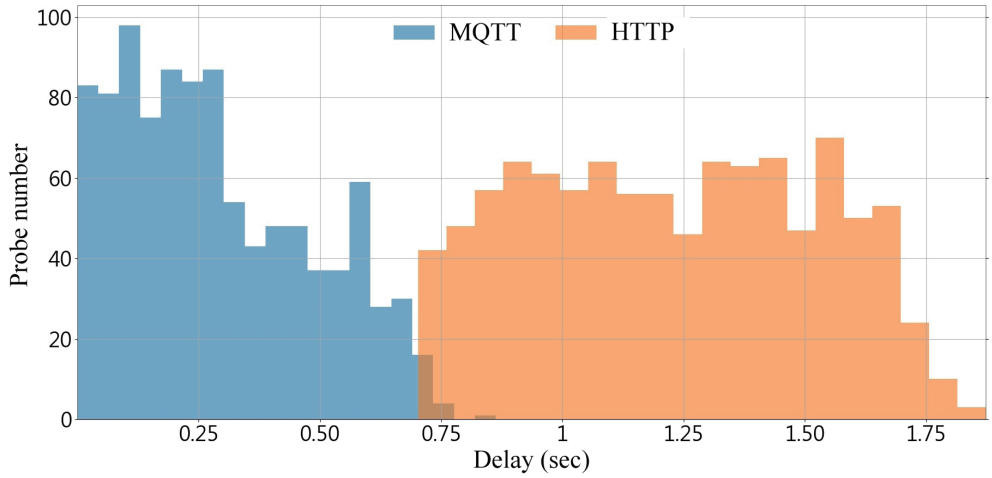


Fig. 11. (Color online) Delay time distribution comparison.

more dispersed distribution. This indicates a longer average delay and less stable delay. Overall, MQTT demonstrated shorter delay and greater consistency under these test conditions, while HTTP exhibited greater instability in both latency and latency variation.

3.4 Clinical validation

This system was applied in clinical practice at a medical center in Kaohsiung. This study was approved by the Ethics Review Committee of Kaohsiung Medical University Hospital (KMUIRB-SV(I)-20210050). We compared the incidence of DD before and after system implementation, as shown in Table 2. Upon newborn hospitalization, nurses assess whether the newborn has DD or whether DD has occurred. After discharge, nurses continuously monitor whether DD has occurred during the newborn's home stay (one month). Before the improvement of DD, standard operating procedures in a general ward were used. After the improvement of DD, this system will be integrated into clinical practice, and the standard operating procedures for DD nursing will be revised. A total of 650 newborns were counted before the implementation of this system and 141 newborns were counted after the implementation of this system. To compare the differences between the two conditions, in this study, we defined the following evaluation metrics:

I_{AO} is the total incidence of DD in infants.

$$I_{AO} = \frac{NIC_A + NIC_O}{NIC_{TN}}, \tag{1}$$

where NIC_{TN} is the total number of infants in the neonatal intensive care unit (NIC) that month, NIC_A is the number of NIC patients with DD (assessment upon hospitalization),[16] NIC_O is the number of NIC patients with DD (occurrence after hospitalization), and I_O is the incidence of DD occurrence after hospitalization.

Table 2
Comparison of incidence of DD before and after improvement.

Number of people/Metrics	Before improvement	After improvement
Total number in the NIC that month, NIC_{TN}	650	141
Number of NIC patients with DD (Assessment at admission), NIC_A	78	8
Number of NIC patients with DD (Occurrence after admission), NIC_O	19	3
Number with DD recurring within 1 month after discharge, NIC_D	23	13
Total incidence of DD in infants, I_{AO}	14.9%	7.8%
Incidence of DD occurrence after admission, I_O	2.9%	2.1%
Incidence of DD recurrence after discharge, I_D	23.7%	9.1%

$$I_O = \frac{NIC_O}{NIC_{TN}} \tag{2}$$

I_D is the incidence of DD recurrence after discharge.

$$I_D = \frac{NIC_D}{NIC_{TN}}, \tag{3}$$

where NIC_D is the number of infants with DD recurring within one month after discharge.

Table 2 shows that the in-hospital DD incidence rate decreased from 2.9 to 2.1%, an improvement of 27.6%. Furthermore, this improvement has reduced the length of stay for children with DD. The average length of stay has decreased from 9.5 to 7.6 days and bed turnover has increased significantly. The post-discharge DD recurrence rate has decreased from 23.7 to 9.1%, an improvement of 61.6%. This system has also improved the quality of care after newborns return home. It reduces the risk of infant discomfort caused by inexperienced caregivers. Its implementation has not only reduced the incidence of DD in both in-hospital and out-patient settings, but has also improved the quality of care.

4. Conclusion

In this study, we developed a diaper moisture status alert system. The system provides a safe and friendly environment for infants to receive medical treatment, and also improves the quality of care after returning home. In this research, we integrated sensing technology, IoT communication protocols, and an instant notification mechanism. In addition to sending alerts to the nursing station, notifications can also be sent via social media APPs such as LINE, demonstrating good system scalability and practicality. This system improves nursing efficiency and patient care quality.

The system's data transmission capabilities were explored. MQTT's latency was long and highly volatile, whereas API's latency was stable and low. This suggests that MQTT is more suitable for data transmission between devices, whereas API is more suitable for real-time monitoring and alarm systems. These results demonstrate the reliability and immediacy of the monitoring system in a multi-device environment. Using this system in the care of newborns with DD has significantly reduced both the in-hospital incidence and recurrence rate of DD after discharge. This has prevented newborns from having extended hospital stays due to DD. The average length of stay has also been significantly reduced, leading to a relative improvement in bed turnover.

The diaper warning system designed by this institute can effectively improve the timeliness and accuracy issues in traditional care processes. In the future, the system can be continuously optimized and promoted to elderly care and long-term care settings.

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