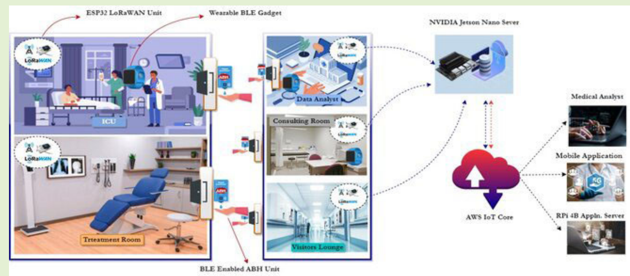
IEEE Sensors Council

A Hand Hygiene Tracking System With LoRaWAN Network for the Abolition of Hospital-Acquired Infections

K. M. Abubeker and S. Baskar

***Abstract*—In healthcare settings, hand hygiene is a crucial step in preventing the spread of disease. Healthcare-associated infections, such as community-acquired pneumonia (CAP) and hospital-acquired pneumonia (HAP), can be mitigated with the help of cutting-edge solutions and intelligent alcohol-based hand sanitizers. Specifically, this research presents a long-range (LoRa) network powered by the Internet of Things (IoT) that can detect, monitor and track hand hygiene habits to reduce the spread of hospital-acquired infections (HAIs). The wearable Bluetooth low energy (BLE) device used by hospital personnel and patients will monitor and track the hygiene activities using LoRa and alcohol-based sanitizers deployed in intensive care units (ICUs), elevators, inpatient rooms, and other hospital facilities. The alcohol dispenser is equipped with a Jetson Nano graphics processing unit (GPU) from NVIDIA, a hand sanitizer, and a door that opens once the user has washed their hands. Using a LoRa wide area network (LoRaWAN) and short-range BLE technology, hand hygiene information, with a user ID and GPS location, has it sent to a LoRa gateway and a cloud server. Various field tests in hospital settings and simulated environments are performed to effectively guarantee the clinical performance of the proposed IoT-enabled LoRa network. In conclusion, the total success percentage in real-world LoRa network conditions is 92.78%, whereas the success rate (SR) in laboratory testing is 98%.**



***Index Terms*—Hand hygiene, Internet of Healthcare Things (IoHT), long-range wide area network (LoRaWAN), pneumonia, wearable biosensors.**

I. Introduction

HEALTHCARE-ASSOCIATED infection is the most common adverse event that patients can acquire during medical procedures, such as receiving treatment, being admitted to an intensive care unit (ICU), or being in the hospital for an extended period following surgery. As it is difficult to get reliable data and seems to be a covert, system-wide issue in many care institutions, including hospitals and long-term care facilities, the worldwide effect, however, remains unknown. Low- and middle-income countries (LICs and MICs) were given far lower ratings than high-income countries (HICs) for their levels of implementation of the key components of the infection prevention and control (IPC) agency, which ranged from inadequate to advanced. LICs' implementation of IPC regulations, education, monitoring, and hospital-acquired infection (HAI) surveillance fell far short compared to what it should have been. Existing data, however, showed that despite some progress, worldwide compliance with hand hygiene recommendations during healthcare delivery remained inadequate, with significant disparities between HICs and LICs.

A thorough approach to hand cleanliness is a vital preventive step in all parts of healthcare, and it is one of the most effective strategies for preventing the transmission of infections [1]. Healthcare-associated infections affect 3.25% of hospital patients in a day and can spread from one patient to the next. Both patients and healthcare workers (HCWs) are at risk of infection while a patient is being treated or when a healthcare professional is treating a patient. Medical workers wipe their hands approximately half as frequently as they should, before and after every contact with a patient, however, depending on the number of patients and the amount of care offered. It is vital to avoid germ transmission in healthcare institutions such as hospitals, critical care units, dialysis units, and nursing stations. One of the most important things to avoid being sick and spreading germs is to keep the hands clean by

Manuscript received 18 December 2022; revised 4 February 2023; accepted 6 February 2023. Date of publication 28 February 2023; date of current version 31 March 2023. The associate editor coordinating the review of this article and approving it for publication was Prof. Guiyun Tian. *(Corresponding author: K. M. Abubeker.)*

K. M. Abubeker is with the Faculty of Engineering, Department of Electronics and Communication Engineering, Karpagam Academy of Higher Education, Coimbatore, Tamil Nadu 641021, India, and also with the Amal Jyothi College of Engineering, APJ Abdul Kalam Technological University (APJAKTU), Thiruvananthapuram, Kerala 686518, India (e-mail: kmabubeker82@gmail.com).

S. Baskar is with the Faculty of Engineering, Department of Electronics and Communication Engineering, Karpagam Academy of Higher Education, Coimbatore, Tamil Nadu 641021, India (e-mail: connectbaskar@gmail.com).

Digital Object Identifier 10.1109/JSEN.2023.3244582

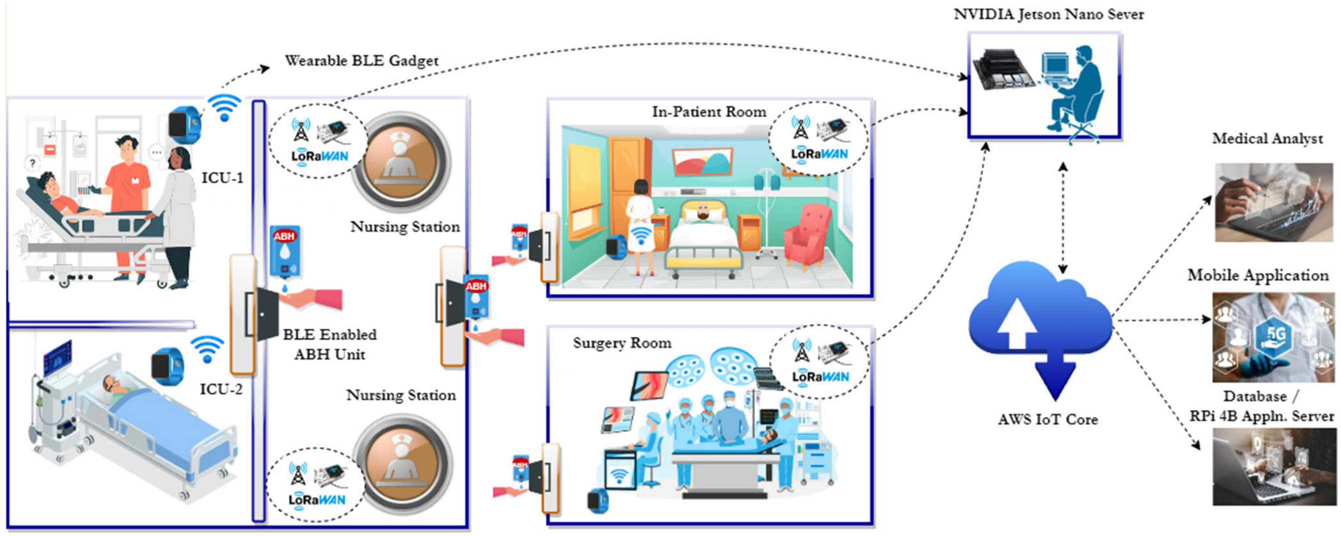


Fig. 1. Hand hygiene tracking system with LoRaWAN for the abolition of HAIs.

washing them with soap and water or using an alcohol-based hand sanitizer. According to the Centers for Disease Control and Prevention (CDC), alcohol concentrations ranging from 60% to 95% are more effective in eradicating germs while keeping the same degree of efficiency. This kind of sanitizer kills germs fast and is best used in clinical environments such as critical care units, treatment rooms, isolated patient rooms, and other hospital facilities.

An improvement strategy is the most effective way to encourage hand hygiene and create IPC in medical facilities. Hospitals can avoid HAI using sophisticated, noninvasive sensors, wireless sensor networks (WSN), and wireless body area networks (WBAN) [2]. The Internet of Healthcare Things (IoHT) allows real-time human–machine interaction, revolutionizing society. This change includes autonomous hospital environmental monitoring [3], noninvasive patient monitoring [4], vision-based hand hygiene tracking [5], sensor-assisted electronic hand hygiene monitoring [6], and healthcare applications. Smart patient monitoring is a prominent application of the Internet of Things (IoT) to detect healthcare-associated infections, Ventilator-Acquired Pneumonia (VAP) [7], Hospital-Acquired Pneumonia (HAP) [8], and Community-Acquired Pneumonia (CAP) [9].

This research presented an IoT-enabled monitoring system for hospital and ICU hand hygiene. Alcohol-based hand hygiene (ABH) dispensers scan for Bluetooth low energy (BLE) signals from patients, hospital workers, and other healthcare professionals, as indicated in Fig. 1. The smartwatch keeps track the number of times a person uses hand sanitizer and their identification number and both are logged when a BLE signal is received. To transmit the information gathered by smart dispensers to a router, each dispenser is equipped with a BLE-enabled TTGO T ESP32 IoT module that is connected to a long-range wide area network(LoRaWAN) gateway. The Jetson Nano graphics processing unit (GPU) computer stores and transmits information to a cloud database where it can be analyzed more deeply. The following are the main contributions of this article.

1) First, a wearable BLE assisted hand hygiene monitoring and tracking device has been deployed in ICUs, operating rooms, dialysis units, and other medical institutions to reduce HAIs, CAP, and HAP.
2) The open-source software for wearable devices and sanitizer dispensers to track hand hygiene activities through the IoT has been developed.
3) Third, the smart dispensers for lowering HAI rates are deployed using both short-range BLE and LoRaWANs.

The remaining portions of this research article are structured as follows. Section II compares sensor- and vision-based hand hygiene monitoring systems. Section III presents the long-range(LoRa)-powered hand hygiene monitoring and tracking system, WSN, and cloud server settings. Section V concludes after discussing system performance in Section IV.

II. Related Works

Monitoring patients' adherence to hand hygiene protocols is an effective way to curb the spread of HAIs, pneumonia, and other pandemic and epidemic diseases. The IoT can avoid HAIs by combining sensor technologies, wireless protocols, cloud computing platforms, and networked gadgets. Stangerup et al. [10] studied long-term hand hygiene techniques, which found that HCWs decreased HAIs by washing their hands but returned to previous habits after improvement efforts were finished. Two independent studies found that HCWs practiced better hand hygiene during and after the pandemic period [11], [12]. Kong et al. [13] identified a reduction in HAIs and increased hand hygiene adherence after the COVID-19 pandemic. According to Casaroto et al. [14], hand hygiene rates increased during the pandemic, while pre-Covid compliance was highest and pandemic compliance lowest. Ojanperä et al. [15] found that HAIs in medical and surgical wards decreased with hand hygiene.

McDonald et al. [16] found that operational and environmental challenges in home care make hand hygiene more challenging than in acute care. Healthcare-associated infection monitoring requires consistent standards, diagnostic facilities, and experienced interpreters. BLE, Wireless Fidelity (Wi-Fi), Radio Frequency Identification (RFID), and ZigBee have made data sharing between devices cheaper and faster [17], [18], [19], [20]. BLE is best for short-range applications in ICUs, treatment rooms, and other hospital buildings.

Repanovici et al. [6] developed a simple and successful image processing and biometric analysis method for monitoring medical personnel's hand hygiene to prevent infection. Knudsen et al. [21] reported that EHHMS enhanced doctors' and nurses' HHC and reduced hospital-acquired bloodstream infections. Haque et al.'s [22] hand hygiene system monitors HCWs' hand-washing activities using videos and machine learning (ML) frameworks. A cost-benefit analysis by Nawaz et al. [23] reveals that an energy-efficient battery management system not only improves cell balance and saves the cell pack's energy but also lowers the total cost of the system and its upkeep. Power utilization can be improved with the development of innovative energy-saving techniques and communication technologies. Páez-Montoro et al. [24] developed a flexible battery, a semi-flexible solar harvester module, and a BLE module to show the viability of combining solar energy harvesting into a practical wearable smart device. Researchers intend to design a standardized electronic device that avoids these difficulties and easily records hand hygiene compliance. The tool should be easy for HCWs and nurses to use in clinical procedures, and its acceptability can be assessed. The research predicted this would aid training and disease outbreak response.

III. Methodology

Connected wearable biosensors, the IoHT, ubiquitous IoT, and robotic surgery are examples of the new care delivery models that are now undergoing a fast transition in the healthcare ecosystem [26]. Artificial Intelligence (AI), ML, data analytics, and other new technologies are reshaping healthcare solutions and delivery models [27], [28]. IoT-assisted sensor networks in healthcare can track patients, healthcare monitoring equipment, and medical workers in real time [29]. Patient infection can be avoided with the use of IoT-enabled hygiene monitoring equipment.

The smart alcohol-based dispensers, wearable BLE device, LoRa gateway, and application server make up the proposed IoT-enabled hand sanitization monitoring and tracking system. A typical method involves installing smart dispensers at the entryways of patient rooms and ICUs. Every healthcare professional with a BLE gadget must use an ABH dispenser to disinfect their hands when entering, moving through, and exiting the facility. Furthermore, an ABH monitoring device is installed at each ICU bedside to track how thoroughly patients decontaminate their hands. The smart dispenser is outfitted to record and transmit personnel IDs and hand sanitizing data through BLE to a gateway, transmitting the subjects and data over LoRaWAN to an IoT gateway. This metadata is stored in the 128-core Jetson Nano System on Module (SoM) computer's local database. To boost hospitals' hand hygiene compliance, this research has provided data visualization on a web interface, remote database, cloud, and mobile application.

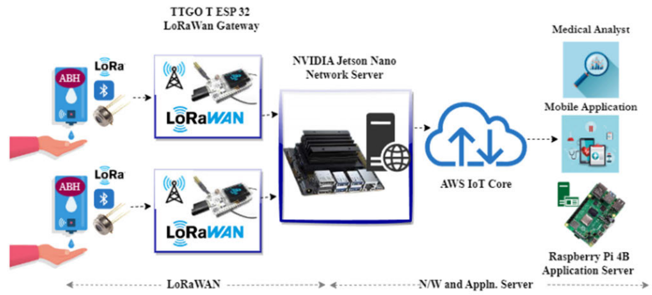


Fig. 2. LoRa-ABH architecture demonstrated for medical/ICU applications.

A. LoRa Wide Area Network

LoRaWAN allows for wireless connectivity between nodes and efficient two-way communication between end nodes and network gateways [30]. LoRa encodes data in a low-power, cost-effective way by using chirp spread spectrum technology (chirped) and multisymbol modulation. LoRa is the physical layer that enables long-distance connection. Devices connected to the internet across a wide area periodically transmit small data packets to a centralized administrator. LoRa-enabled devices communicate with one another, and the network server carries out data integrity and security checks through the gateway. Also, nodes in a star or peer-to-peer architecture use less power since they are not constantly processing data. When the spreading factor (SF) is low, more data can be transferred in the same amount of time without increasing the bandwidth or the time it takes to send it. We have set the SF for LoRa to 10 to get the best possible performance in data rate and transmission distance, albeit its normal range is 6–12. Similarly, by increasing the bandwidth to 915 MHz and using a 4/5 coding rate, we increased receiver sensitivity and decreased transmission overhead. The LoRaWAN architecture configured in this research is presented in Fig. 2.

To deploy a LoRaWAN, numerous LoRa gateways, one for each building, are linked to a central server running the apache HTTP server on a 128-core NVIDIA Jetson Nano GPU. Gateways are the central protocol bridges in LoRaWANs, collecting radio signals modulated with the LoRa standard from all of the end nodes in the network. Each valid LoRaWAN frame is transmitted to the subsequent network server. Gateways are positioned at a minimal distance, or the number of LoRaWAN gateways in a building is raised to improve the battery life of end nodes. Important gateways are prefixes, and the arrangement of terminal nodes might change based on the subject's depth and the gateway's significance.

There are currently a wide variety of competing standards, each with its own set of pros and downsides in areas like battery life, range of transmission, and range of possible applications. Three aspects of wireless transmission must be controlled: the amount of energy used to send data, the speed at which it is sent, and the range over which it travels. BLE is a short-range wireless technology that uses 0.01 W of power and can transfer data in bursts of up to 2 megabytes. The wireless unit only awakes when it detects a signal specific to the gadget itself; otherwise, it sleeps while using very little power. When in a deep sleep, a BLE system on a chip (SoC) typically uses a few hundred nA; when the CPU is active, it can use up to 30 mA. With limited resources and the need for prolonged battery life, IoT devices need the usage of BLE, which prioritizes low power consumption over constant data transmission. IoT devices like wearables would be more desirable and helpful if their battery life could be greatly prolonged to years using a wake-up signal.

To lower the power consumption, this research utilized BLE devices powered by two series 25A-LR8D425-AAA alkaline batteries. Normal operation for BLE, in this case, entails it being on for 120 s/h at a transmission current of 10 mA. If the average BLE sleep current is 8 μA, and the average BLE sleep time is 3480 s/h. Then the total current (I_{total}) utilized per hour is calculated as

$$\begin{aligned} I_{\text{total/hour}} = &\ (\text{BLE}I_{\text{active}}\text{time})/3600 \\ &+ \left(\text{BLE}I^{*}_{\text{sleep}}\text{time}\right)/3600. \end{aligned} \quad (1)$$

In (1), BLE I_{active} and BLE I_{sleep} are the current utilization of BLE device in active and sleep mode, respectively,

$$\begin{aligned} I_{\text{total/hour}} = &\ \left(10000\ \mu\text{A}^{*}120\ \text{s}\right)/3600\ \text{s} \\ &+ \left(8\ \mu\text{A}^{*}3480\ \text{s}\right)/3600\ \text{s} \sim= 341\ \mu\text{A}. \end{aligned} \quad (2)$$

Then the total power requirement for the BLE device for a day is calculated as

$$I_{\text{total/day}} = 341\ \mu\text{A}^{*}24\ \text{h} \sim= 8.18\ \text{mA}. \quad (3)$$

BLE peaks in the discharge current are seldom a concern for lithium ion and polymer batteries. Most devices' peak BLE current is lower than the typical discharge rate (20 mAh) for a battery with 100 mAh capacity. The total amount of power the LoRa device uses is cut down by the sleep and awake function. Consequently, alkaline batteries are the most practical power source for this gadget. Using alkaline batteries eliminates overvoltage, overcurrent, undervoltage, and thermal protection concerns.

B. Intelligent ABH Dispenser Unit

The commercially available touchless hand sanitizer unit does not offer intelligence and is wrongly triggered even with obstacles and nonhuman subjects. Therefore, creating a smart sanitizing unit that can only function when people are around is important. A smart ABH unit built on a TTGO T ESP 32 IoT module serving as the main controller for human presence detection using an MLX 90 614 infrared (IR) temperature sensor, facilitating BLE communication between a wristwatch and a LoRa gateway and establishing real-time connectivity between the LoRaWAN and AWS IoT core connectivity.

ESP32 is a low-cost, low-power SoC microcontroller powered by a 32-bit Xtensa LX6 dual-core microprocessor with integrated Wi-Fi and dual-mode BLE, radio frequency (RF) unit, low-noise receive amplifier, embedded serial communication protocols, and power-management modules. This IoT module is specially engineered for mobile devices, wearable gadgets, and IoT applications, with ultralow power consumption through power-saving features. Melexis MLX90614 is

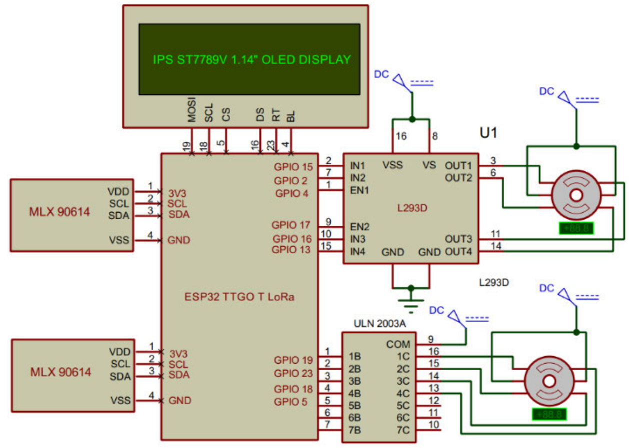


Fig. 3. Interfacing diagram of ABH dispenser unit deployed in ICUs and hospitals for the abolition of HAIs.

used to identify the presence of a human body on the premises of the ABH system. The MLX90614 is a noncontact IR thermometer consisting of IR sensitive thermopile detector chip and the signal conditioning application-specific integrated circuit (ASIC) integrated chip. MLX90614 generates object temperature T_{obj} and an ambient temperature T_{amb} ranging from −70 °C to 382.2 °C and −40 °C to 125 °C, respectively, with a resolution of 0.02 °C and accuracy of 0.5 °C. The interfacing diagram of the intelligent ABH dispenser unit is shown in Fig. 3. The T_{obj} can identify a human subject; BLE signals from the wearable gadget also trigger human presence. When both signals are matched the ABH system, the controller will only activate the spraying mechanism after verifying the presence of a hand in the outlet area with IR proximity signals.

The signals from the ABH system also control the hybrid entry mechanism of the ICU and inpatient room; a linked emergency pull cord/switch to the door mechanism can manage unanticipated situations. The controller verifies the BLE signals from the user, and the hand hygiene status using the ABH system is sent to the LoRa gateway and AWS IoT core along with the meta information, GPS location, and timing credentials.

C. TTGO T ESP32 and BLE Connectivity

The TTGO T ESP32 module is equipped with 915/886 MHz LoRa protocol, Wi-Fi Bluetooth (BT) classic, and BLE with 2.4 GHz. It uses relatively little power, around 100 times less than BT, and is set for a point-to-point connection, broadcast, or mesh network mode. In this point-to-point server–client mode, a user or wearable gadget is configured as the client node and the ABH unit as the server node. The server unit can be found by the clients and establish a connection and listen for incoming data using a generic attribute profile (GATT) using attribute protocol (ATT).

The server and client BLE have a 128-bit universally unique identifier (UUID), which can be used to differentiate the client devices, and the meta information of each user can be accessed from the server unit. When the server identifies a BLE unit, it will check for the authenticity of the client and human presence by the MLX 90614 sensor. When both are matched, the human hand is identified within the dispenser unit, alcohol is sprayed, and the user information, along with time and GPS location, is updated in the LoRa server and application server without delay. ICU and inpatient room access is controlled in hybrid mode; if the above two steps are completed, the stepper motor mechanism connected to the door is activated, and ensure the user entry using the IR sensors placed in the door. The door mechanism will be deactivated after the user entry or after the 5-s interval. The ABH dispenser will detach the wearable BLE device and relay data to a LoRa gateway after this operation is complete. This information can be viewed by authorized persons from the AWS IoT core; this user or patient position can also be tracked from the GPS data.

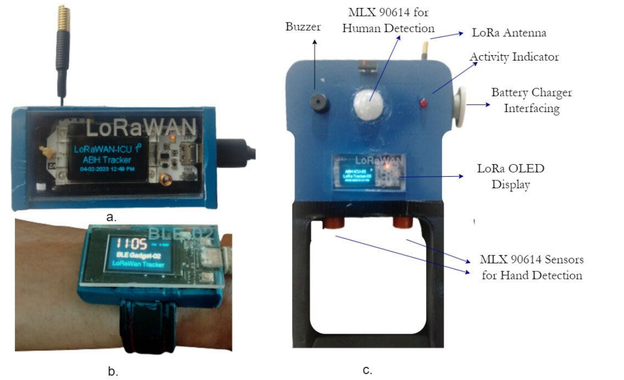


Fig. 4. Real-time deployment of the ABH dispenser unit. (a) LoRaWAN. (b) LoRa BLE device placed on the patient's hand. (c) Intelligent IoT enabled LoRaWAN ABH unit.

D. Network and Application Server

The local server is a dedicated host outfitted with NVIDIA's 128-core Jetson Nano GPU computer, powered by a Quad-core ARM Cortex-A57 MPCore CPU and 4 GB of 64-bit LPDDR4 memory. For data security, this server employs two layers of storage: first, data are saved on GPU hardware, and second in the IoT cloud. The IoT framework's physical things or sensors will perform data detection, process, and communicate the processed data to the cloud server. AWS IoT offers device software services, cloud data protection, and analysis. This research employed communication protocols such as MQTT, LoRaWAN, end-to-end encryption, and authentication. The application can access the information received from the LoRa network for additional analysis. An application server with a Raspberry Pi 4B computer is set up to verify ABH status, track the location and status of sanitizer dispenser units in real time, and track the GPS position of LoRa clients. Algorithm 1 explains the overall software structure.

Algorithm 1: BLE- and LoRaWAN-enabled hand-hygiene tracking system.

---

1. Start.
2. Scan for BLE devices, and if BLE is available, continue; else, go to step 1.
   2.1 Establish the BLE connectivity with the client node and read the user credentials.
   2.2 Read the T_{obj} and T_{amb} from MLX sensor 1.
   2.3 If ($T_{obj} > T_{amb}$) and BLE ID are matched with the database, continue to step 3; else, go to step 2.
3. Read the Tobj and T_{amb} from MLX sensor 2.
   3.1 If ($T_{obj} > T_{amb}$):
      3.1.1. Activate Motor 1 for sanitizing purposes and wait for 5 seconds
      3.1.2. Deactivate Motor 1 and activate Motor 2 for door opening and deactivate it after 5 seconds.
4. Establish the LoRaWAN connectivity with the server node and Jetson Nano network server, then update the user ID, activity status, and GPS location.
5. Establish the AWS connectivity and update the user details to the cloud and application server.

The LoRa client and server nodes are set up using the TTGO T ESP 32 IoT module. The sensor nodes are linked to the client through the Interintegrated circuit (I2C) protocol for short-distance embedded communication. Custom modules with embedded C codes manage the module's general purpose input–output terminals. The Jetson Nano supports the NVIDIA JetPack with the CUDA-XTM software stack, including the most recent NVIDIA application development and optimization tools. The Jetson Nano manages the LoRa network and cloud storage functions. The applications server is set up with a Raspberry Pi 4B, an SoC computer running the Linux operating system Raspbian. The Raspberry Pi controls data processing and IoT device administration, while the ESP32 handles LoRa connection and database management.

IV. Discussion

To validate the developed IoT-assisted LoRaWAN for hand hygiene monitoring and tracking system, a two-step validation procedure is adopted. Initially, a single end-node sensor unit is tested for the performance of different configurations for reducing the missed or faulty detection of sensor events. Further, eight sanitizer dispensers were deployed in a building as a field test, for real-world application. Intelligent ABH dispensers are deployed in ICU entry, inpatient rooms, hospital wards, and nursing rooms with different testing scenarios. All LoRa ABH dispensers record the subject's hand-sanitizing activity and communicate it to the LoRa gateway, which will forward the unique ID, status, and GPS coordinates, through the LoRa ABH unit to the LoRa gateway and then to the local server, followed by the cloud and application server.

Fig. 4 shows the developed BLE device operating in the industrial, scientific, and medical (ISM) 2.4 GHz range for patient and subject tracking and the LoRaWAN-based ABH sensor used in ICU access and several entries. It establishes one-way communication with superior low latency (6 ms) and less power consumption (0.01–0.5 W) compared to BT classic. In this scenario, persons entering the entrance premises are provided with a basic, single-function BLE device that captures data on where they travel and to which ABH they interact. On the other hand, this data can be utilized to monitor hand hygiene tracking and ensure everyone's safety.

Challenges with the BLE signal strength and success rate (SR) with the ABH system were encountered during real-time testing. When comparing the quality of a BT signal

TABLE I
RSSI OF IoT-BASED ABH DISPENSER UNIT IN REAL-WORLD AND LABORATORY TESTING SCENARIOS

	BLE signal analysis in filed (MAC ID-:40:5B:D8:16:3D:C2)		BLE signal analysis in Laboratory (MAC ID-40:5B:D8:16:3D:C2)	
SI. No.	RSSI (dBm)	BLE Signal Strength (%)	RSSI (dBm)	BLE Signal Strength (%)
1	-100	35	-100	31
2	-97	43	-95	46
3	-93	54	-91	57
4	-84	88	-88	90
5	-81	86	-80	84
6	-79	97	-77	94
7	-77	91	-75	95
8	-64	96	-69	99
9	-59	93	-56	100
10	-52	100	-45	100
11	-46	100	-38	100

TABLE II
SR OF IoT-BASED ABH DISPENSER UNIT IN REAL-WORLD AND LABORATORY TESTING SCENARIOS

SI. No.	Field Type	Real-World (SR %)	Laboratory Testing (SR %)
1	ICU-1	97.00	99.00
2	ICU-2	98.50	98.00
3	Ward-1	83.70	94.50
4	Ward-2	87.00	96.00
5	Inpatient Room-1	89.00	100.00
6	Inpatient Room-2	92.70	99.00
7	Inpatient Room-3	99.00	94.50
8	Inpatient Room-4	96.50	96.00

received over an ABH and a LoRaWAN, the received signal strength indicator (RSSI) is the metric of choice. BT's RSSI values are always reported in a negative logarithmic scale and decibels (dBm). The ESP32 BT module allows for a wide range of transmission strengths, from 0 to 7, with a 3 dBm step between each. A higher RSSI value indicates a stronger signal; in particular, an RSSI value of less than -50 suggests a strong signal, -70 to -80 indicates a good signal, -90 dBm is unstable, and -100 implies either no signal or poor coverage. Table I displays RSSI values obtained from the BLE-01 device and tested at various distances in a laboratory and a real-world scenario.

According to the research findings, for optimal connection, the sweet spot for RSSI on a BT device is between -46 and -64 in a real-time environment, while the sweet spot for a laboratory test is between -34 and -75. Table II reveals that laboratory testing has a lower error rate and stronger signal strength. During field testing, obstacles such as people, electronics, and inanimate objects impacted the signal strength.

After the sensor module is installed, a test has carried out to assess its efficiency in minimizing the number of missed detections. The experiment with the missed detection was carried out at various distances between the sensor unit and the human body. During the testing phase, we determined that the optimal distance was within 15 ft for the BLE connection and 5 ft for the optimum distance overall. The accuracy of the MLX sensor was excellent, and using it helps to minimize the number of times humans overlook throughout the sanitizing process. The use of multiple scenarios with the MLX sensor, which was used for human and hand detection, led to an improvement in accuracy and efficiency by lowering the rate of missed detections. In controlled laboratory testing, researchers achieved an SR of 98%; in real-world scenarios involving multiple LoRaWANs, researchers achieved an SR of 92.78%. The percentage of field experiments that were a success or failure is presented in Table II for each location.

The test results recommend that the proposed hand hygiene monitoring and tracking system can be used to enhance hand-washing compliance in hospitals, which will ultimately help to reduce the number of infections, particularly those caused by CAP. BT uses RF transmissions to send data from one device to another. During this time, the BT signal might fade if its outgoing signals are interrupted by physical obstacles. BT RSSI sends a packet to de-authenticate a wireless base station. If only one access point (AP) is available to the wireless station, then RSSI will direct it to use that AP. When in its normal state, the RSSI does not prevent a wireless station from reconnecting to the same AP. This will enable network-wide, real-time monitoring of all BLE devices without requiring frequent reconfiguration. In addition, we compared the proposed system to existing research on hand hygiene monitoring systems in terms of communication technologies, cloud connectivity, gateway implementation, sensor technologies, and target applications.

Most of the work has been finished using proximity sensors, short-range communication protocols, RFID, and Wi-Fi networks used to interact with the gateway and server. The primary drawbacks of such systems are that a Wi-Fi network is not suited for real-time systems since it requires more Wi-Fi modules to give continuous internet access. Furthermore, Wi-Fi is not a robust network and requires a greater implementation cost in terms of hardware and software. BT was also employed in a few research works; however, since it was used in portable tags or devices, its power consumption was greater than that of BLE technology.

Individual HCWs can be identified, and their hand hygiene activity recorded by the ABH system without any human intervention, making it more efficient than prior systems that required manual intervention. The hybrid network design, which includes a short-range BLE network LoRa network for data transfer, has increased SRs while decreasing fault rates. The LoRa protocol enhances network coverage while using less power on the server and client nodes without interfering with the current Wi-Fi and other wireless communication networks.

V. CONCLUSION

In this research, we present an IoT-based hand hygiene monitoring and tracking system for the reduction of healthcare-associated infections, as well as the prevention of HAP and CAP. The proposed gadget for dispensing alcohol-based sanitizer uses BLE and pyroelectric IR signals to identify the presence of humans. The alcohol-based hand sanitizing dispenser communicates with the LoRa gateway and server unit when activated, transmitting data and activity status, subject ID, and GPS location. ICUs and hospital rooms can use the BLE network for short-distance communication. Inside a building, LoRaWANs can carry data over both short and long distances, and they can connect users to the internet through both local and application servers. The local server powered by the GPU on the NVIDIA Jetson Nano computer improved data transport and processing speed. A Raspberry Pi 4B SoC computer serves as an application server at the end-point. The system has been put through its paces, has shown itself superior to existing technology, and is fully functional. By analyzing how to reduce power consumption and create a touchless intelligent system, the ABH and BLE unit is powered with rechargeable batteries and configured with a sleep mode function. The MLX90614 IR sensor improves the hit rate and human presence detection of the system by reducing the miss rate. In closely managed laboratory conditions, the researchers attained a 98% SR; in real-world scenarios, including those involving many LoRa networks, they acquired a 92.78% SR.

References

[1] F. Wu et al., "An autonomous hand hygiene tracking sensor system for prevention of hospital associated infections," *IEEE Sensors J.*, vol. 21, no. 13, pp. 14308–14319, Jul. 2021, doi: 10.1109/JSEN.2020.3041331.

[2] A. Alaiad and L. Zhou, "Patients' adoption of WSN-based smart home healthcare systems: An integrated model of facilitators and barriers," *IEEE Trans. Prof. Commun.*, vol. 60, no. 1, pp. 4–23, Mar. 2017, doi: 10.1109/TPC.2016.2632822.

[3] C. Tseng, X. He, W. Chen, and C.-L. Tseng, "Evaluating automatic hand hygiene monitoring systems: A scoping review," *Public Health Pract.*, vol. 4, Dec. 2022, Art. no. 100290, doi: 10.1016/j.puhip.2022.100290.

[4] W. Boonsong, N. Senajit, and P. Prasongchan, "Contactless body temperature monitoring of in-patient department (IPD) using 2.4 GHz microwave frequency via the Internet of Things (IoT) network," *Wireless Pers. Commun.*, vol. 124, no. 3, pp. 1961–1976, Jun. 2022, doi: 10.1007/s11277-021-09438-4.

[5] T. Xie, J. Tian, and L. Ma, "A vision-based hand hygiene monitoring approach using self-attention convolutional neural network," *Biomed. Signal Process. Control*, vol. 76, Jul. 2022, Art. no. 103651, doi: 10.1016/j.bspc.2022.103651.

[6] A. Repanovici, D. Cotoros, M. Haineala, C. Nemet, and E. Dinu, "Systems for monitoring hands hygiene of medical staff in hospitals," in *Proc. Int. Conf. e-Health Bioeng. (EHB)*, Oct. 2020, pp. 1–4, doi: 10.1109/EHB50910.2020.9280101.

[7] K.-T. Tang et al., "A 0.5 V 1.27 mW nose-on-a-chip for rapid diagnosis of ventilator-associated pneumonia," in *IEEE Int. Solid-State Circuits Conf. (ISSCC) Dig. Tech. Papers*, Feb. 2014, pp. 420–421, doi: 10.1109/ISSCC.2014.6757496.

[8] S. C. Munro et al., "Nonventilator hospital-acquired pneumonia: A call to action: Recommendations from the national organization to prevent hospital-acquired pneumonia (NOHAP) among nonventilated patients," *Infection Control Hospital Epidemiol.*, vol. 42, no. 8, pp. 991–996, Aug. 2021, doi: 10.1017/ice.2021.239.

[9] D. S. Obrosky, S. M. Edick, and M. J. Fine, "The emergency department triage of community-acquired pneumonia project data and documentation systems: A model for multicenter clinical trials," *IEEE Trans. Inf. Technol. Biomed.*, vol. 10, no. 2, pp. 377–384, Apr. 2006, doi: 10.1109/TITB.2005.864369.

[10] M. Stangerup et al., "Hand hygiene compliance of healthcare workers before and during the COVID-19 pandemic: A long-term follow-up study," *Amer. J. Infection Control*, vol. 49, no. 9, pp. 1118–1122, Sep. 2021, doi: 10.1016/j.ajic.2021.06.014.

[11] S. G. Sandbøl, E. N. Glassou, S. Ellermann-Eriksen, and A. Haagerup, "Hand hygiene compliance among healthcare workers before and during the COVID-19 pandemic," *Amer. J. Infection Control*, vol. 50, no. 7, pp. 719–723, 2022, doi: 10.1016/j.ajic.2022.03.014.

[12] T. Yifan et al., "Symptom cluster of ICU nurses treating COVID-19 pneumonia patients in Wuhan, China," *J. Pain Symptom Manage.*, vol. 60, no. 1, pp. e48–e53, Jul. 2020, doi: 10.1016/j.jpainsymman.2020.03.039.

[13] A. Kong, C. S. B. Suarez, B. Rahamatalli, J. Shankweiler, and O. Karasik, "Hand hygiene and hospital-acquired infections during COVID-19 increased vigilance: One hospital's experience," *HCA Healthcare J. Med.*, vol. 2, no. 5, Oct. 2021, doi: 10.36518/2689-0216.1296.

[14] E. Casaroto et al., "Hand hygiene performance in an intensive care unit before and during the COVID-19 pandemic," *Amer. J. Infection Control*, vol. 50, no. 5, pp. 585–587, May 2022, doi: 10.1016/j.ajic.2022.01.018.

[15] H. Ojanperä, P. Ohtonen, O. Kanste, and H. Syrjälä, "Impact of direct hand hygiene observations and feedback on hand hygiene compliance among nurses and doctors in medical and surgical wards: An eight-year observational study," *J. Hospital Infection*, vol. 127, pp. 83–90, Sep. 2022, doi: 10.1016/j.jhin.2022.06.007.

[16] M. V. McDonald et al., "Observation of hand hygiene practices in home health care," *J. Amer. Med. Directors Assoc.*, vol. 22, no. 5, pp. 1029–1034, May 2021, doi: 10.1016/j.jamda.2020.07.031.

[17] P. Locatelli, P. Spadaccino, and F. Cuomo, "Ruling out IoT devices in LoRaWAN," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, May 2022, pp. 1–2, doi: 10.1109/INFOCOMWKSHPS54753.2022.9798063.

[18] S. Scheithauer, J. Bickenbach, H. Heisel, P. Fehling, G. Marx, and S. Lemmen, "Do WiFi-based hand hygiene dispenser systems increase hand hygiene compliance?" *Amer. J. Infection Control*, vol. 46, no. 10, pp. 1192–1194, Oct. 2018, doi: 10.1016/j.ajic.2018.03.026.

[19] N. Masroor, M. Doll, M. Stevens, and G. Bearman, "Approaches to hand hygiene monitoring: From low to high technology approaches," *Int. J. Infectious Diseases*, vol. 65, pp. 101–104, Dec. 2017, doi: 10.1016/j.ijid.2017.09.031.

[20] C. C. Lee, Y. Shen, W. C. Lee, F. H. Hung, and K. F. Tsang, "ZigBee LNA design for wearable healthcare application," in *Proc. IEEE 14th Int. Conf. Ind. Informat. (INDIN)*, Jul. 2016, pp. 1134–1136, doi: 10.1109/INDIN.2016.7819336.

[21] A. R. Knudsen, S. Kolle, M. B. Hansen, and J. K. Møller, "Effectiveness of an electronic hand hygiene monitoring system in increasing compliance and reducing healthcare-associated infections," *J. Hospital Infection*, vol. 115, pp. 71–74, Sep. 2021, doi: 10.1016/j.jhin.2021.05.011.

[22] A. Haque et al., "Towards vision-based smart hospitals: A system for tracking and monitoring hand hygiene compliance," in *Proc. 2nd Mach. Learn. Healthcare Conf.*, vol. 68, 2017, pp. 75–87. [Online]. Available: https://proceedings.mlr.press/v68/haque17a.html

[23] M. Nawaz, J. Ahmed, and G. Abbas, "Energy-efficient battery management system for healthcare devices," *J. Energy Storage*, vol. 51, Jul. 2022, Art. no. 104358, doi: 10.1016/j.est.2022.104358.

[24] A. Páez-Montoro, M. García-Valderas, E. Olías-Ruíz, and C. López-Ongil, "Solar energy harvesting to improve capabilities of wearable devices," *Sensors*, vol. 22, no. 10, p. 3950, May 2022, doi: 10.3390/s22103950.

[25] H. Worlikar et al., "Is it feasible to use a humanoid robot to promote hand hygiene adherence in a hospital setting?" *Infection Prevention Pract.*, vol. 4, no. 1, Mar. 2022, Art. no. 100188, doi: 10.1016/j.infpip.2021.100188.

[26] A. Elsts, M. Ivanovs, R. Kadikis, and O. Sabelnikovs, "CNN for hand washing movement classification: What matters more—The approach or the dataset?" in *Proc. 11th Int. Conf. Image Process. Theory, Tools Appl. (IPTA)*, Apr. 2022, pp. 1–6, doi: 10.1109/IPTA54936.2022.9784153.

[27] P. Zhang, J. White, D. Schmidt, and T. Dennis, "Applying machine learning methods to predict hand hygiene compliance characteristics," in *Proc. IEEE EMBS Int. Conf. Biomed. Health Informat. (BHI)*, Feb. 2017, pp. 353–356, doi: 10.1109/BHI.2017.7897278.

[28] N. Xu et al., "Influence of the Internet of Things management system on hand hygiene compliance in an emergency intensive care unit," *J. Hospital Infection*, vol. 109, pp. 101–106, Mar. 2021, doi: 10.1016/j.jhin.2020.12.009.

[29] J. Zhao, B. Zhou, J. P. Butler, R. G. Bock, J. P. Portelli, and S. G. Bilén, "IoT-based sanitizer station network: A facilities management case study on monitoring hand sanitizer dispenser usage," *Smart Cities*, vol. 4, no. 3, pp. 979–994, Jul. 2021, doi: 10.3390/smartcities4030051.

[30] F. H. C. D. S. Filho et al., "Performance of LoRaWAN for handling telemetry and alarm messages in industrial applications," *Sensors*, vol. 20, no. 11, p. 3061, May 2020, doi: 10.3390/s20113061.

K. M. Abubeker is a Research Scholar with the Faculty of Engineering, Department of Electronics and Communication Engineering, Karpagam Academy of Higher Education, Coimbatore, Tamil Nadu, India; and an Assistant Professor L-XII with the Amal Jyothi College of Engineering, affiliated to APJ Abdul Kalam Technological University (APJAKTU), Thiruvananthapuram, Kerala, India. He has authored several academic books and research articles in peer-reviewed international journals, some of which are part of APJ AKTU and Mahatma Gandhi University, Kottayam, Kerala, India curricula. The Internet of Things, machine learning, open-source hardware and software development, and medical image processing are some of his research interests.

S. Baskar is an Assistant Professor with the Faculty of Engineering, Department of Electronics and Communication Engineering/the Center for Interdisciplinary Research, Karpagam Academy of Higher Education, Coimbatore, Tamil Nadu, India. He worked as a Research Associate with the Department of Nano Science and Technology and the Department of Pervasive Computing Technology. He has published more than 35 research papers in international journals, book chapters, and conferences. So far, he has guided more than 20 M.E./M.Tech./B.E. projects. His research interests include wireless sensor networks, low-power VLSI, the Internet of Things (IoT), and material science.

Prof. Baskar is a Young Scientist Awardee by the Department of Science and Technology, Government of India. He is a Reviewer of refereed journals, like *Wireless Sensor Networks*, IEEE ACCESS, Inderscience, and IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY.