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Development and performance analysis of a ZigBee and LoRa-based smart building sensor network

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A wireless sensor network employing ZigBee and LoRa (Long Range) communication protocols for integration into smart building energy management systems is presented in this article. The design and implementation details are provided, and the performance parameters of the communication network are defined and analyzed based on the test results obtained from different configurations. The developed embedded system can be used in smart environments so that the room temperature, humidity, lighting systems, and so on can be automatically monitored and controlled. By customizing the embedded code, a variety of Internet of Things (IoT) applications can be introduced owing to their scalability. Taking advantage of the complementing low-power and long-range features of ZigBee and LoRa communication technologies, a system comprising an end device, a multi-protocol gateway, and a central data collector (CDC) unit is developed. The end device collects temperature and humidity as well as light intensity data using low-power sensors and sends the data to the gateway *via* the LoRa wireless transceiver module. The gateway was designed as an intermediate device that allows data exchange between the LoRa and ZigBee transceiver modules. It receives sensor data from the end device *via* LoRa and sends them to the CDC unit *via* a ZigBee-based XBee S2 commercial wireless transceiver module. Sensor data are monitored in the CDC unit by using an open-source IoT software platform. A commercial STM32 integrated circuit (IC) was used as a microcontroller unit for the end device and gateway. Performance parameters such as communication range and throughput data were studied for both the ZigBee and LoRa wireless transceiver modules.

KEYWORDS
ZigBee, LORA, IoT, wireless technologies, smart buildings, smart energy management

Introduction

A smart home or a smart building that uses wireless and/or Internet-connected devices enables remote monitoring and management of electric appliances. Smart buildings are considered one of the most common platforms utilizing Internet of Things (IoT) technologies. A smart building becomes part of the IoT network as soon as two devices start communicating with each other (Pătru et al., 2016). The term IoT encompasses everything connected to the Internet. Without the necessity of human interactions, IoT devices can transfer data by using wireless communication technologies (Al-Fuqaha et al., 2015; Adam B et al., 2017; Kelati and Gaber, 2021). IoT devices use various technologies to support their communications. These technologies differ in terms of communication range, data rate, operating frequency, bandwidth, cost, and security (Mendes et al., 2015; Al-Sarawi et al., 2017). For instance, Wi-Fi is a ubiquitous communication technology; however, owing to its high-power consumption, it is not considered the best solution for IoT devices. Due to its low data rate and low-power characteristics, the ZigBee technology seems to be an ideal candidate for IoT applications, especially smart building automation systems, but because of its limited short-distance coverage, it cannot be used for long-distance outdoor wireless communication systems. In contrast to Wi-Fi and ZigBee, the LoRa protocol, which is a new wireless technology, stands out with its long-range, low-power consumption, and extended coverage features. To understand LoRa's interoperability with other low-power wide area network (LPWAN) technologies, specifically the ZigBee wireless technology, a wireless sensor mesh system using LoRa- and ZigBee-based modules has been developed.

Wireless communication technologies are key factors in IoT applications, and different studies have been conducted in this field. Chentao Li et al. (Li et al., 2019) introduced a ZigBee and Wi-Fi-based smart home application system that uses an STM32 microcontroller as the main controller. The system comprises of a terminal unit, a gateway, and a remote-control unit. S Ravim et al. (Ravi et al., 2017) proposed a smart home control system that uses power line carrier communication (PLCC) and the ZigBee communication technology. The control messages for smart home devices are transferred using PLCC and the ZigBee communication technology. In (Mukherji and Sadu, 2016), the performance analysis of the ZigBee wireless device is evaluated in terms of the range, the time taken to start and join a ZigBee wireless network, power consumption in different stages, and interoperability tests between ZigBee devices from different manufacturers. Xiaobo Mao et al. (Mao et al., 2017) developed a smart home remote monitoring system that uses the ZigBee communication protocol for data collection. The system contains a gateway, a cloud server, and a smartphone app. Tahar Dahoumane et al. (Dahoumane et al., 2018) designed a smart home control system by using ZigBee-based XBee modules, Raspberry Pi, Global System for Mobile communication (GSM), and smart plugs. In Juha et al., 2017, the LoRa network throughput and capacity of a LoRaWAN cell were analyzed. The obtained results show that in the best-case scenario, a single LoRa-enabled end device may upload data with 1.8 kbps. In Wang et al., 2017, the transmission performance of LoRa, from LoRa end devices to the LoRa gateway under different transmission powers, antenna angles, and payload lengths, is measured by using a PM2.5 air quality monitoring system. The design and implementation of a LoRa-based smart home system are presented in Opipah et al., 2020. The designed system contains a LoRa client and a LoRa server. The Dragino wireless LoRa module which utilizes the 915 MHz frequency band is used as a communication module. Hnin Yu Shwe et al. (Shwe and Chong, 2015) have proposed an energy-efficient communication protocol based on wireless sensor networks. Mu'amar Wildan F.A.R et al. (Mu'amar Wildan et al., 2020) developed a web-based graphical user interface (GUI) for LoRa-based smart home applications that allow users to interact with the connected devices. In Celtek et al., 2017 an IoT-based smart home system is designed by using wireless sensors and actuators. The collected sensor and actuator data are transmitted to a cloud database. The authors claim that their system will be more suitable for existing buildings since it does not require wire connections. Satyendra K. Vishwakarma et al. (Vishwakarma et al., 2019) proposed and developed an energy-efficient home automation system that allows users to remotely access and control home appliances and devices. The system is a multimodal system that can be used with a voice command through Google Assistant or a web application.

In Ali et al., 2019, the co-authors considered a general implementation of wireless sensors for smart environments. Then, in this study, a specific implementation is considered for smart buildings and home energy management systems, and a detailed performance analysis of ZigBee- and LoRa-based wireless sensor networks is presented with experimental results. The ZigBee and LoRa wireless transceiver modules as well as the wireless sensors used in this study were chosen because of their sleep mode features. The sleep mode feature which is also known as the standby mode enables the devices to only consume energy when needed. Furthermore, the researchers can visualize the ZigBee- and LoRa-based solutions presented here and decide whether these would be preferable over other communication protocols for smart building applications.

Design and implementation of ZigBee and LoRa-based communication systems

Wireless communication technologies play a significant role in connecting IoT smart devices. Many wireless communication technologies are available for IoT applications, including ZigBee, LoRa Sigfox, bluetooth, and Wi-Fi. These technologies exhibit different characteristics in terms of power consumption, communication range, data rate, frequency, bandwidth, interoperability, and security (Mendes et al., 2015). In this article, two of the most widely used wireless communication protocols in IoT applications are presented. Using the low-power and long-range features of ZigBee and LoRa communication

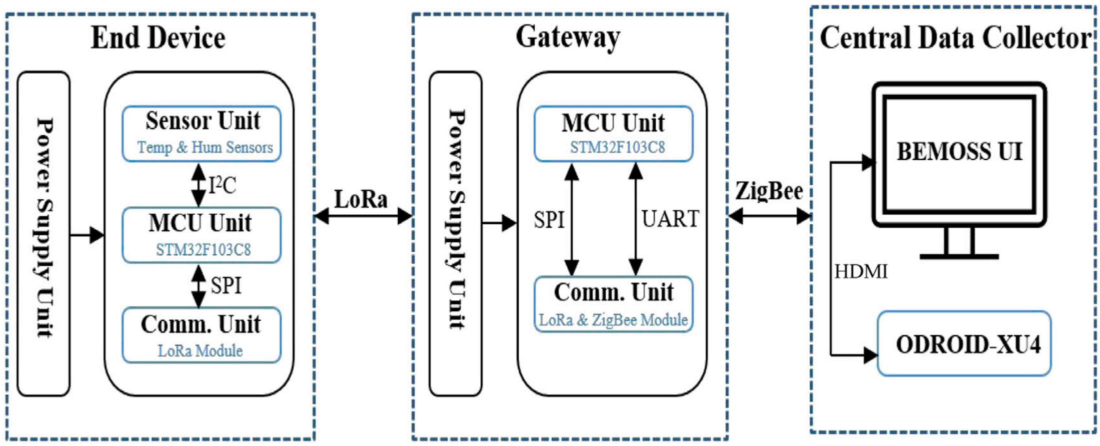

FIGURE 1
Block diagram of the system.

technologies, an energy-efficient wireless communication system was designed and experimentally tested. The ZigBee wireless technology is one of the most popular wireless mesh networking standards for connecting sensors, control systems, and IoT networks (Cilfone et al., 2019). The ZigBee protocol stack architecture is based on the open system interconnection (OSI) reference model and is defined by IEEE 802.15.4 and ZigBee Alliance (ZigBee Alliance, 2019). ZigBee utilizes unlicensed Industrial Scientific and Medical (ISM) frequency bands, such as 2.4GHz, 915MHz, and 868 MHz (Ramya et al., 2011; Beula and Rathika, 2020). The ZigBee network consists of several types of devices, and they are the main components of the wireless personal area network (WPAN). These devices are classified into three types: ZigBee coordinators, end devices, and routers (Khalaf and Mokadem, 2016). The LoRa wireless technology, which has compelling features such as low-power, long-range, and secure data transmission, has become an ideal technology for IoT networks. In other words, the long-range and low-power communication features of the LoRa technology make it an ideal platform for IoT-based applications, especially in smart building automation systems (Obaid et al., 2014). The LoRa protocol stack specification contains a set of OSI layers defined by Semtech and LoRa Alliance (Lavric and Popa, 2017). The LoRa physical (PHY) layer, which enables low-power, long-range, and low-throughput communications, operates on ISM frequency bands such as 433 MHz, 868 MHz, and 915 MHz (LoRa Alliance, 2018). To tune the communication link performance and power consumption, a LoRa end device can be configured to use a different coding rate (CR), spreading factor (SF), carrier frequency (CF), bandwidth, and transmission power (TP) (Augustin et al., 2016; Bor and Roedig, 2017). In the LoRa communication protocol, SF is defined as the number of transmitted bits in one symbol (Noreen et al., 2017). The designed system consists of three main parts: an end device, a multi-protocol gateway, and a central data collector (CDC) unit. The block diagram of the developed system is illustrated in Figure 1. The end device communicates with the gateway *via* a LoRa wireless protocol, while the gateway communicates with the CDC unit *via* a ZigBee wireless protocol.

End device

The end device is a printed circuit board (PCB) card that contains four layers: a power supply layer, a sensor layer, a microcontroller unit (MCU) layer, and a communication layer. This card is designed to collect room temperature, humidity, and light intensity data and send the collected sensor data wirelessly *via* LoRa to the gateway. The schematic diagrams of these four layers are shown in Figures 2–5. The power supply layer, which is an important part of the circuit, provides the necessary power to all other circuit elements. The end device was designed to work with 3.3 DC voltage. In addition, the end device is designed to have two different power sources. The first power source is a 5 V AC/DC power adapter, while the second is a rechargeable lithium battery. Two different voltage regulators were used in the circuit to regulate the input voltage.

The MCU layer provides full control of the system and processes the incoming and outgoing sensor data. A temperature and humidity sensor (Si7021) and a light sensor (APDS-9300) were used in the sensor layer of the end device. The Si7021 sensor was used to measure the room temperature and relative humidity, whereas the APDS-9300 sensor was used to

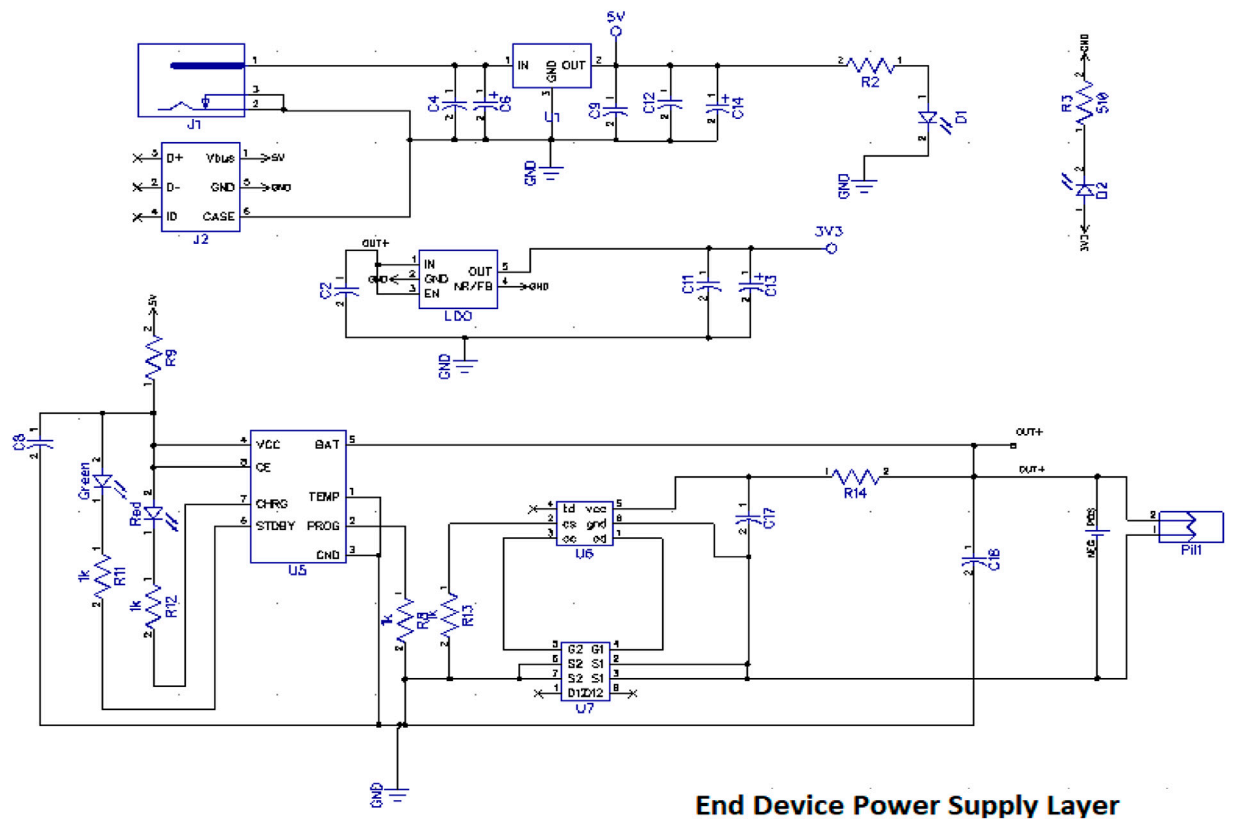

FIGURE 2
Schematic diagram of the end device's power supply layer.

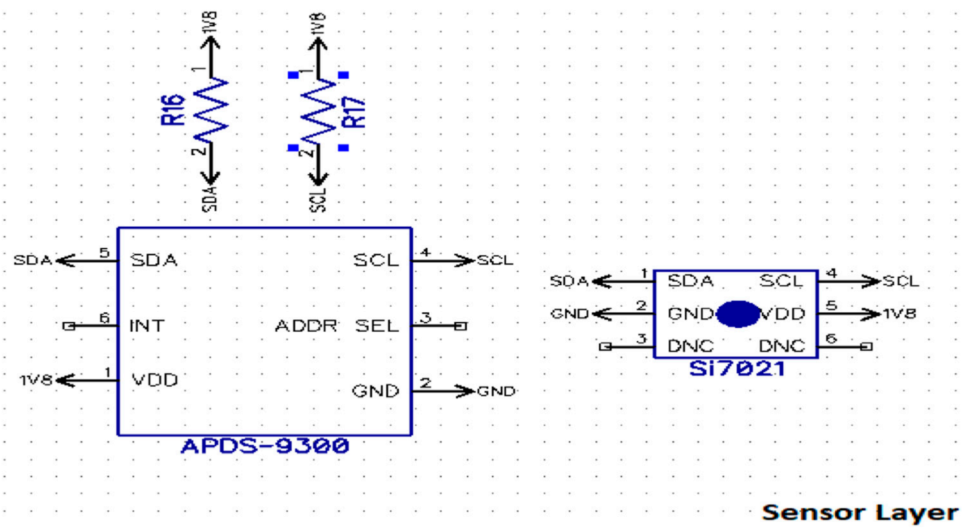

FIGURE 3
Schematic diagram of the end device's sensor layer.

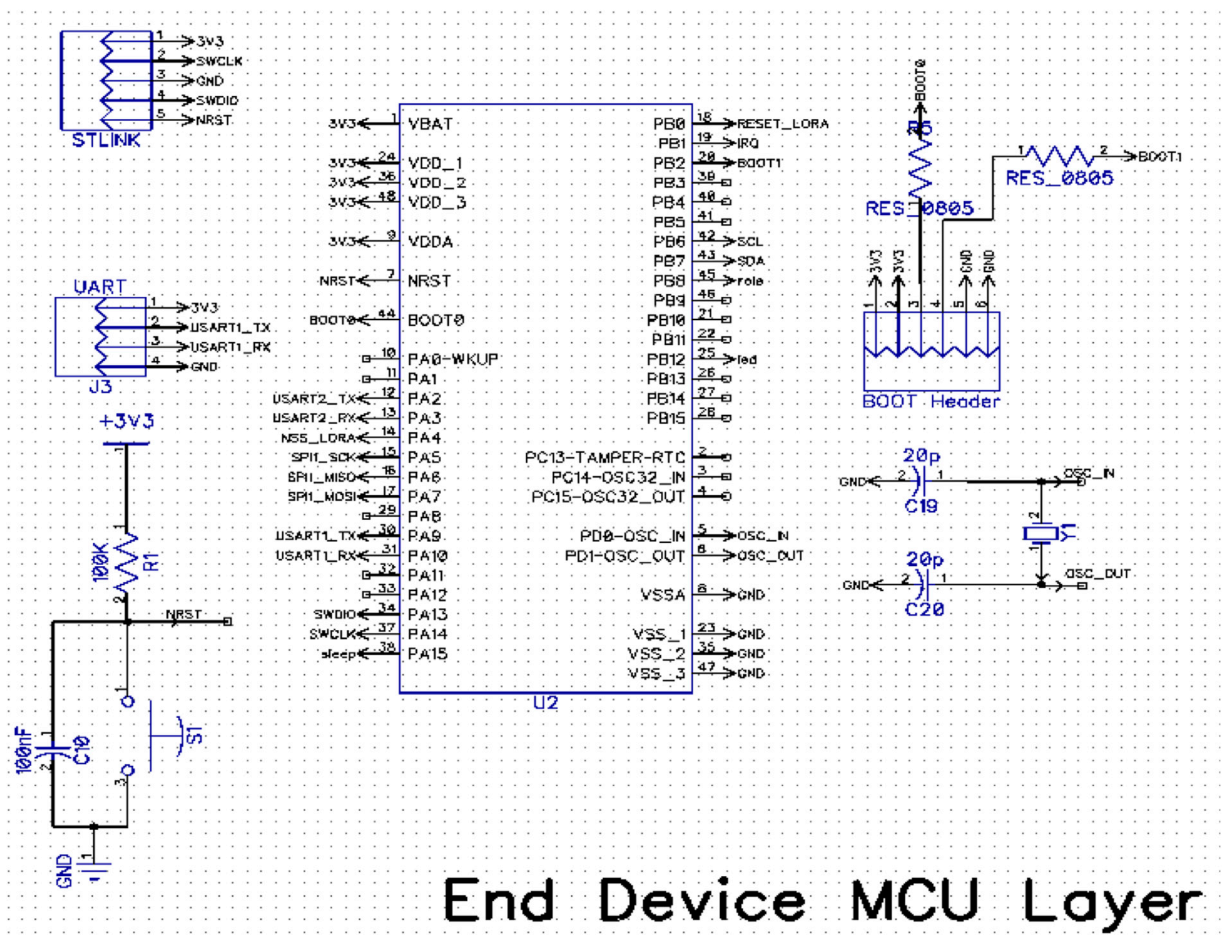

FIGURE 4
Schematic diagram of the end device's MCU layer.

measure the light intensity of the room. Both sensors utilized the I^2C protocol to communicate with the MCU and sent the collected sensor data through this protocol. The microcontroller in the MCU layer of the end device received sensor data from the wireless sensors and sent them to the communication layer. The communication layer was designed to be compatible with the low-power wireless LoRa transceiver module. The LoRa module used in this experimental study is based on Semtech's SX1278 chip and operates on 433 MHz. The physical PCB card of the developed end device is shown in Figure 6.

Multi-protocol gateway

The multi-protocol gateway was designed to be compatible with the ZigBee-based XBee S2 and SX1278-based LoRa transceiver modules. The multi-protocol gateway consists of three layers, which are the power supply layer, the MCU layer, and the communication layer. The gateway was designed to support only one power supply. A 9 V AC/DC power adapter was used to feed the gateway, and two different voltage regulators (LM78M05 and LDO) were added to the circuit to reduce the voltage from 9 to 5 V and from 5 to 3.3 V. Like the end device card, the gateway was also developed to work with 3.3 DC voltage. There is no direct communication between LoRa and XBee modules because they use different protocols. In this case, the gateway was designed to be an intermediate device that allows data exchange between the LoRa and XBee transceiver modules. Similar to the end device, an Arduino-compatible STM32 microcontroller was also used in the gateway's MCU layer. The microcontroller receives the sensor data from the LoRa wireless module *via* a serial peripheral interface (SPI) and sends it to the ZigBee-based wireless XBee S2 module *via* a Universal Asynchronous Receiver/Transmitter (UART) interface. The microcontroller was programmed using the Arduino IDE. The schematic diagrams of the gateway's power supply and

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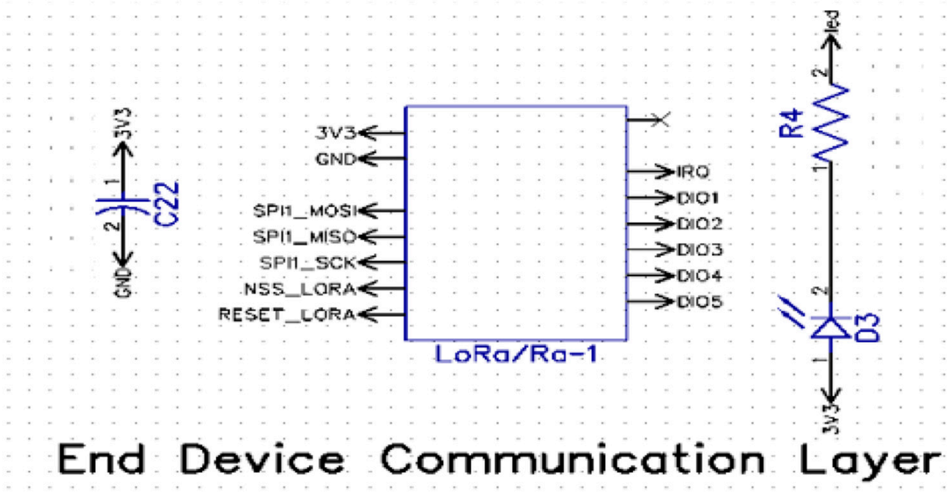

FIGURE 5
Schematic diagram of the end device's communication layer.

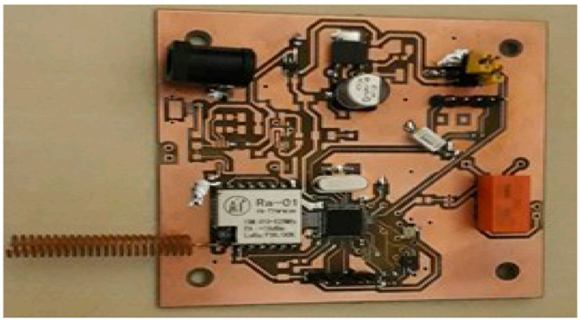

FIGURE 6
PCB card of the end device.

communication layers are shown in Figure 7 and Figure 8, respectively.

The LoRa wireless module (Receiving LoRa) in the communication layer of the multi-protocol gateway receives modulated data (sensor data) from the transmitting LoRa in the communication layer of the end device. The receiving LoRa demodulates and sends the data to the MCU layer. The MCU layer sends the sensor data to the XBee S2 wireless transceiver module. The sensor data were then transferred to a local XBee S2 module that is connected to the CDC unit. The physical PCB card of the multi-protocol gateway is shown in Figure 9.

Central data collector unit

The CDC unit used in this study is a single board computer (SBC) called Odroid-XU4 which supports wired and wireless communication protocols and can transfer data collected from the end device to the Internet wirelessly. Odroid-XU4 is a minicomputer with stronger, low-power hardware and a smaller form factor (Odroid Wiki). The reasons why Odroid is preferred over normal computers are its energy efficiency, high data transfer, and ease of use. The CDC unit receives sensor data from the gateway through the XBee transmitter module. The XBee receiver module was configured as a ZigBee coordinator and connected to the CDC unit to communicate with the XBee transmitter module. An open-source software, BEMOSS (Building Energy Management Open-Source Software), was installed on the CDC unit to monitor and control the sensor data of the developed end device in a web interface. BEMOSS is a Linux-based open-source operating system software developed by the Virginia Polytechnic Institute and State University (Virginia Tech) to improve the detection and control of heating, ventilation, and air conditioning (HVAC); lighting; and socket loads of smart buildings (Pipattanasomporn et al., 2015; Bemoss.org and Features–BEMOSS™). In this study, BEMOSS was used as the basic operating system platform in the CDC unit and for monitoring and controlling the sensors in the designed end device.

Test results

In this section, the results of the study, including monitoring and control of the temperature, humidity, and light intensity sensors integrated into BEMOSS, as well as performance tests of the ZigBee and LoRa wireless modules in

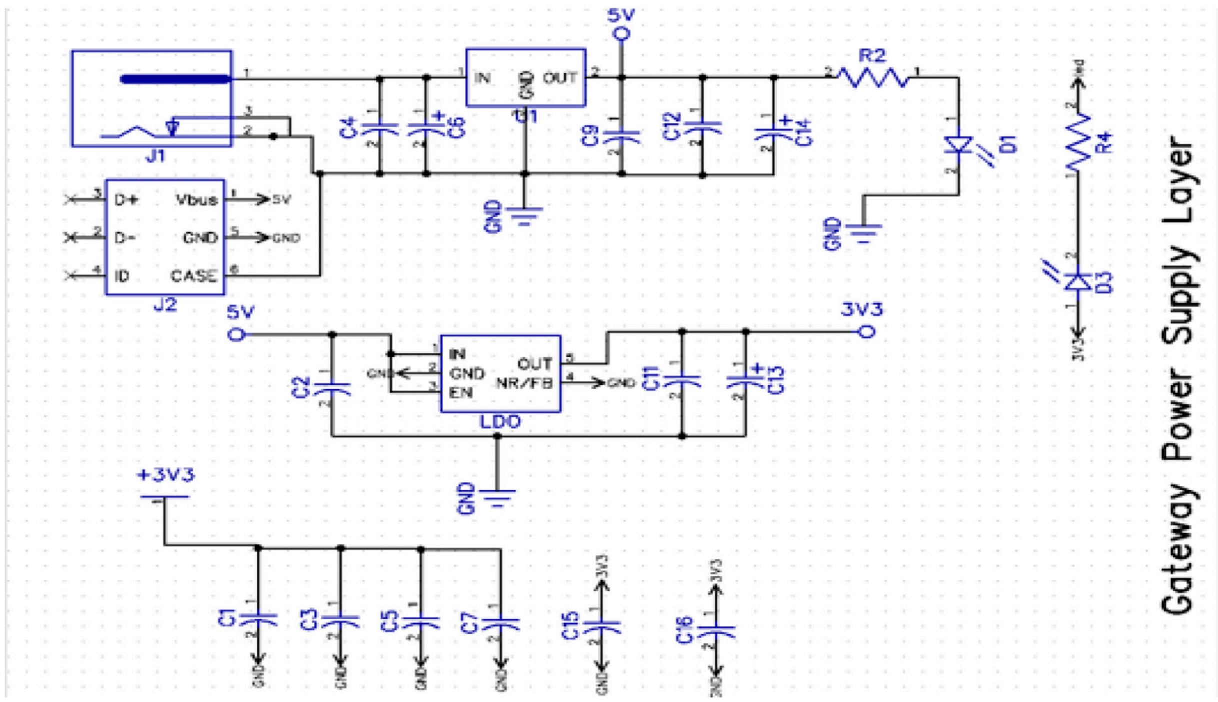

FIGURE 7
Schematic diagram of the gateway's power supply layer.

terms of communication range and network throughput, are presented.

ZigBee communication range test

To specify the communication range and link quality between the two XBee transceiver modules, a communication range test was carried out using the XCTU program developed by DIGI. One XBee module (local XBee module) was connected to the CDC unit and configured as a ZigBee network coordinator, while the other module (Remote XBee module) was configured as a ZigBee end device. The ZigBee coordinator and the ZigBee end device were configured to use the same personal area network identifier (PAN ID) at a 9,600 bps baud rate. The coordinator was configured to operate in the application programming interface (API) mode, while the end device was configured to operate in the transparent (AT) mode. The XBee communication range test involved sending data packets from the coordinator to the end device. Throughout this process, the XCTU program recorded the number of data packets sent and received by each module and measured the RSSI value of the end device. The end device collected data packets from the coordinator at a 30 m line-of-sight. In Figure 10, the RSSI chart of the ZigBee end device is depicted. The graph shows how the end device's signal strength changes as the distance between the end device and the coordinator changes (Ali et al., 2019).

ZigBee throughput measurements

Network throughput is a measure of how many units of data and information a system can process in a given period. The network throughput of the system depends on the payload size and the speed and can be calculated using the following equation.

$$Tp = \frac{8 * \text{number of bytes}}{\text{Total transmission time}} [\text{bps}] \quad (1)$$

The XCTU throughput tool was used to measure the network throughput between the two XBee wireless transceiver modules. The purpose of this experiment was to measure the network throughput of the XBee modules as a function of the payload size and baud rate. The XBee coordinator (local module) was connected to the CDC unit, while the XBee end device (remote module) was placed slightly far from the coordinator. To perform a ZigBee throughput measurement, the XBee coordinator and XBee end device were added to the XCTU program. The XBee coordinator which initiates the ZigBee network was configured to send data packets to the XBee end device and calculate the total transmission time every 30 s. Several throughput measurements with different payload size

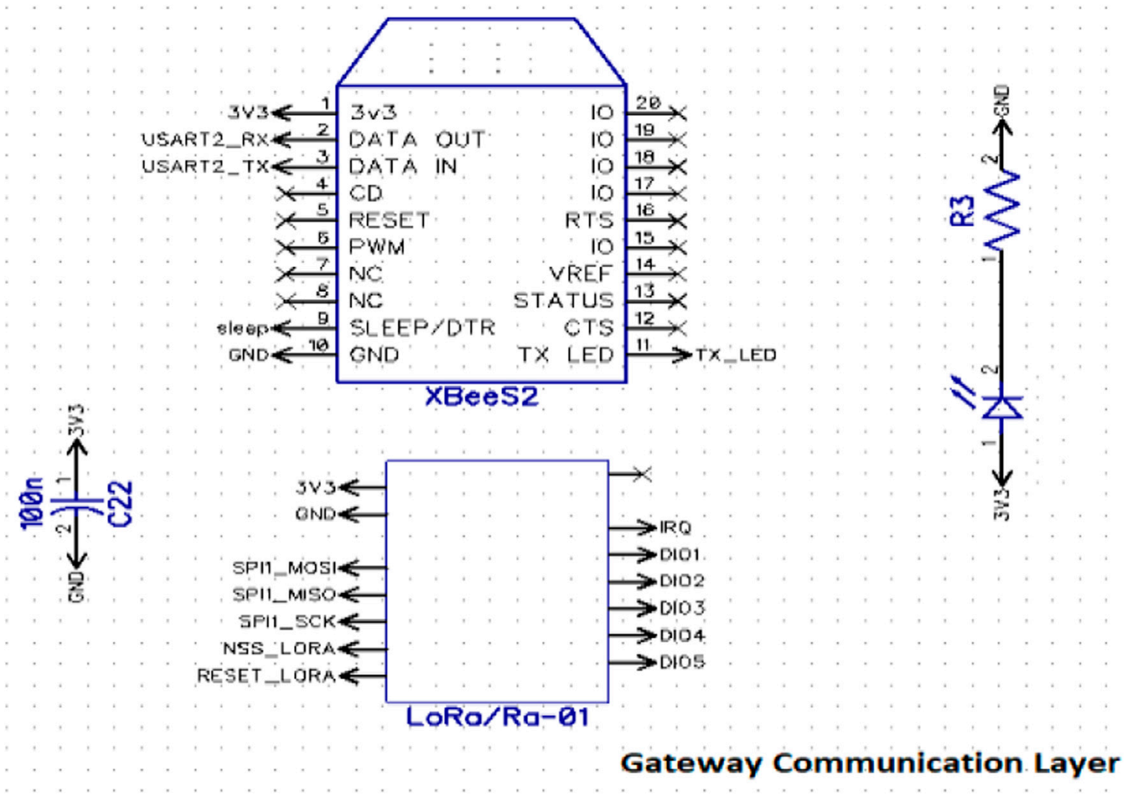

FIGURE 8
Schematic diagram of the gateway's communication layer.

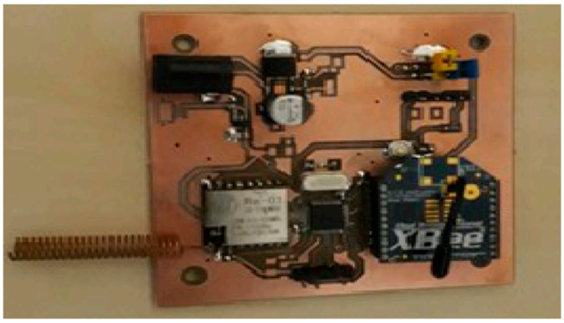

FIGURE 9
PCB card of the multi-protocol gateway.

values (10–80 bytes) and baud rates (9,600–112,500 bps) were performed. This experiment was repeated five times. The experimental results showed that the XBee throughput increased as the baud rate increased. In other words, the ZigBee network throughput is directly proportional to the selected baud rate. According to the ZigBee specification, the transmission data rate reaches up to 250 kbps, but the experimental results obtained show that the network performance is quite far from this performance level. A throughput of 7.95 kbps at a 112,500 bps baud rate was achieved using the maximum offered payload as depicted in Figure 11.

LoRa communication range test

A LoRa communication range test was performed using two identical LoRa wireless modules based on SX1278 chips. One of the LoRa transceiver modules was installed stationary on the Yildiz Technical University campus, whereas the other LoRa transceiver module was used as a remote unit. One of the LoRa transceiver modules was connected to a temperature and humidity sensor and programmed with Arduino, while the other module which was used as a remote module was connected to an Android phone *via* a USB On-The-Go (OTG). The communication between the two LoRa transceiver modules was monitored on a mobile phone screen by using a serial USB terminal, which is a line-oriented terminal/console mobile application for microcontrollers, and other devices with a serial interface. The LoRa communication

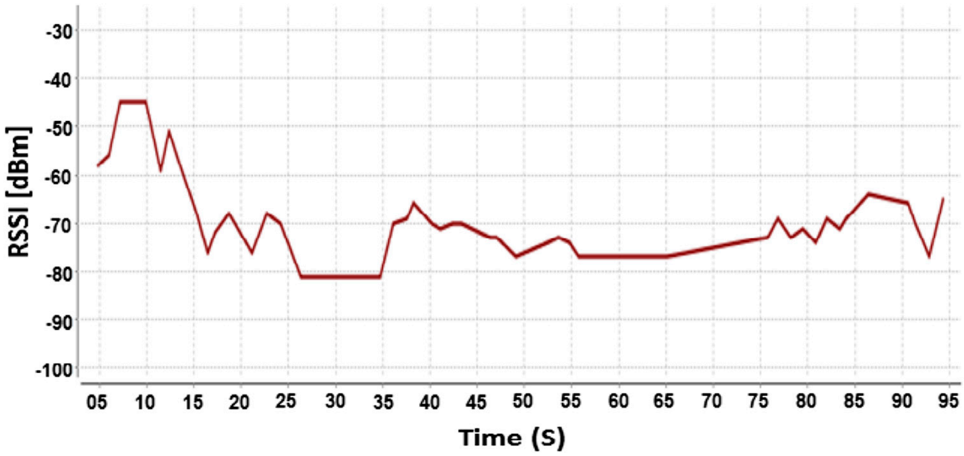

FIGURE 10
RSSI chart of the ZigBee end device.

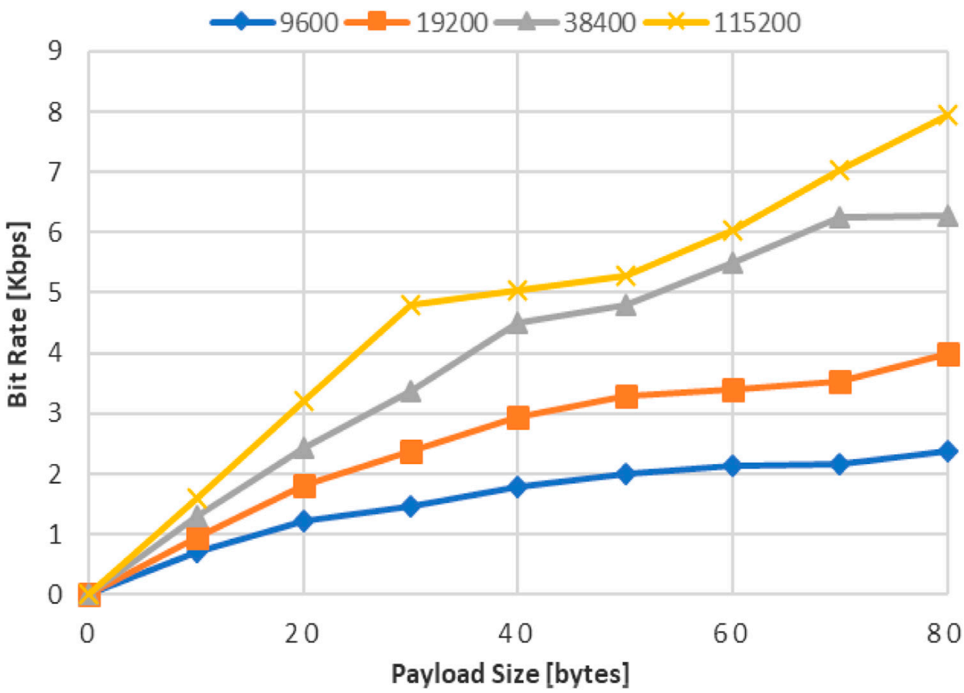

FIGURE 11
ZigBee network throughput.

range test was conducted under different weather conditions, and data were collected by walking and carrying the remote LoRa module through the campus. On a rainy day, the remote LoRa wireless module was able to obtain sensor data from the transmitter wireless module at a 400 m line-of-sight, while on a non-rainy day, the LoRa remote module was able to get the sensor data at a distance of 650 m from the transmitter. As illustrated in Figure 12, the RSSI values of the remote LoRa module decreased as the distance between the LoRa modules increased.

The longest distance that the tested LoRa transceiver module can operate with a GPS mobile application is shown in Figure 13.

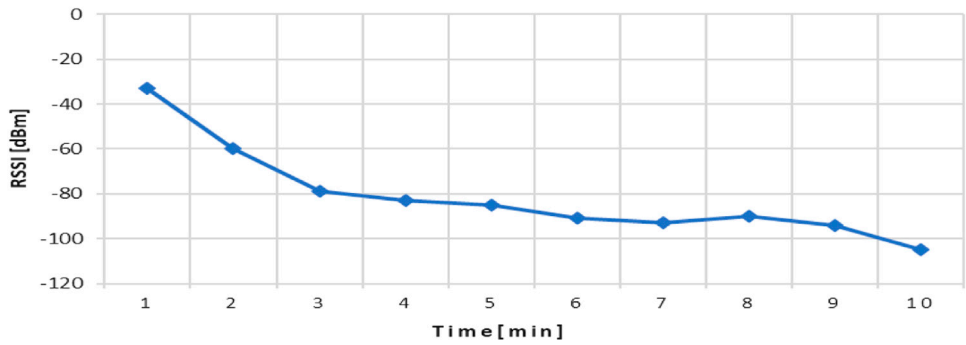

FIGURE 12
RSSI chart of the remote LoRa module.

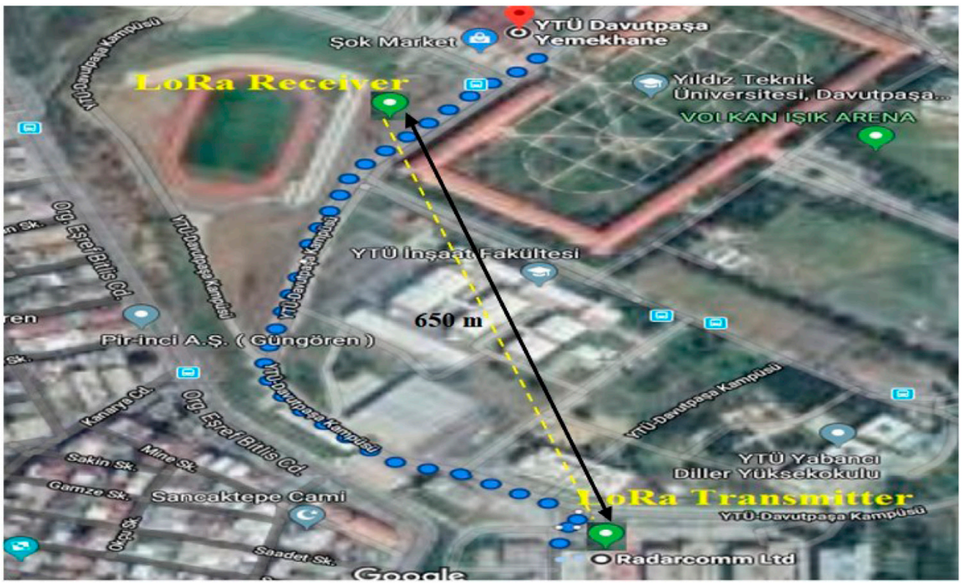

FIGURE 13
GPS locations of the LoRa modules.

It was observed that the system operated at a distance of 650 m under good weather conditions, and after 650 m, the remote LoRa module was still able to capture some data packets with a very low RSSI value. During the experiment, it was observed that the data could not be received from the transmitter module at values less than −120 dBm (RSSI value).

LoRa throughput calculation

Unlike ZigBee, the LoRa network throughput depends on the transmission mode, where each mode is specified by a combination of SFs, CRs, and the channel bandwidth. Since the LoRa wireless modules used in this experimental study are not USB-based modules and cannot be connected to the CDC unit or a computer, their throughput was calculated using the equation below, where Rb is the bit rate.

$$Rb = 2^{SF} \times \frac{BW}{2^{SF}} \times CR[bps] \tag{2}$$

From the calculations, the combinations of SF = 12, CR = 4 and SF = 7, CR = 1 yield the lowest and highest transmission rates, respectively. From the calculations, the highest rate was 5,460 bps, while the lowest rate was 183 bps. An increase in the

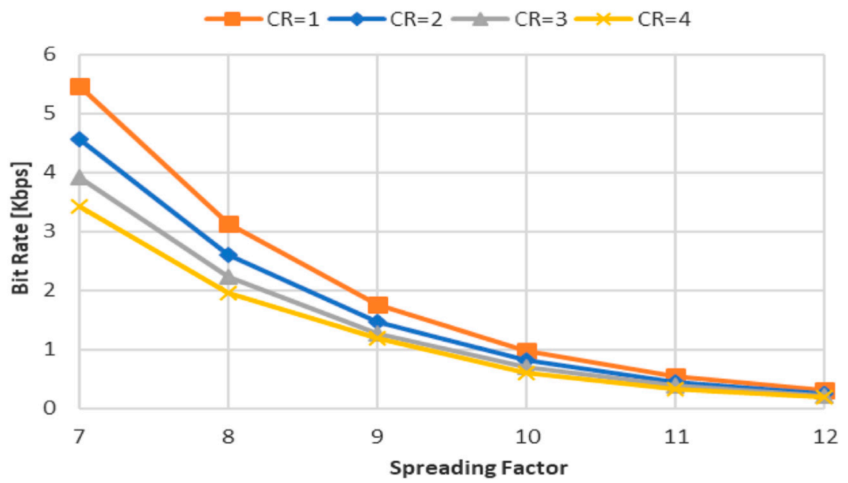

FIGURE 14
Calculated LoRa throughput.

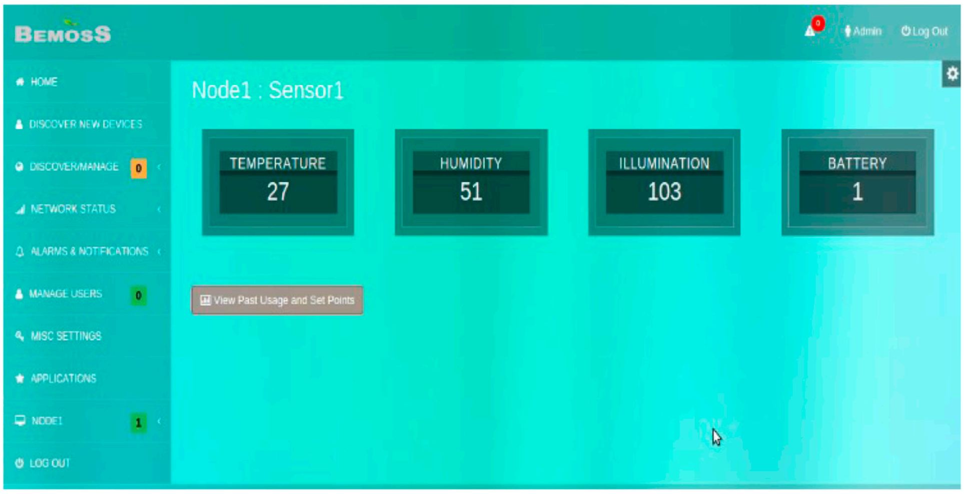

FIGURE 15
Sensor data shown in BEMOSS UI.

bandwidth lowers the receiver sensitivity, whereas an increase in SF increases the receiver sensitivity. The calculated throughput of LoRa is shown in Figure 14.

Monitoring sensor data in the open-source user interface software

The end device was integrated into the BEMOSS platform to control and monitor the status of the wireless sensors. The integration was performed using a device API, written in the Python programming language for the end device. The sensors used in this experimental study are energy-saving. Both sensors can switch to the sleep mode when they send data to the gateway to save energy. The designed end device sent sensor data (room temperature, humidity, and light intensity) collected by the sensors to the BEMOSS platform *via* the gateway. As shown in Figure 15, the temperature, humidity, and light intensity data from the sensors are displayed on the BEMOSS User Interface (UI).

The BEMOSS UI allows the user to control and monitor the connected end devices. The measured temperature, humidity, and light intensity units were °C, percentage, and Lux, respectively. The battery segment shown in the BEMOSS UI indicates whether the end device is powered by a battery or not.

Conclusion

In this experimental study, a low-power communication system based on the ZigBee and LoRa protocols was designed and implemented, and the system performance was analyzed based on the obtained test data. The system was designed to conform to the ZigBee-based XBee S2 and SX1278-based LoRa wireless transceiver modules using a CAD drawing tool. The designed end device was used to collect the room temperature, humidity, and light intensity by using integrated wireless sensors. The collected data were then transferred to a multi-protocol gateway *via* an SX1278-based LoRa wireless module. The gateway was used as an intermediate device that allows data exchange between the LoRa and ZigBee transceiver modules. The BEMOSS was installed on the CDC unit to monitor the sensor data in real time. The designed end device was integrated into BEMOSS by writing API codes. The STM32 microcontroller unit was configured, programmed, and then used in both the end device and gateway. Various range tests were performed for both the ZigBee-based XBee S2 and SX1278-based LoRa transceiver modules under different weather conditions on different days. Throughput performance tests were also conducted for ZigBee- and LoRa-based wireless modules, and the results were plotted. This study showed that ZigBee and LoRa can both be used in the same IoT system. ZigBee can be used for high data-rate applications that require a mesh network. On the other hand, LoRa can be used for low-power applications that require longer distances and a lower data rate. The developed system is different from already available systems designed for IoT applications because it uses both ZigBee- and LoRa-based wireless modules and can significantly improve the energy efficiency. The LoRa-based wireless modules used in this study support only point-to-point communication and can only communicate with one device at a time. The designed system can be developed, and LoRaWAN-based modules that support point-to-multipoint communication can be used to integrate multiple end devices into the gateway. The wireless sensors with ZigBee and LoRa communication protocols used in this study can be integrated into the HVAC and lighting systems of smart buildings so that the room temperature, relative humidity, and lighting systems can be automatically monitored and controlled.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, AA and SZ; methodology, AA; software, AA; validation, AA and SZ; writing—AA; writing—review and editing, AA and SZ; supervision, SZ.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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