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Design and implementation of hybrid low power wide area network architecture for IoT applications

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Abstract. The rapid proliferation of Internet of Things (IoT) devices and applications has resulted in an increasing demand for Low Power and Wide Area Network (LPWAN) solutions. The adoption of IoT networks still faces several challenges, despite the rapid advancement of low-power communication technology. Homogenizing this sector requires allowing interoperability between many technologies, which is now one of the largest obstacles. In this article, we present the design and implementation of the hybrid LPWAN architecture that can accomplish wide-area communication coverage and low-power consumption for IoT applications by leveraging two LPWAN technologies, Wireless Smart Ubiquitous Network (Wi-SUN) and Long Range (LoRa). In particular, LoRa is used for long-range communication, and Wi-SUN for a low-latency mesh network. Additionally, we implemented smart street light controlling system as a real-world deployment at the university campus to showcase the efficiency of the hybrid network. Our results demonstrate that the hybrid LPWAN architecture provides a better coverage and capacity while consuming less power than that of the LoRa or Wi-SUN network. The results of this study demonstrate the effectiveness of the proposed hybrid LPWAN architecture as a viable solution for next-generation IoT applications.

Keywords: Internet of Things, hybrid networks, LoRa, wireless communication, Wi-SUN

1. Introduction

The Internet of Things (IoT) has emerged as a potentially game-changing paradigm for the next generation of computing, networking, and sensing in a wide variety of settings. By 2030, analysts predict that there will be 100 billion internet-connected devices [19]. Numerous IoT application areas, including smart cities, smart agriculture, campus monitoring, and healthcare monitoring will extensively deploy these devices [6]. The IoT devices establish a wireless sensor network by sensing, computing, and communicating, typically in environments with limited resources. As part of a smart city infrastructure, IoT devices may track the flow of energy and water through a smart grid, facilitate the installation of automated public transit and home automation, etc. Considering the rapid growth in the number of connected devices, a hybrid IoT architecture that is compatible with a wide range of IoT protocols and applications is essential. Wireless connectivity options are plentiful and range from self-deployable private

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networks to fully managed services by network operators. The features of each wireless protocol differ with others, however, the Low Power Wide Area Networks (LPWANs) such as Wi-SUN and LoRaWAN are most relevant to utility, smart city, and industrial IoT applications [18,26,27].

The communication patterns between different IoT network components are determined by the network topology. The security, cost, complexity, and power consumption of topologies can all be quite different. Identifying the topology that best fits requirements of IoT application is essential before selecting a specific communication technology to employ [4]. The most prevalent networking topologies for IoT applications are the mesh topology, the star topology, and the point-to-point topology. In a network with a mesh architecture, each node works together to ensure that information is disseminated as efficiently as possible. Common applications of this network architecture include smart home systems, HVAC control, and smart buildings. Zigbee, Z-Wave, and Wi-Sun are some examples of mesh network topology-based industry standards. Star topology is an alternate method of wireless IoT networking in which all sensor nodes connect with a single hub or access point called a gateway [10]. Mesh networks are not the sole option for IoT applications that require low power to function. In reality, a star network architecture is used by the vast majority of LPWAN technologies, in addition to WiFi and cellular networks [15]. Multiple network topologies and communication technologies could be combined to create hybrid communication architectures that significantly outperform traditional designs.

In the realm of remote monitoring solutions, the IoT ecosystem has witnessed significant advancements. However, certain regions such as rural areas, marine areas, and ports still lack high-speed radio coverage, posing challenges for connectivity [13]. The need for environmental monitoring in these regions remains crucial and intriguing. Overcoming this obstacle requires the integration of innovative hybrid low-power wide-area communication technologies. By leveraging these technologies, it becomes feasible to establish connectivity between these regions and internet access points. This connectivity empowers the more efficient utilization of sensor data within the network, unlocking new possibilities for data-driven insights and applications.

The main objective of this study is to develop a hybrid network architecture that caters to diverse IoT scenarios, leveraging low-power, long-range devices capable of transmitting data at acceptable rates. The key addressed difficulty is the organization of a hybrid network with several associated technologies. The network should allow seamless switching between different communication protocols without causing disruptions for users or the wider network. However, to successfully install such a hybrid network, some challenges need to be addressed and resolved. These include harsh climate patterns, transmission range, quality of service, deployment cost, and power consumption. By considering the aforementioned difficulties, we presented a hybrid network architecture, as well as tested the performance with the real time implementation.

The design of a hybrid network stems from two distinct motivations. The first requirement of an IoT network is to facilitate data collection over a vast geographical region. To fulfill this need, the primary communication protocol selected is LoRa [23], known for its extensive range and low power consumption. Additionally, the mesh network capabilities of Wi-SUN [32] are employed to create a compact hybrid network. The second motivation arises from the growing density of smart devices in IoT networks. In locations with dense sensor deployments, the use of LoRa alone may lead to network congestion. To address this, a Wi-SUN mesh network is established in subareas to conserve energy while collecting data. The proposed hybrid network combines the advantages of LoRa's long-range capabilities with the potential of Wi-SUN mesh networks, aiming to achieve the following design objectives:

- Designing a hybrid network architecture that covers a large geographic area.
- Implementing a hybrid network architecture that enables seamless communication between diverse technologies.
- Developing and testing a hybrid backbone network to support various IoT applications throughout the university campus.

2. Background

Hybrid LPWAN integrates multiple LPWAN technologies to capitalize on the benefits of each. LPWANs are intended to offer low-power, long-range connectivity for Internet IoT devices, although different LPWAN technologies may be better suited for different use cases. A hybrid LPWAN can provide a more robust and adaptable solution by merging different LPWAN technologies, allowing for improved coverage, scalability, and dependability. Hybrid LPWANs are gaining popularity in the IoT market as a versatile and cost-effective method for deploying IoT systems. Some of the researchers have looked into the implementation of hybrid LPWANs in the published research [1–3,5,8,11,12,17,20,21,24,28,30,34].

In [12], the authors presented a hybrid LPWAN architecture that makes use of both, sub-GHz radio (LoRa) and 2.4-GHz short-range radio (ANT) technologies. The authors of this paper employed a TDMA strategy for building a LoRa mesh network; nevertheless, the scheduling and updating of information to nodes is inefficient and complicated. Jiang et al. [11] proposed real-time monitoring system that combined ZigBee with LPWAN (LoRa and NB-IoT) technologies for long-distance transfer of temperature data in high-voltage transmission lines. Employing licensed LPWAN, such as NB-IoT, will increase system costs. This system employs many tiers of hardware, which also contributes to its high cost. An edge-based hybrid network system architecture is described in [34]. By incorporating LoRa communication, the suggested system increases the short-range capabilities of BLE and XBEE devices. An IoT gateway that supports numerous IoT protocols, such as LoRa, BLE, and XBEE is proposed. It also performs sophisticated edge computing activities.

The proposed hybrid network architecture in [5] implements a cellular network by incorporating both radiofrequency and optical wireless technologies into the IoT ecosystem. Three distinct communication protocols are utilized for this purpose: Zigbee, LoRa, and VLC. ZigBee and VLC networks are utilized to interconnect sensors and actuators, while LoRa serves as backbone of the system for long-range communications. The end nodes restricted range and mobility are drawbacks of system. A technology-independent hybrid network frame is used to send data through different communication protocols. Pérez, Parada and Monzo [17] presented a hybrid network using WPAN and LPWAN to establish a communication architecture for emergency systems. The proposed architecture consists of Sigfox gateway to manage and monitor Bluetooth subnets through LoRa connections. Sigfox is used since its infrastructure already exists throughout Europe. Using LoRaWAN alone can eliminate the need for two LPWANs (LoRa and Sigfox) in a system. Slany et al. [28] deal with the development and deployment of a hybrid IoT platform for measuring consumption and data transmission in the field of water management. A combination of LoRaWAN and VLC/IR technology was chosen for this.

According to the research presented above, LoRa is the preferred LPWAN for the development of hybrid networks. In light of the foregoing, we presented a novel hybrid LPWAN using LoRa and Wi-SUN, which has not been previously explored in the literature. Many hybrid networks in the literature need either complicated hardware configurations or intricate programs to function. In contrast, we employed basic hardware and oneM2M international standards as the middleware for integrating LPWAN protocols. The oneM2M technical standards [16] outline how oneM2M can be used to interoperate with various IoT protocols.

3. System overview

In order to facilitate data collection from a diverse range of sensors while ensuring wide-area coverage with minimal energy consumption, a hybrid network architecture is proposed. This architecture combines star and mesh communication links to meet the desired objectives. The design of this hybrid network architecture involves the integration of two prominent LPWAN technologies, namely LoRa and Wi-SUN. By merging the capabilities of LoRa and Wi-SUN, the proposed architecture aims to leverage the strengths of both technologies, enabling efficient data collection and extended coverage.

3.1. Wi-SUN

The Wi-SUN or IEEE 802.15.4g [9] is a standard controlled by the Wi-SUN Alliance that makes use of IPv6 mesh networking to facilitate the deployment of a high number of IoT devices in scenarios such as Smart Cities, Smart Agriculture, and other similar use cases. Wi-SUN uses unlicensed Sub-GHz Industrial Scientific Medical (ISM) band frequencies and provides up to 300 Kbps bandwidth, 0.02 s latency. The different operating frequency ranges of Wi-SUN are 470–510 MHz, 779–787 MHz, and 920.5–924.5 MHz in China, 863–870 MHz, and 870–876 MHz in Europe, 865–867 MHz in India, and 920–928 MHz in the United States, Canada, and Japan. One of the Wi-SUN standards, known as Wi-SUN Field Area Network (FAN) can be used for smart city infrastructure. The devices of a Wi-SUN FAN network are categorized as Border Router (BR), router, and leaf node according to their responsibilities. The BR is a Destination Oriented Directed Acyclic Graph (DODAG) root node that provides the personal area network with a connection to a wide area network and gathers network data. The router is a special kind of node that acts as a parent to other nodes and also can be a child to some nodes, allowing it to forward data both up and down in the network. The leaf node is a minimum functional node that only communicates with the router node. Wi-SUN FAN is self-forming, so it is simple to add new devices to an existing network, and self-healing, so it can immediately re-route to the gateways if a connection breaks. The Wi-SUN network is responsible for collecting data from smart devices, managing devices which joins the mesh network, and facilitating device-to-device and device-to-application communication. With a radio module that is compatible with the Wi-SUN network technology, users may connect a wide variety of devices to the mesh network, allowing for the creation of a wide range of IoT applications [7].

3.2. LoRaWAN

LoRa is a physical layer acquired and developed by Semtech corporation [23], with higher-level properties for implementing LPWANs. LoRa is based on CSS modulation. It has similar low-power characteristics as frequency shift keying with improved coverage. Multiple IoT nodes in the LoRa network can be connected with a network server via gateways using a virtual channel. There are six virtual channels called spreading factors, ranging from 7 to 12 are used for communication between LoRa nodes and gateway. LoRa data rate varies between 300 bits to 50000 bits per second relative to the selection of SF and bandwidth. A LoRa receiver can decode signals that are 19.5 decibels below the noise floor, allowing for extremely extended communication ranges [14]. The possible communication range of LoRa is 15 km in rural and 5 km in urban areas [25].

LoRaWAN [31] is a LoRa Alliance standardized MAC layer protocol with open access. It operates on regional ISM band frequencies of 433 MHz-868 MHz (EU), 865–867 MHz (IN), 915 MHz (AUS and US), and 923 MHz (ASIA). The topology of the network, which is a star of stars in this case, is dictated by the LoRaWAN MAC layer. LoRa Nodes (LNs), LoRa Gateways (LGs), and Network Server (NS) are the three main components of a LoRaWAN network. LNs are divided into three classes: class A, class B, and class C, with output varying according to data rate and enhanced battery life. LGs serve as transparent links between LNs and NS. Typically, LG-to-NS connections are implemented using a non-LoRa network. Due to the fact that LGs do not enforce higher-level protocols and just function as a pass-through mechanism, application data is encrypted from the LNs. NS is the place where the real intent of the application is performed. Before arriving at the application server, packets from gateways are examined and probable copies are dismissed. The robustness and efficiency of LoRaWAN make it a crucial enabler for establishing seamless connectivity and facilitating efficient data transmission within hybrid network architectures across a diverse array of IoT applications.

3.3. Network architecture

The network topology adopted in this research study is a hybrid design that integrates both mesh and star topologies. The proposed architecture, depicted in Fig. 1, consists of multiple layers, each with distinct responsibilities. At the base layer, we have IoT nodes equipped with essential components such as sensors and actuators. These IoT nodes are designed to transmit or receive sensory data based on the specific application requirements, utilizing LoRa or Wi-SUN communication technologies.

The intermediate layer plays the most important role in network architecture since it serves as a bridge between IoT nodes and applications. This layer facilitates bidirectional communication between the nodes and application servers. To fulfill this role, two LPWAN network devices, namely the LoRa gateway and the Wi-SUN BR, are positioned within this layer. The LoRa gateway receives sensory data from nodes equipped with LoRa communication capability in the base layer and forwards it to the network server. It also transmits downlink communication from the network server to LoRa nodes. On the other hand, the Wi-SUN BR focuses on maintaining the mesh network.

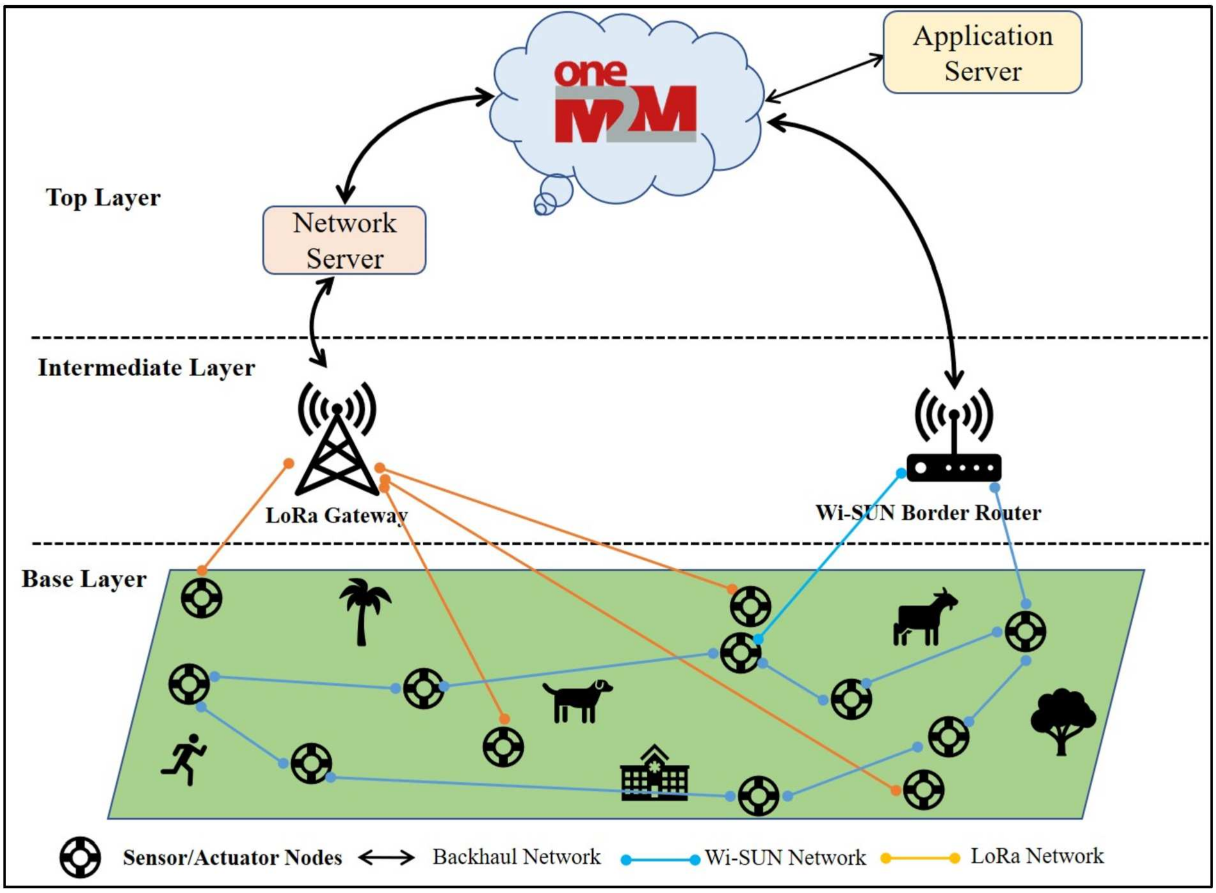


Fig. 1. Representation of hybrid LPWAN architecture.

Sensory data from Wi-SUN nodes is transmitted to the server via the Wi-SUN BR. The sensory data received from the server is passed on to Wi-SUN nodes that are directly connected to the BR enabling its dissemination throughout the network by forming a mesh network.

The integration of the two networks is facilitated through the utilization of an oneM2M server positioned in the top layer of the architecture. This oneM2M server implements an open-source version of the M2M (Machine-to-Machine) standard developed by the European Telecommunications Standards Institute. Its purpose is to enable the deployment of vertical applications and heterogeneous devices by providing a platform that allows the design of services independently of the underlying network infrastructure [29]. The oneM2M functional architecture consists of three main entities: the Application Entity (AE), the Common Services Entity (CSE), and the Network Services Entity (NSE). The CSE offers various standard services such as discovery, security, and device management to both AEs and other CSEs.

The oneM2M system employs a resource-based information model, where all resources including AEs, CSEs, and data are organized in a hierarchical structure called a resource tree. To access these resources, oneM2M provides RESTful APIs, which allow developers to interact with the available resources [33]. The server hosts an Infrastructure Node CSE, which is further divided into IN-CSEs. Each vertical or application is stored in a separate IN-CSE, and within each IN-CSE, there are multiple AEs. Each AE consists of multiple container instances that store descriptors and data related to the application. This hierarchical organization within the oneM2M server ensures efficient management and access to resources for seamless integration and processing of data from the integrated networks.

4. Implementation

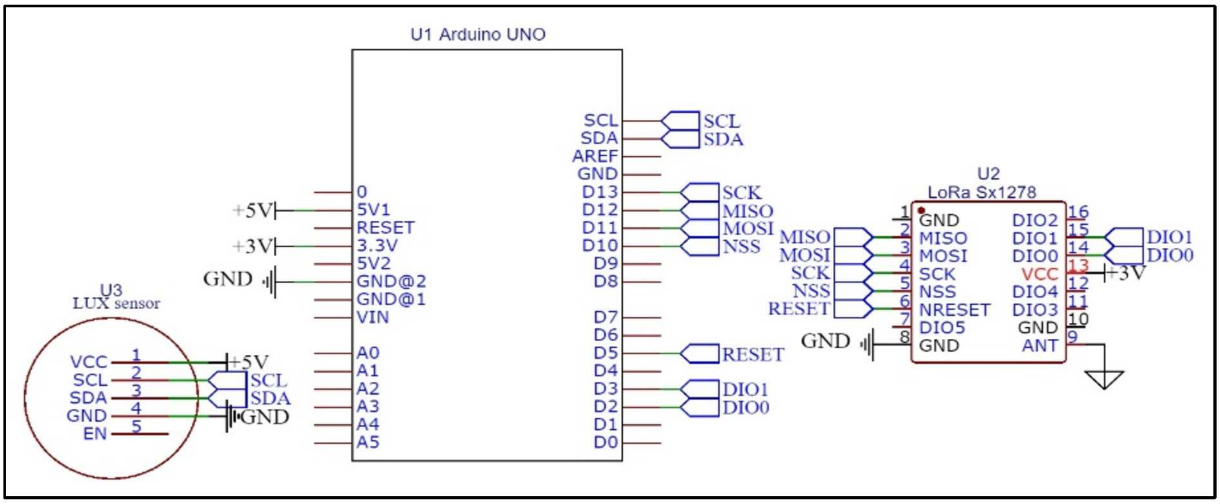
The hybrid network architecture we have developed demonstrates compatibility with a wide range of IoT applications. Our work focuses on establishing a large-scale wireless sensor network suitable for remote monitoring applications like digital agriculture, smart healthcare, and smart city monitoring. The main objective is to enable environment sensing in areas where internet connectivity may be limited. To address this challenge, we utilize the LoRa protocol for transferring information from remote locations to gateways. In various IoT applications that rely on sensor data, it is crucial to promptly execute actions across a vast geographical region using multiple actuator nodes. The proposed hybrid architecture effectively addresses this requirement. It enables remote monitoring of specific parameters via LoRa and, upon receiving sensory information, facilitates the execution of appropriate actions across a wide area through the Wi-SUN mesh network.

In our work, we present a real-time implementation of the proposed hybrid network architecture. To validate its functionality, we developed and tested a smart street light controlling system within the IIIT Hyderabad campus. This practical implementation demonstrates the effectiveness and viability of our hybrid network architecture in a real-world scenario. In process of implementation of the proposed architecture, we developed and deployed the LoRa network and integrated it with the existing Wi-SUN backbone network on campus. In the initial deployment, we opted for LoRa point-to-point communication instead of the star network configuration mentioned in the proposed hybrid architecture. Implementing LoRa point-to-point communication offers several significant advantages over utilizing LoRaWAN for building networks. By using only, the LoRa physical layer, we can avoid the need for costly gateways and back-end infrastructure. This allows for individual frequency bands to be assigned to specific devices, minimizing interference and optimizing network performance. In the basic configuration, devices can be set to operate in a send-and-forget mode, simplifying and expediting the setup process, especially when the application is already established. This approach leads to improved power efficiency and reduced cost per device. Unlike a LoRaWAN deployment, where devices must be registered to the network before transmitting packets, point-to-point LoRa devices can transmit data without prior registration. This flexibility eliminates the registration step, further streamlining the implementation process.

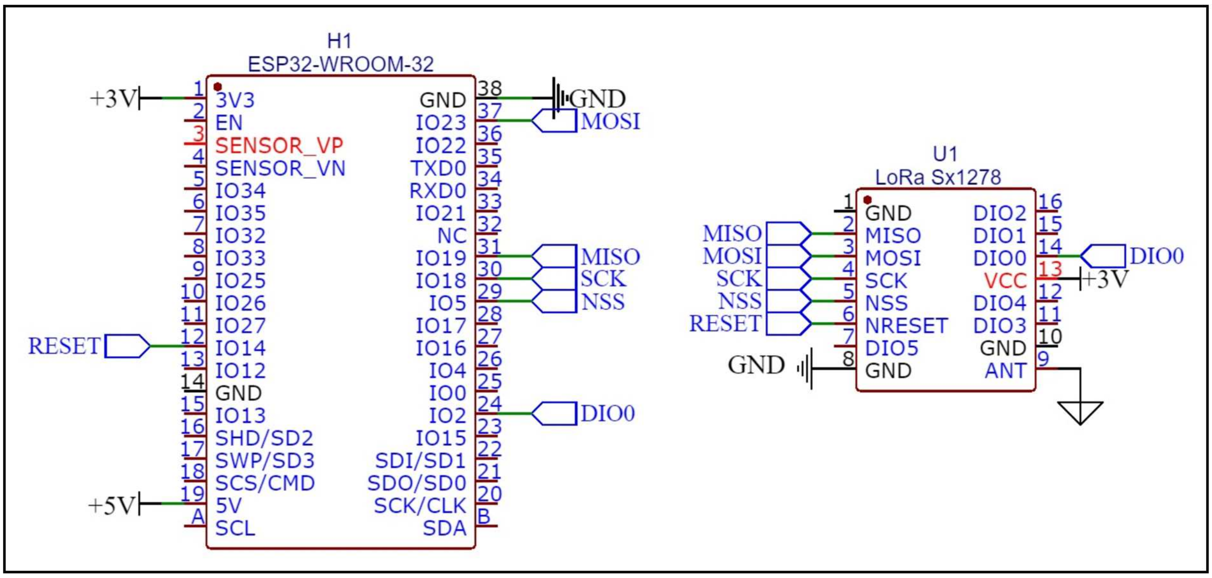
4.1. Hardware

The LoRa network comprises three transmitters and one receiver. Each LoRa transmitter consists of a Dragino LoRa shield (SX1278) mounted on an Arduino Uno. The transmitters are connected to luminosity sensors (GY-302) for capturing ambient light data. The GY-302 BH1750 sensor is an I2C bus-interfaced digital ambient light sensor with a wide dynamic range of 1 to 65535 lux, making it ideal for accurate light intensity measurements. The sensor data is transmitted to a LoRa SX1278 module connected to an ESP32, which serves as the LoRa receiver. The LoRa receiver gathers data from all the transmitters and, with the availability of backhaul connectivity, forwards the collected data to the oneM2M server. The oneM2M server acts as a centralized hub for storing and processing the received data. Figure 2 illustrates the circuit design of the LoRa hardware setup, showcasing the connections between the Arduino Uno, Dragino LoRa shield, and GY-302 luminosity sensor. Figure 3 showcases the physical hardware deployed for the LoRa network, providing a visual representation of the transmitters, receiver, and associated components. By utilizing this hardware configuration, the LoRa network enables the collection and transmission of ambient light data to the oneM2M server, facilitating further processing and utilization of the gathered information.

At the IIIT Hyderabad campus, the Wi-SUN mesh network has been successfully deployed and consists of one Wi-SUN BR and 30 router nodes. The Wi-SUN BR is composed of a Wi-SUN development board and a radio module, both connected to a Raspberry Pi. The Raspberry Pi serves as the central connectivity hub to the oneM2M server, facilitating communication between the Wi-SUN network and the server. The network of router nodes within the Wi-SUN mesh network utilizes custom-designed hardware. Each router node comprises a radio board, an off-the-shelf controller board, and other necessary peripherals. These components work together to enable wireless connectivity and data transmission within the mesh network. Figure **??** provides a visual representation of the deployed hardware for the Wi-SUN mesh network. By leveraging this hardware setup, the Wi-SUN mesh network establishes reliable communication among the router nodes, allowing for efficient data exchange and connectivity



(a)



(b)

Fig. 2. (a) Schematic diagram of LoRa transmitter. (b) Schematic diagram of LoRa receiver.

across the IIIT Hyderabad campus. The integration of the Wi-SUN network with the oneM2M server enables seamless interaction between the mesh network and the centralized server, facilitating data management, analysis, and further application integration.

4.2. Experimental implementation

In the proposed architecture, the sensory data collected from the base layer is transmitted to the intermediate layer through either LoRa or Wi-SUN communication technologies. The data is formatted according to the oneM2M standard, typically utilizing hierarchical resource structures based on RDF (Resource Description Framework) and XML (Extensible Markup Language). LoRa gateway/Wi-SUN BR will establish communication with the oneM2M server using backhaul technology. The formatted data is transmitted through this connection in real-time or at predefined

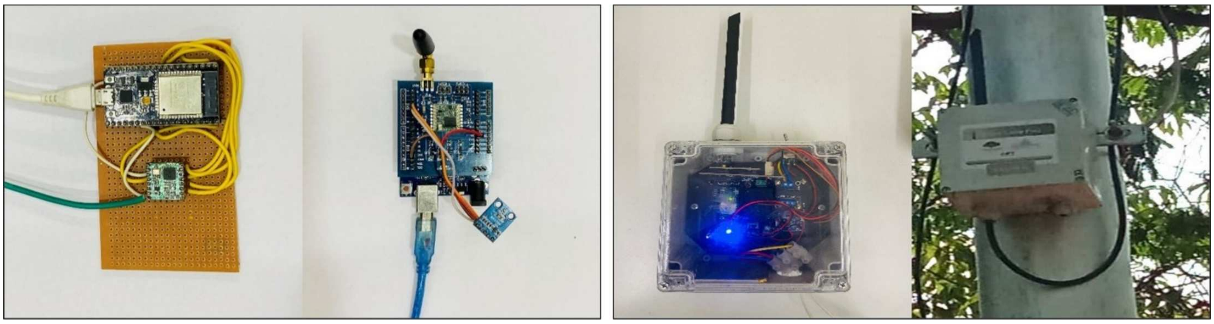


Fig. 3. (a) LoRa hardware (left – receiver, right – transmitter), (b) Wi-SUN hardware deployed at the campus.

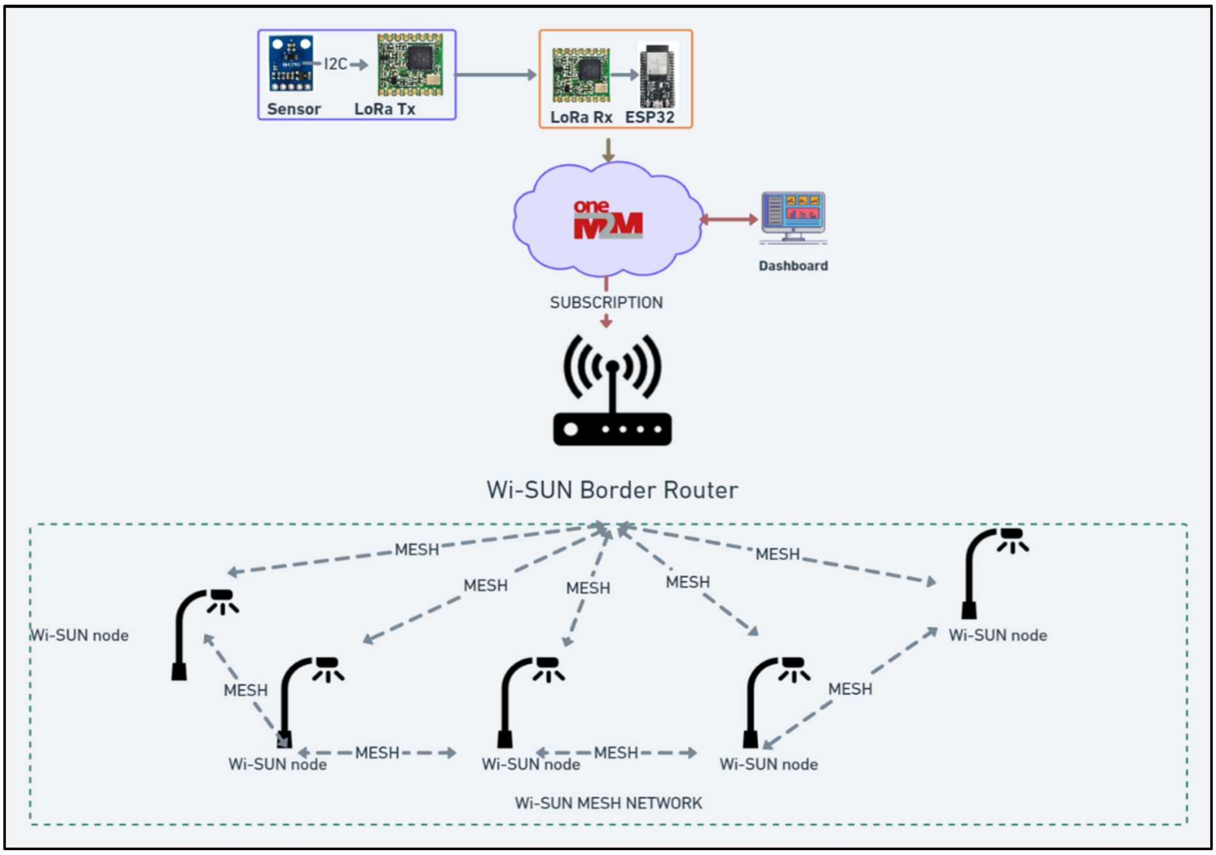


Fig. 4. Network architecture of a smart street light controlling system.

intervals, using the chosen oneM2M protocol. The server receives the data and performs storage and processing operations based on the specific application requirements. The network architecture of the smart street light control system is illustrated in Fig. 4. The implementation process begins with the sensing phase, where an ambient light sensor measures the light intensity in the surroundings. If the measured value falls below a predetermined threshold, the corresponding LoRa transmitter transmits this information to the LoRa receiver using LoRa communication technology. The LoRa receiver, equipped with an ESP32, then transmits the received data to the OneM2M server via a Wi-Fi network. The OneM2M server serves as a central hub and maintains a database with dedicated containers for each sensor node.

Regarding the integration of data collected from different LPWAN technologies, oneM2M provides a standardized framework that allows for interoperability. It offers a common data model and interface, enabling seamless integration and processing of data from diverse LPWAN sources. This means that regardless of the LPWAN technology used, such as LoRaWAN or Wi-SUN, the oneM2M server can handle and process the collected data uniformly. To manage the data effectively, a separate AE is created for each sensor node in the oneM2M server. Each AE contains multiple containers to organize the instances of sensory data collected by the respective node. Once the data is stored in the oneM2M server, it can be accessed and utilized for further applications. This includes retrieving the data for analysis, generating insights, and making informed decisions. The oneM2M server may provide APIs or other interfaces to access the data, allowing developers to build applications, dashboards, or other visualizations that enable monitoring, analytics, and the implementation of various IoT applications. To collect the sensory information, the Wi-SUN BR connects to the OneM2M server as a subscriber. Upon receiving the sensory data, the BR forms a mesh network using Wi-SUN communication and sends ON/OFF commands to each node within the network. This allows for automatic control of streetlights based on the ambient light level, eliminating the need for manual operation at fixed times.

Overall, this integration enables efficient data transmission, organization, and actuation within the architecture, ensuring seamless communication and control between the various layers and components. The designed network architecture can be applied to various IoT applications, including smart agriculture, smart buildings, and smart healthcare, among others. It offers the potential for improved automation, energy savings, and enhanced operational control in diverse scenarios.

5. Results

This study provides a resilient hybrid LPWAN architecture for IoT applications. In terms of coverage, the greatest distance at which each subnet of the system may be reached is a vital aspect for the development of network architecture. The tests are conducted to analyse the coverage area of each network. The coverage tests include line-of-sight (LOS) and non-line-of-sight (NLOS) testing in both indoor and outdoor locations. We established both LoRa and Wi-SUN wireless networks. These technologies describe the existing conventional LPWAN communication protocols and give a performance foundation for the communication protocols in a real-world setting for the proposed hybrid LPWAN architecture.

In this study, the LoRa nodes were configured with a bandwidth of 125 kHz, spreading factor SF 9, and coding rate 4/7 to achieve an optimized balance between transmission time and range. The experiments utilized Semtech SX1278 [22] chipset-based LoRa modules operating in the 865–867 MHz ISM band. To evaluate the range of the LoRa signal, a LoRa receiver was placed at a fixed location outdoors, while the transmitter was moved along a line of sight (LOS) path. During the experiment, RSSI readings were recorded at various points to monitor the signal intensity. Employing a transmission power of 14 dBm and an antenna with a gain of 2 dBi, successful transmissions were achieved between two LoRa nodes at a distance of 600 m in an outdoor LOS environment. To assess performance in a non-line-of-sight (NLOS) setting, the same procedure was followed, with RSSI values recorded for different distances. The maximum distance achieved in an NLOS environment was 380 m. For the indoor LOS experiment, the LoRa receiver was installed on the ground level of a laboratory, while the LoRa transmitter was moved throughout all corners of the same floor. RSSI readings were taken to evaluate signal strength. In the indoor NLOS experiment, the LoRa transmitter was relocated to multiple floors and rooms to assess coverage in an obstructed environment.

The Wi-SUN network coverage studies involved the deployment of a fixed Wi-SUN BR in a specific location to evaluate the coverage characteristics. The BR was configured and kept stationary throughout the experiments. A mobile Wi-SUN node was utilized, comprising a Wi-SUN radio module operating at a transmission power of 19 dB, a data rate of 50 kbps, and a frequency of 865 MHz. The experiments encompassed both line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios conducted in outdoor and indoor environments. In the LOS experiments, direct line-of-sight paths between the mobile Wi-SUN node and the BR were established without any obstructing elements. This allowed for an assessment of the network's performance in ideal, unimpeded conditions. Conversely, the NLOS experiments simulated real-world situations with obstructed paths caused by physical obstacles and

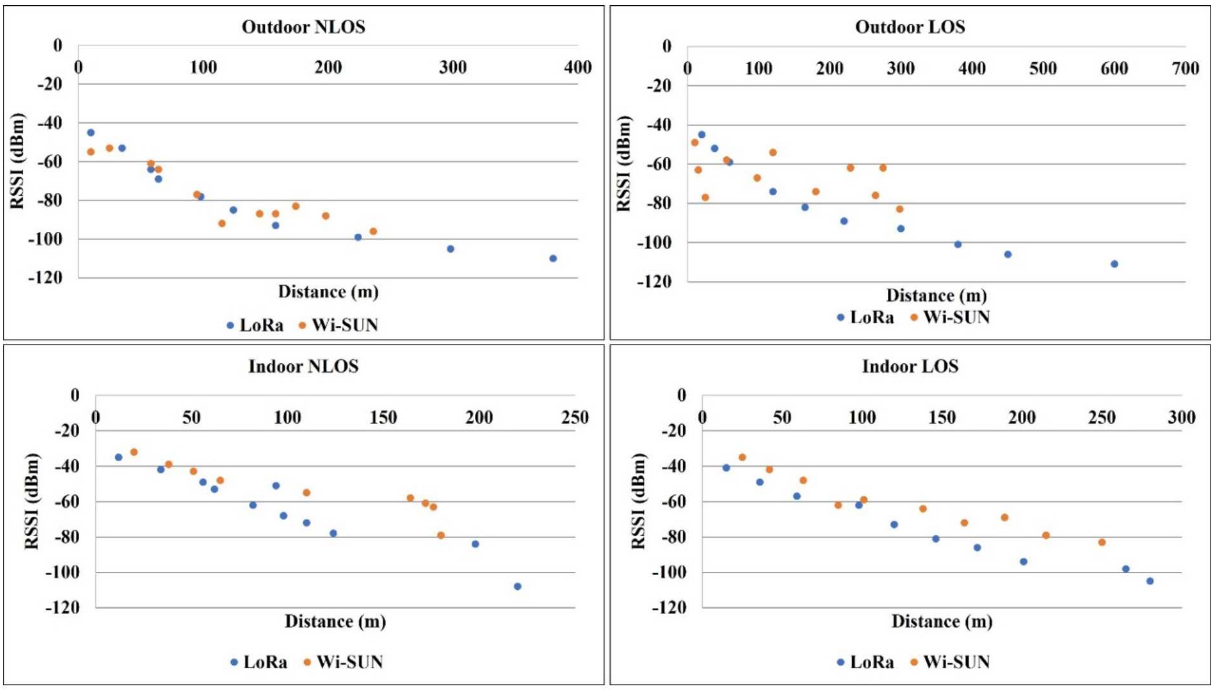


Fig. 5. RSSI vs distance graphs for LoRa and Wi-SUN networks.

Table 1

Results of coverage experiments for LoRa and Wi-SUN networks

Network	Outdoor				Indoor			
	LOS		NLOS		LOS		NLOS	
	RSSI (dBm)	Distance (meters)	RSSI (dBm)	Distance (meters)	RSSI (dBm)	Distance (meters)	RSSI (dBm)	Distance (meters)
LoRa	−102	600	−98	380	−101	280	−96	220
Wi-SUN	−82	298	−77	236	−72	250	−63	180

environmental structures, such as walls and buildings. The graphs in Fig. 5 show the measured RSSI values as a function of distance for every single experiment. Table 1 summarizes the average RSSI values for all experiments together with their respective observed average distances.

By analysing the above results, in an open field, the coverage of LoRa devices is very extensive, but indoors, their signal is attenuated by natural obstacles in the buildings. Comparatively Wi-SUN has less coverage than LoRa in outdoor environments and almost equal coverage in indoor environments. However, its mesh topology allows for the expansion of its operating area. As the number of nodes in a mesh network grows, the number of available communication pathways also grows, which boosts the reliability and performance of the network. The proposed hybrid LPWAN architecture achieves good coverage by combining the long-range and wide operating area capabilities of LoRaWAN and Wi-SUN, respectively.

Despite the similarities between these two low-power communication technologies, their power requirements will vary depending on the operation of nodes. Wi-SUN nodes are designed for frequent communication and take less than 2 μA when resting, around 8 mA when listening, and less than 14 mA for transmitting at +10 dBm, on the other hand, LoRaWAN devices are typically designed for infrequent communication, so they only draw 1 μA at rest but 12 mA when listening and 18 mA for transmitting at +7 dBm. The power consumption of the hybrid LPWAN network is satisfactory when compared to individual LoRaWAN and Wi-SUN networks as shown in Fig. 6.

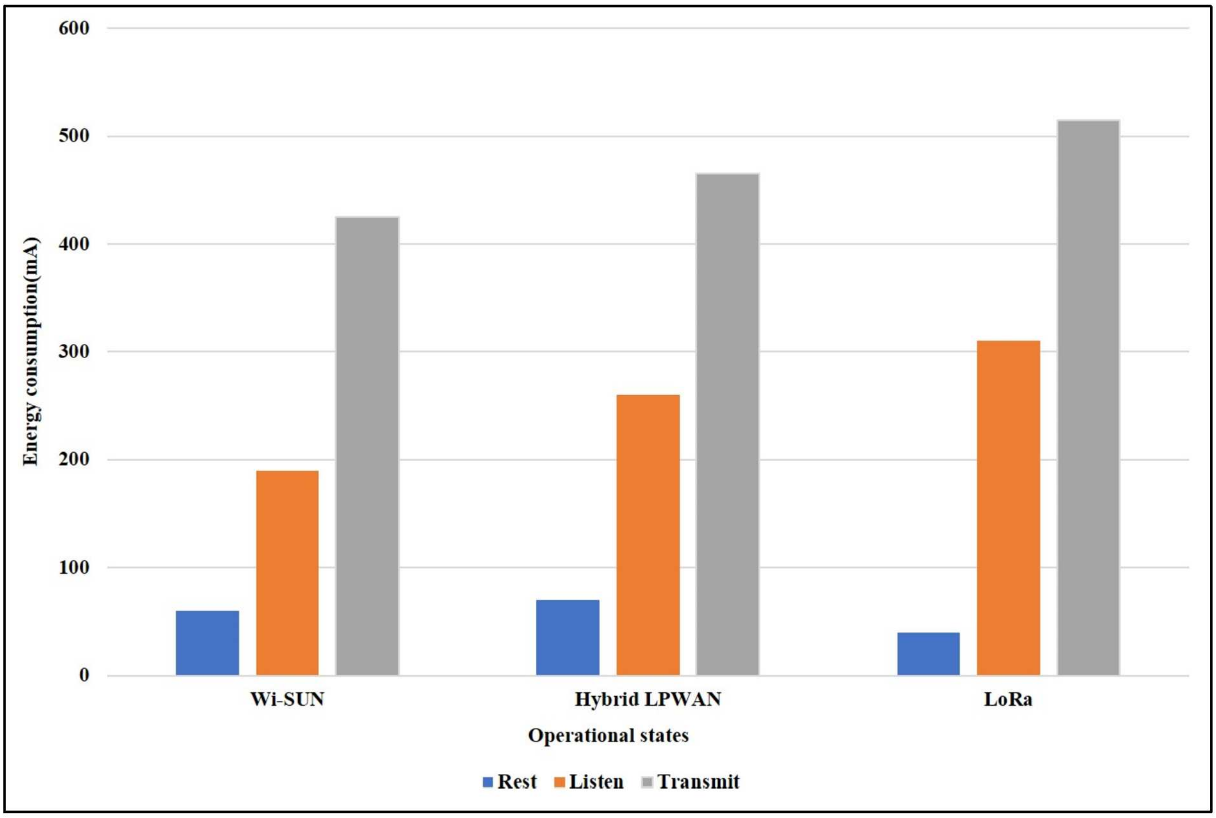


Fig. 6. Energy consumption of hybrid LPWAN in comparison with LoRa and Wi-SUN networks.

Individual LoRaWAN network energy consumption is high because all LoRa nodes communicate with the gateway independently, and retransmissions will be more due to the increased number of devices.

In addition to the hybrid network architecture, we have developed a system for effectively controlling multiple street lights across university campus using the hybrid network. To assess its practicality, a field test was conducted, involving thirty Wi-SUN nodes connected to a BR and three LoRa transmitters with a single receiver, covering a wide area within the campus environment. The LoRa transmitters were strategically positioned on the top of buildings, approximately 60 meters away from the receiver. Each LoRa transmitter node was configured to transmit data to the receiver upon detecting a specific sensor threshold related to lighting conditions. The street lights, equipped with Wi-SUN nodes connected to the Wi-SUN network, were controlled by Arduino Nano controllers. The Wi-SUN BR was subscribed to the OneM2M server, allowing for seamless interoperability. The OneM2M framework facilitated the reception of data from the LoRa receiver by the BR. Upon receiving the data, the BR sent commands to the Wi-SUN nodes installed on the street lights, enabling them to be turned on or off based on the received instructions. The status of each street light could be monitored and tracked on a customizable dashboard. The dashboard provided comprehensive insights into the general system status, while the notification engine delivered alerts for important events. Furthermore, the map interface allowed for a detailed examination of specific details and configurations related to the street lights.

We claim that the proposed hybrid architecture successfully cover a campus-sized environment and provide a stable network solution. The integration of LoRa nodes for data collection and feedback greatly enhances the coverage of the Wi-SUN network. With capabilities of LoRa, the data of each street can be efficiently collected and transmitted. Moreover, by leveraging local data processing capabilities at the receiver, the response time of the system can be further reduced. This combination of LoRa and Wi-SUN technologies optimizes data collection, enhances network coverage, and enables faster data processing for improved system efficiency. The hybrid LPWAN-based smart streetlight control system incorporates various energy-saving and cost-reducing mechanisms, such as precise scheduling, automated on/off operations, sensor-driven activation, and centralized control and monitoring. Sensor-triggered lighting ensures that street lights are activated only when necessary, saving energy during daylight hours or when ambient lighting is sufficient. The centralized command and control mechanism, facilitated by the Wi-SUN BR and OneM2M server, enables efficient monitoring and management of the entire network, further optimizing energy usage. Real-time monitoring and a dashboard interface provide proactive maintenance and quick identification of faulty lights, reducing energy wastage. Leveraging existing wireless technologies such as Wi-SUN and LoRa contributes to the cost-effectiveness of the system, allowing for scalability, flexibility in deployment, and reduced infrastructure costs.

6. Conclusion and future work

This research article presents the design and development of a hybrid LPWAN architecture for IoT applications, combining the strengths of LoRa star network and Wi-SUN mesh network. The proposed architecture enables long-distance data transmission with low-power nodes while maintaining high-quality service. The system has been successfully tested and validated through real-world IoT applications, particularly in the context of smart street light management on a university campus. By integrating custom-designed hardware and leveraging the hybrid network architecture, the system demonstrates the potential for accelerating the creation and implementation of IoT systems, enhancing heterogeneity, expanding wireless protocol coverage, and improving the quality of service for IoT-based applications. The versatility of the proposed hybrid LPWAN architecture extends to diverse IoT domains such as smart cities, smart agriculture, and industrial automation, where reliable and high-capacity connectivity with low power consumption is crucial. Future research directions include scaling up the deployment to city-level scenarios with multiple communication interfaces, further optimizing the hybrid LPWAN architecture's performance by considering additional parameters such as power consumption and latency. This work sets a foundation for advancing IoT technologies and contributes to the realization of robust and efficient IoT systems in various application domains.

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Conflict of interest

None to report.

References

[1] J. Bravo-Arrabal, J.J. Fernandez-Lozano, J. Serón, J.A. Gomez-Ruiz and A. García-Cerezo, A development and implementation of a hybrid wireless sensor network of low power and long range for urban environments, *Sensors* **21** (2021), 567. doi:10.3390/s21020567.

[2] G.D. Campo, I. Gomez, G. Cañada and A. Santamaria, Hybrid LPWAN communication architecture for real-time monitoring in power distribution grids, in: *2019 IEEE 5th World Forum on Internet of Things (WF-IoT)*, Limerick, Ireland, 2019, pp. 920–924. doi:10.1109/WF-IoT.2019.8767267.

[3] M. Chen, Y. Miao, X. Jian, X. Wang and I. Humar, Cognitive-LPWAN: Towards intelligent wireless services in hybrid low power wide area networks, *IEEE Transactions on Green Communications and Networking* **3**(2) (2019), 409–417. doi:10.1109/TGCN.2018.2873783.

[4] G. De Masi, The impact of topology on Internet of Things: A multidisciplinary review, in: *Advances in Science and Engineering Technology International Conferences (ASET)*, 2018, pp. 1–6.

[5] F. Delgado-Rajo, A. Melian-Segura, V. Guerra, R. Perez-Jimenez and D. Sanchez-Rodriguez, Hybrid RF/VLC network architecture for the Internet of Things, *Sensors* **20** (2020), 478. doi:10.3390/s20020478.

[6] A. Gaur, B.W. Scotney, G.P. Parr and S.I. McClean, Smart city architecture and its applications based on IoT, *Procedia Computer Science* **52** (2015), 1089–1094. doi:10.1016/j.procs.2015.05.122.
[7] R. Hirakawa, H. Keiichi and M. Hiroshi, Specification and performance analysis of Wi-SUN FAN, TechRxiv, Preprint, 2022. doi:10.36227/techrxiv.21545493.v1.
[8] A. Hoeller, R.D. Souza, H. Alves, O.L. Alcaraz López, S. Montejo Sánchez and M.E. Pellenz, Optimum lorawan configuration under wisun interference, *IEEE Access* **7** (2019), 170936–170948. doi:10.1109/ACCESS.2019.2955750.
[9] IEEE, 802.15.4-2020 – IEEE standard for low-rate wireless networks, 2020. doi:10.1109/IEEESTD.2020.9144691.
[10] M.A. Jamshed, K. Ali, Q.H. Abbasi, M.A. Imran and M. Ur-Rehman, Challenges, applications, and future of wireless sensors in Internet of Things: A review, *IEEE Sensors Journal* **22**(6) (2022), 5482–5494. doi:10.1109/JSEN.2022.3148128.
[11] C. Jiang, J. Xie, J. Zhao and X. Zhang, A novel high-voltage transmission line joint temperature monitoring system using hybrid communication networks, *IEEE Access* **9** (2021), 109478–109487. doi:10.1109/ACCESS.2021.3097372.
[12] X. Jiang, H. Zhang, E.A. Yi, N. Raghunathan, C. Mousoulis, S. Chaterji, D. Peroulis, A. Shakouri and S. Bagchi, Hybrid low-power wide-area mesh network for IoT applications, *IEEE Internet of Things Journal* **8**(2) (2021), 901–915. doi:10.1109/JIOT.2020.3009228.
[13] S. Krishnamoorthy, A. Dua and S. Gupta, Role of emerging technologies in future IoT-driven Healthcare 4.0 technologies: A survey, current challenges and future directions, *J Ambient Intell Human Comput* **14** (2023), 361–407. doi:10.1007/s12652-021-03302-w.
[14] D. Magrin, M. Capuzzo and A. Zanella, A thorough study of LoRaWAN performance under different parameter settings, *IEEE Internet of Things Journal* **7**(1) (2020), 116–127. doi:10.1109/JIOT.2019.2946487.
[15] M.N. Ochoa, A. Guizar, M. Maman and A. Duda, Evaluating LoRa energy efficiency for adaptive networks: From star to mesh topologies, in: *Proc. IEEE 13th Int. Conf. Wireless Mobile Comput. Netw. Commun. (WiMob)*, 2017, pp. 1–8.
[16] OneM2M, Global IoT technical specifications. https://www.onem2m.org/technical. Accessed on [Mar 22, 2023].
[17] E. Pérez, R. Parada and C. Monzo, Global emergency system based on WPAN and LPWAN hybrid networks, *Sensors* **22** (2022), 7921. doi:10.3390/s22207921.
[18] U. Raza, P. Kulkarni and M. Sooriyabandara, Low power wide area networks: An overview, *IEEE Communications Surveys Tutorials* **19**(2) (2017), 855–873. doi:10.1109/COMST.2017.2652320.
[19] E.A. Rogers and E. Junga, *Intelligent Efficiency Technology and Market Assessment*, American Council for an Energy-Efficient Economy, Washington, DC, USA, 2017.
[20] M. Saravanan, A. Das and V. Iyer, Smart water grid management using LPWAN IoT technology, in: *2017 Global Internet of Things Summit (GIoTS)*, 2017, pp. 1–6.
[21] G. Scaramella, G.C. Heck, L. Lippmann Junior, R.A. Hexsel, T. Santana and V.B. Gomes, Enabling LoRaWAN communication over Wi-SUN smart grid networks, in: *ICC 2022 – IEEE International Conference on Communications*, Seoul, Korea, Republic of, 2022, pp. 4842–4847. doi:10.1109/ICC45855.2022.9838959.
[22] Semtech, SX1278. https://www.semtech.com/products/wireless-rf/lora-connect/sx1276.
[23] Semtech LoRa Technology overview. https://www.semtech.com/lora. Accessed on [Jan 8, 2023].
[24] T. Shahgholi, A. Sheikhahmadi, K. Khamforoosh et al., LPWAN-based hybrid backhaul communication for intelligent transportation systems: Architecture and performance evaluation, *J Wireless Com Network* **2021** (2021), 35. doi:10.1186/s13638-021-01918-2.
[25] B. Shilpa and M.R. Mahamood, Design and implementation of framework for smartcity using LoRa technology, *Sreyas Int J Scientists Technocrats* **1**(11) (2017), 36–43. doi:10.24951/sreyasijst.org/2017041005.
[26] B. Shilpa, S. Malipatil and J. Reddy, Lora technology-based potholes and humps detection for smart city transportation, *Int J Eng Adv Technology (IJEAT)* **8**(6) (2019), 702–705. doi:10.35940/ijeat.F7970.088619.
[27] B. Shilpa, R. Radha and P. Movva, Comparative analysis of wireless communication technologies for IoT applications, *Lecture Notes in Electrical Engineering* **806** (2022), 383–394. doi:10.1007/978-981-16-6448-9_39.
[28] V. Slany, P. Koudelka, E. Krcalova, J. Jobbagy and L. Danys, New hybrid IoT LoRaWAN/IRC sensors: Smart water metering system, *Computers, Materials & Continua* **71**(3) (2022), 5201–5217. doi:10.32604/cmc.2022.021349.
[29] J. Swetina, G. Lu, P. Jacobs, F. Ennesser and J. Song, Toward a standardized common M2M service layer platform: Introduction to oneM2M, *IEEE Trans. Wireless Communication* **21**(3) (2014), 20–26. doi:10.1109/MWC.2014.6845045.
[30] A.F.D.S. Veloso, J.V.R. Júnior, R.D.A.L. Rabelo and J.D.-F. Silveira, HyDSMaaS: A hybrid communication infrastructure with LoRaWAN and LoraMesh for the demand side management as a service, *Future Internet* **13** (2021), 271. doi:10.3390/fi13110271.
[31] What is LoRaWAN specification, LoRa Alliance, San Jose, CA, USA, 2020. [Online]. https://lora-alliance.org/about-lorawan/.
[32] Wi-SUN alliance. https://wi-sun.org/. Accessed on [March 8, 2023].
[33] C.-W. Wu, F.J. Lin, C.-H. Wang and N. Chang, OneM2M-based IoT protocol integration, in: *2017 IEEE Conference on Standards for Communications and Networking (CSCN)*, Helsinki, Finland, 2017, pp. 252–257. doi:10.1109/CSCN.2017.8088630.
[34] F. Wu, C. Qiu, T. Wu and M.R. Yuce, Edge-based hybrid system implementation for long-range safety and healthcare IoT applications, *IEEE Internet of Things Journal* **8**(12) (2021), 9970–9980. doi:10.1109/JIOT.2021.3050445.