Research

Optimising urban lighting efficiency with IoT and LoRaWAN integration in smart street lighting systems

Waheb A. Jabbar[1] · Tan Keng Keat[2] · Fares A. Dael[3] · Lee Chee Hong[2] · Yusra Farhana M. Yussof[2] · Abdul Nasir[2]

Abstract

The integration of the Internet of Things (IoT) into smart city frameworks ushers in new opportunities for merging and enhancing diverse services, enabling seamless connectivity across multiple application domains. This paper presents the LoRaWAN-IoT-SSLS, an advanced automated streetlight control system that leverages IoT technology to achieve substantial energy savings and minimise the need for manual intervention. By employing LoRaWAN as the sensor network backbone, the system effectively addresses challenges related to long-range data transmission in IoT applications. The setup integrates a programmed Arduino board with PIR and LDR sensors, a GPS module, a LoRa shield, and a LoRaWAN gateway. The system is powered by a monocrystalline solar panel with a solar charger shield and battery and utilises LED lights for illumination. These components collectively enable automated switching and adaptive brightness control based on real-time environmental conditions, optimising energy use and enhancing safety. The system's performance was validated across distances up to 1000 m, maintaining stable operation with SNR values ranging from 9.8 to 1.5 dB and reliable RSSI levels, demonstrating robust communication and monitoring capabilities. Real-time status updates are visualised through the TagoIO platform, allowing for continuous remote management. The deployment of LoRaWAN-IoT-SSLS has the potential to significantly reduce electricity consumption and CO_2 emissions by harnessing renewable energy resources. By activating lighting only when pedestrians or vehicles are detected and dimming or turning off when no presence is sensed, the system demonstrates superior performance over conventional models. This scalable and secure solution lays the groundwork for future innovations in smart urban infrastructure, setting new benchmarks for energy-efficient city lighting.

1 Introduction

The accelerating pace of urbanisation has amplified the demand for innovative services and applications to enhance urban living standards [1]. In this context, smart street lighting systems have emerged as a crucial component of smart city infrastructures, offering energy-efficient and cost-effective outdoor illumination solutions [2]. These systems play a vital role in improving safety and visibility for all road users, while also reducing electricity consumption and environmental

✉ Waheb A. Jabbar, waheb.abdullah@bcu.ac.uk | [1]College of Engineering, Faculty of Computing, Engineering and the Built Environment, Birmingham City University, Birmingham B4 7XG, UK. [2]Faculty of Electrical and Electronics Engineering Technology, Universiti Malaysia Pahang Sultan Abdullah, 26600 Pekan, Pahang, Malaysia. [3]Management Information Systems Department, İzmir Bakırçay University, 35665 İzmir, Turkey.

impact [3]. As urban environments become increasingly complex, the integration of advanced technologies within city planning is essential for sustainable development [4, 5].

The advent of the Internet of Things (IoT) has transformed urban infrastructure by enabling street lighting systems to harness real-time data for adaptive and efficient performance [6]. Such systems dynamically adjust lighting based on environmental conditions, optimising energy usage and extending equipment lifespan [7]. Traditional street lighting—typically activated at dusk and deactivated at dawn—represents a significant and often inefficient energy burden worldwide [8]. To counteract this, the transition to Light Emitting Diode (LED) technology, coupled with smart control mechanisms, has become a standard approach for energy reduction [9, 10].

Recent studies have highlighted the integration of Light Dependent Resistors (LDRs) and Pyroelectric Infrared (PIR) sensors as key elements of smart street lighting systems. LDRs enable automatic detection of ambient light levels, ensuring that lights remain off during daylight hours, while PIR sensors enhance responsiveness by detecting pedestrian and vehicular movement, thus triggering illumination only when needed [11, 12]. These advancements not only conserve energy but also allow precise control and scheduling, aligning with sustainable urban development goals.

The integration of LoRa (Long Range) and LoRaWAN (Long Range Wide Area Network) technologies in smart city applications heralds a new era of connectivity and efficiency for urban infrastructure [13, 14]. LoRaWAN, a media access control (MAC) layer protocol built on LoRa technology, facilitates long-range, low-power communication between IoT devices, making it an ideal solution for the widespread and diverse needs of smart cities [15]. This technology enables streetlights to be part of a vast, interconnected network, allowing for real-time data transmission and remote management over considerable distances with minimal energy consumption. The use of LoRaWAN in smart street lighting systems not only enhances their responsiveness and adaptability to environmental changes and urban dynamics but also significantly reduces operational costs [16]. By leveraging the capabilities of LoRa/LoRaWAN, municipalities can implement a more sustainable, efficient, and intelligent street lighting network. This approach aligns with the broader objectives of smart cities to optimise resource use, decrease carbon footprints, and improve the overall quality of urban life, showcasing the potential of advanced communication technologies in facilitating urban sustainability and resilience.

This paper explores the development and implementation of a LoRaWAN-based smart street lighting system, designed to address the dual objectives of energy efficiency and improved urban lighting. The system is specifically designed to address and surmount the inherent challenges associated with transmitting IoT data. By strategically incorporating LoRaWAN into its sensor network architecture, it ensures robust, efficient data communication across the IoT ecosystem. This integration not only facilitates reliable long-range connectivity but also optimises energy consumption, making it an ideal solution for the expansive and demanding environments of smart cities. Through this approach, the system leverages LoRaWAN's capabilities to enhance data transmission reliability and network scalability, effectively bridging the gap between diverse IoT devices and applications within the urban infrastructure. The proposed solution integrates an Arduino with PIR, LDR, and GPS sensors, along with a LoRa shield, a LoRaWAN gateway, a solar panel fitted with a solar charger shield and battery, and LED lights. These components work together to control the switching and automatically adapt the brightness of illumination based on the surrounding environment. This improvement not only improves the levels of illumination but also enables real-time control of street lighting via the TagoIO platform.

The integration of renewable energy sources, such as solar power, into the system further underscores its sustainability and autonomy [7]. By leveraging solar energy, the system reduces reliance on the traditional power grid, thus contributing to a reduction in CO2 emissions and promoting environmental conservation. The real-time data monitoring and management capabilities provided by the TagoIO platform offer an unprecedented level of control and efficiency, enabling city managers to make informed decisions regarding street lighting policies and practices.

In conclusion, the implementation of a LoRaWAN-IoT-SSLS system represents a significant advancement in the field of smart urban infrastructure. It not only demonstrates the potential of integrating IoT and LoRaWAN technologies to enhance urban lighting systems but also sets a benchmark for future developments in smart city initiatives. Through its focus on energy efficiency, environmental sustainability, and enhanced urban livability, this system exemplifies the transformative potential of smart technologies in shaping the cities of the future.

1.1 Motivations *and problem statement*

Street lighting plays a critical role in road safety by ensuring visibility for drivers and pedestrians, thereby reducing accidents and crime [17]. Contemporary systems have advanced towards greater energy efficiency and networked operation, enabling remote monitoring and maintenance via server-based platforms [18].

To further improve performance, many countries have adopted smart street lighting systems that replace high-pressure sodium lamps with LEDs, offering superior energy efficiency and environmental benefits [19]. Additionally, the integration of solar panels mitigates reliance on fossil fuels, promoting sustainable energy use [20].

The core operation of smart streetlights relies on ambient light and motion detection. LDRs monitor light intensity to activate illumination at night, while PIR sensors detect movement, ensuring lights operate only when needed. Wireless Sensor Networks (WSNs) such as LoRa and ZigBee provide remote monitoring capabilities, enhancing maintenance efficiency. However, existing systems still face challenges, including high electricity consumption, limited data transmission reliability, and design flaws that hinder real-world application.

To address these gaps, our proposed system employs a robust Printed Circuit Board (PCB) design with reliable soldering and weather-resistant enclosures. This ensures greater durability and operational stability, overcoming previous limitations and paving the way for practical, scalable deployment in urban environments.

2 Research contributions

This paper introduces a cutting-edge smart street lighting system, epitomising innovation in urban infrastructure through its comprehensive design and strategic integration of advanced technologies. The proposed LoRaWAN-IoT-SSLS presents a transformative contribution to smart city technologies, integrating the Intelligent Solar-Powered Street Lamp (ISPSL) into a broader networked ecosystem. By employing LoRaWAN communication protocols, the system facilitates long-range, low-power connectivity that enables real-time data transmission and remote management capabilities. This comprehensive approach to street lighting management encompasses energy savings, predictive maintenance, and enhanced data-driven decision-making. The deployment of LoRaWAN-IoT-SSLS as a holistic system offers a blueprint for future development in intelligent lighting systems, promoting sustainable city planning and connected community solutions Our contributions, which are poised to make significant impacts in the realm of smart cities, are meticulously detailed as follows:

- The design and fabrication of the Intelligent Solar-Powered Street Lamp (ISPSL) represent a significant advancement in sustainable urban lighting. Meticulously engineered to be both aesthetically pleasing and highly functional, the ISPSL incorporates a solar panel-topped body with integrated LED lighting, PIR motion detection, and ambient light sensing. The unit's modular design, featuring 3D-printed components made from durable and weather-resistant materials, ensures ease of installation and maintenance. This novel streetlamp design contributes to the field of smart urban infrastructure by providing a self-sustaining, eco-friendly lighting solution that enhances public safety and urban aesthetics.
- We present an optimised lamp post structure that is not only aesthetically pleasing but also engineered for maximum efficiency in light distribution. This design incorporates modular components for easy installation and maintenance, setting a new standard in street lighting infrastructure.
- Central to our system is the use of high-efficiency LED lights, chosen for their low energy consumption and long lifespan. These LEDs provide superior illumination while significantly reducing operational costs and carbon footprint, aligning with sustainable urban development objectives.
- Our system harnesses solar energy through high-performance monocrystalline solar panels, coupled with robust battery storage. This configuration ensures a reliable and sustainable power supply, making street lighting autonomous and green.
- Another contribution is underscored by the deployment of a sophisticated multi-sensor system, comprising PIR for motion detection, LDR for ambient light sensing, and a GPS sensor for precise geolocation. This configuration facilitates intelligent, dynamic lighting control, adjusting intensity in real-time to meet environmental and situational demands, thereby optimising energy consumption. The GPS sensor, in particular, revolutionises street lighting network management by enabling exact lamp post mapping. This capability greatly enhances the efficiency of installation, maintenance, and troubleshooting, ensuring quick and accurate location targeting without manual intervention.
- Leveraging the LoRa/LoRaWAN network, our system achieves long-range, low-power communication across the street lighting infrastructure. This network backbone facilitates the seamless transmission of sensor data and control commands, ensuring efficient operation even in expansive urban areas.
- At the core of our system's intelligence is its integration with the TagoIO IoT platform. This platform provides robust data management and analytics capabilities, enabling the aggregation and analysis of data from our network of

streetlights. A bespoke dashboard/GUI, developed on the TagoIO platform, offers intuitive and real-time monitoring and management of the street lighting system. This user-friendly interface allows for the visualisation of system metrics, control of light settings, and insight into performance analytics, enhancing decision-making and operational efficiency.

Our system's holistic approach, from the innovative lamp post design to the sophisticated dashboard/GUI, underscores our paper's novelty and contribution to the field. It demonstrates a successful blend of design, technology, and sustainability, promising to advance the dialogue in high-impact journals and among stakeholders aiming to reimagine urban lighting.

The structure of this paper is organised as follows: Section II provides a review of related literature, laying the groundwork for understanding the context and advancements in smart street lighting systems. Section III details the design and construction of the smart street lighting system, highlighting the innovative approaches employed. Section IV focuses on the intricacies of the control circuit within the developed LoRaWAN-IoT-SSLS, elucidating its key functionalities and operational procedure. Section V presents a thorough discussion of the findings, encompassing both the results and their validation. Lastly, Section VI concludes the paper, summarising the study's significant contributions and implications.

3 Related works

The section's structure starts by first reviewing previous methods like the use of Zigbee for streetlight control, highlighting their limitations such as range and data speed. Then, discuss the use of Arduino in smart lighting systems, noting its popularity and ease of use. Following by including review of studies employing LDRs for light sensitivity and energy efficiency, followed by an examination of solar panels as a sustainable energy source. Finally, delve into the use of LoRaWAN in similar projects, pointing out its advantages in IoT applications, especially in smart street lighting. Conclude by contrasting these methods with our approach, underscoring how our system addresses the limitations of previous studies and contributes to the field.

Zigbee is a popular wireless communication technology used in various smart street lighting systems. It is known for its low power consumption and ability to form mesh networks. The use of Zigbee for streetlight control has been a popular choice in recent years due to its low cost, low power consumption, and two-way communication capabilities. However, there are some limitations to using Zigbee for streetlight control, such as:

- *Communication range*: Zigbee operates as a short-range wireless communication protocol, which restricts its effective coverage. This limitation poses challenges when deployed over large areas or in environments with physical obstructions that can disrupt signal transmission. [21].
- *Complexity and data speed*: Zigbee systems often involve intricate setup and configuration processes, and their data transmission rates may be inadequate for applications requiring high bandwidth, such as real-time monitoring or high-resolution video streaming [22].
- *Compatibility issues*: Although Zigbee is a well-established technology, it may not seamlessly integrate with all existing streetlight infrastructures or broader smart city systems. Such limitations can create integration difficulties and potential interoperability challenges [23].
- *Energy consumption*: While Zigbee is specifically designed to operate with low power requirements, it nonetheless contributes to overall energy usage through ongoing radio frequency (RF) signal transmissions and the periodic maintenance demands of connected devices. In large-scale deployments, especially in urban environments with dense sensor networks, these cumulative energy expenditures can become significant. Additionally, maintaining reliable network performance may require periodic recalibration or firmware updates, further contributing to operational power consumption over time [24].
- *Limited support for real-time monitoring*: Zigbee is fundamentally designed for wireless data exchange, but it often falls short in delivering the low-latency performance required for real-time monitoring and control in advanced smart street lighting applications [23].

While numerous studies have demonstrated successful implementations of Zigbee-based streetlight control systems—highlighting tangible benefits in energy savings and operational efficiency—these systems may struggle to meet the responsiveness and precision demanded by modern urban infrastructure. Therefore, despite its proven potential, it

is critical to carefully evaluate and address Zigbee's inherent limitations during the design and deployment phases to ensure that the system aligns with the specific operational and performance needs of the application.

The use of Arduino in smart lighting systems has gained popularity due to its ease of use and versatility. Several recent studies have demonstrated the effectiveness of Arduino in developing smart lighting solutions. For instance, a study focused on the design and optimization of a smart house lighting system using Arduino and LED rings/bands, which was controlled through a mobile application, showcasing the multidisciplinary nature of such projects [25]. Another study aimed to design a smart and green street lighting system (SGStreet-LS) using Arduino-based controllers with RF wireless communication support, enabling the efficient control of street lighting based on sunlight availability and motion detection, while also utilising low-power LEDs supplied from solar panels [5]. Additionally, a GSM-based Arduino controlled smart street illumination system was developed, allowing for remote controlling and illuminance logging, demonstrating the potential of Arduino in creating energy-efficient street lighting systems [26]. These studies highlight the versatility and ease of use of Arduino in developing smart lighting systems for various applications, including smart homes and street lighting. The use of Arduino enables the integration of different sensors and communication modules, making it a suitable platform for creating energy-efficient and environmentally friendly lighting solutions.

Several studies have employed LDR for light sensitivity and energy efficiency in smart lighting systems. For instance, a study proposed a smart and green street lighting system (SGStreet-LS) that utilised LDRs to detect lower levels of light intensity and PIR motion sensors to detect the presence of objects in the street, enabling efficient control of street lighting based on sunlight availability and motion detection [5]. Another study developed a GSM-based Arduino controlled smart street illumination system that utilised LDRs and PIR sensors to control street lighting based on ambient illuminance levels and motion detection, respectively [26]. These studies demonstrate the potential of LDRs in creating energy-efficient and environmentally friendly lighting solutions. By detecting the ambient light levels, LDRs can help reduce energy consumption by turning off or dimming the lights during daylight hours or when the ambient light levels are high. Additionally, by detecting motion, PIR sensors can help reduce energy consumption by turning off or dimming the lights when there is no movement in the street. Overall, the use of LDRs and PIR sensors in smart lighting systems can help reduce energy consumption and improve the sustainability of urban environments.

The use of LDRs in smart lighting systems has been a focus of several studies. LDRs are utilised to detect ambient light levels, enabling the automatic adjustment of lighting intensity to conserve energy and improve efficiency. For example, a study on smart street lights highlighted the use of LDRs for automatic intensity control, ensuring that the lights shine brightly during peak hours and gradually reducing their intensity during late-night hours to conserve energy [27]. Another study focused on smart and green street lighting system that employed LDRs to detect lower levels of light intensity, triggering the street lights to switch on, and PIR motion sensors to detect the presence of objects, ensuring efficient control of street lighting based on sunlight availability and motion detection [5]. Additionally, a study on a smart house lighting system utilised LDRs in combination with Arduino to create an intelligent lighting system, demonstrating the potential of LDRs in various lighting applications [25].

Furthermore, solar panels have been integrated into smart lighting systems to provide a sustainable energy source. In the context of smart streetlights, solar panels have been used to harness solar power through photovoltaic cells, enabling energy-efficient operation by automatically turning the lights on at dusk and off at dawn, while also allowing for intensity control through pulse width modulation. Another study focused on a smart and green street lighting system highlighted the use of solar panels to supply low-power LEDs, replacing conventional high-power lights, thus contributing to energy savings and the efficient utilization of renewable energy sources [5]. These studies demonstrate the potential of LDRs and solar panels in enhancing the energy efficiency and sustainability of smart lighting systems, making them valuable components in the development of environmentally friendly and cost-effective lighting solutions.

Table 1 reviews diverse research on smart street lighting systems, highlighting the integration of IoT and various technologies like LoRa, NB-IoT, and solar power for energy efficiency, automation, and multifunctional urban applications. Studies explore innovative solutions, including environmental monitoring, EV charging, and adaptive lighting based on traffic and ambient conditions. Key technological components range from sensors and communication modules to energy sources, emphasizing hardware and software synergies for performance enhancement. The research collectively demonstrates significant advancements in smart lighting's efficiency, safety, and sustainability, contributing to smarter, greener urban environments.

To provide a comprehensive background and illustrate the growing relevance of LoRa/LoRaWAN in diverse smart infrastructure applications, recent studies have explored its implementation across various domains, highlighting its adaptability, range, and efficiency. Our prior survey [15] underscored the crucial role of LPWAN technologies in supporting IoT applications, especially where long-range communication, low energy use, and cost efficiency are key. Among these, LoRa/LoRaWAN

Table 1 Overview of IoT-based smart street lighting systems

Refs.	Research focus	Technological components	IoT implementation	Multifunctional applications	Hardware and software aspects	Performance and efficiency
[28]	On IoT and LoRa (Long Range) technology in smart lampposts for smart cities	integrating multiple sensors, communication protocols, and energy distribution infrastructure in lampposts	explores IoT-assisted fog and edge-based architecture for smart lampposts	Environmental monitoring, EV charging ports, Wi-Fi hotspots	Lighting systems, environmental parameters, and image sensing	The study assesses the performance of the prototype in real-time scenarios
[29]	On the installation of smart metresin smart cities for monitoring streetlights (SLs), emphasizing the improvement of energy efficiency and operation of installations	The study discusses the development of three devices: Measure and Control Device for Street Lights (MCDSL), Lighting Level Measurement Device (LLMD), and Gateway LoRa Network (GWLN). These components are used to monitor electrical variables and lighting levels of streetlights	The paper addresses the energy crisis and environmental pollution by implementing new communication and control technologies to minimize electricity consumption in street lighting systems	Street lighting systems in smart cities	Based on the Arduino open-source electronic platform, along with the development of an algorithm (EESL) to enhance the energy efficiency of public lights using dynamic control based on the illumination level measured on the same set of streetlights	An Energy Efficiency for Street Lights (EESL) algorithm is developed, which dynamically adapts the luminous flux of streetlights based on the illumination level and pedestrian traffic, thereby optimizing electricity consumption
[30]	An IoT-based street lighting system powered by solar and piezoelectric sources. It focuses on energy conservation, automation, air quality monitoring, and the detection of faulty streetlights	The system incorporates solar panels, piezoelectric transducers, light-dependent resistor (LDR) sensors, infrared (IR) sensors, and voltage and current sensors for detecting faulty streetlights	The system uses IoT for smart maneuvering and monitoring of streetlights and air quality. It controls streetlights at different intensities based on the presence of vehicles and pedestrians, and sunlight. The ThingSpeak server is used for online monitoring and data analysis	Urban or city level focusing on the implementation and impact of the IoT-based smart street lighting system on energy conservation, automation, and air quality monitoring within a specific urban environment	The streetlights are smartly controlled using LDR and IR sensors, adjusting the intensity based on environmental conditions. For air quality monitoring, MQ135 sensors are deployed at every 6th streetlight, and data is analysed using the ThingSpeak server	The system is designed to conserve energy significantly (up to 84%) and enhance the lifetime of streetlights. It also provides an eco-friendly solution by reducing carbon footprints
[31]	Concerned with developing and implementing a smart street lighting control system using LED lamps and LoRa wireless communication. It aims to improve upon traditional street lighting systems that rely on timers or day/night sensors	The system utilises LED lamps for their energy efficiency, long lifetime, high reliability, and environmental friendliness. It is designed to control and monitor devices via wireless transmission frequencies below 1 GHz	The smart street lighting system integrates IoT technology, using LoRaWAN data transmission for its low power, long-range, anti-interference capability, and spread spectrum features. This facilitates seamless interoperability between smart devices and the Internet of Things	Effectiveness of the smart street lighting system using LoRaWAN data transmission technology in terms of real-time analytics, sensing, reduced energy costs, and connectivity to the Cloud, while maintaining urban safety and efficient operation and maintenance	The system is divided into stages, including LED lamps, LED drivers, RF nodes, gateways, and a control centre with data management. It features remote management software for real-time communication and control of the lighting system	The system allows for automated control tasks, such as dimming based on environmental sensors and power meters. This includes the ability to adjust light intensity based on the presence of people, enhancing both energy efficiency and safety

Table 1 (continued)

Refs.	Research focus	Technological components	IoT implementation	Multifunctional applications	Hardware and software aspects	Performance and efficiency
[32]	The study proposes a large-scale smart Street Lighting Control System using solar lampposts and LoRa technology. It aims to dynamically manage street lighting with full remote-control capabilities	The network employs a LoRaWAN star of star topology, consisting of end-devices (sensors), gateways, and a network server. It allows bidirectional communication and is optimised for low power consumption and long-range communication	The system uses IoT technology for interconnecting various devices and objects with communication technologies. It incorporates solar streetlights to enhance safety and reduce human intervention	Minimize energy costs without degrading the quality of lighting. The system automatically switches on or off based on sunlight and adjusts lighting intensity dynamically according to time, weather, movement, and lighting level	The implementation includes deployment of solar lampposts and evaluation of the LoRa network's performance. End-devices generate data every 30 min, which is sent to the network server	The study examines the impact of the number of gateways on network performance, including packet delivery ratio and energy consumption
[33]	To manage streetlighting in smart cities remotely using LoRa technology. It emphasizes the importance of streetlighting for city security and improving the quality of life, while addressing the high cost of energy for urban streetlighting	The proposed solution utilises intelligent street lighting with remote control capabilities. It involves replacing high-pressure sodium (HPS) lamps with energy-efficient LED lamps, potentially powered by solar energy panels		Reduce energy wastage and improve maintenance services. It uses adaptive lighting management to control the brightness of streetlights based on traffic intensity and environmental conditions, thereby saving energy	Includes LED light fixtures with embedded controllers, a LoRa gateway, a LoRa network server, a central unit, and a Graphical User Interface (GUI). The central unit collects data and delivers commands to adjust the brightness of LED light fixtures	LoRa technology is chosen for its low-power, long-range, wide-coverage capabilities, making it a cost-effective choice for smart city applications. It operates on an unlicensed frequency band and is deployed in a star topology

stood out for its open standard and autonomy, outperforming alternatives like NB-IoT and SigFox in device longevity, adaptive data rates, and scalability. Our review not only benchmarked LoRa/LoRaWAN against other LPWANs but also examined its core technical attributes, recent simulation tools, and key advancements aimed at enhancing energy efficiency, network capacity, and security—laying the groundwork for further research and implementation in smart city infrastructures. In [36] developed a LoRaWAN-based IoT system enabling low-cost, long-range communication, independent of existing cellular networks. Their prototype was tested in urban, rural, and mountainous areas, proving effective for remote connectivity and environmental resilience. In our previous work [37], we developed the LoRaWAN-IoT-AQMS, a smart sensing system designed to monitor key air quality indicators and update data in real time via the TTN platform, with seamless integration to web and mobile dashboards. The system demonstrated reliable outdoor performance, powered sustainably by a solar panel, and its accuracy was validated against industry-standard Aeroqual devices, confirming its effectiveness for continuous environmental monitoring.

Integrated LoRa into a campus safety system in Taiwan, showcasing its capability to link safety devices across large educational facilities. Their work confirmed reliable long-range communication and real-time alerts, critical for smart campus operations [38]. In another of our studies [39], we developed a LoRaWAN-based Flood Monitoring and Warning System (FMWS), designed to provide real-time flood level updates and early warnings through integrated IoT platforms like TagoIO and ThingSpeak. The system, powered by solar energy and validated in real-world deployments, demonstrated effective long-range data transmission and reliable performance, enabling timely alerts and proactive flood risk management. We further extended our research by developing the IoWT-HHMS [40], a wearable health monitoring system that leverages both Wi-Fi and LoRaWAN networks to track vital health parameters in real time. The system, validated across multiple testing scenarios, demonstrated high accuracy and reliable data transmission over long distances, highlighting the potential of LoRaWAN for scalable, remote healthcare monitoring in both urban and rural settings.

Smart street lighting is a growing field of research that aims to improve the quality and efficiency of urban illumination. Recent studies have explored the use of various technologies, including Zigbee wireless modules, Arduino microcontrollers, LDR, solar panels, LoRaWAN, LED lights, PIR sensors, and GPRS-based automation controllers. These technologies can be used to monitor and control street lighting, reduce energy consumption, and improve environmental sustainability. For example, LoRaWAN has been used in Indonesia to monitor and control street lighting [28], while solar panels have been used to provide renewable energy for street lights. LED lights have been shown to reduce energy consumption compared to conventional streetlights, and PIR sensors can be used to detect movement and control lighting accordingly. GPRS-based automation controllers can be used for remote monitoring and control of streetlights. Smart street lighting systems have the potential to significantly reduce energy consumption and improve the sustainability of urban environments.

Table 2 presents a comparative analysis of various studies on LED-based smart streetlighting technologies, emphasizing IoT integration, energy efficiency, and control methodologies. It showcases the use of Arduino and microcontrollers as the primary control units, solar power as the energy source, and a mix of auto-dimming, auto turn on/off features, and sensor-based operations for efficiency. LoRaWAN is highlighted for network topology in some studies, with real implementations and user interfaces ranging from LCD displays to web-based systems. Sensor usage includes PIR, LDR, and others for environmental monitoring and user interaction.

Our study advances the smart street lighting domain by integrating LoRaWAN for enhanced coverage and IoT for real-time monitoring and control. Unlike the limitations observed with Zigbee's short-range and complex setup, our system leverages LoRaWAN's long-range capabilities, overcoming large area communication challenges. Additionally, while Arduino-based systems demonstrate ease of use and flexibility, our approach further optimises energy consumption by incorporating solar panels and LED lighting, ensuring an environmentally friendly solution. Furthermore, the use of LDRs and PIR sensors in previous studies has been refined in our work to not only adjust lighting based on ambient light and motion but also to introduce a novel energy-saving mechanism through intelligent dimming and operational efficiency. This comprehensive integration addresses previous systems' energy, range, and complexity issues, marking a significant step towards sustainable and efficient urban lighting.

4 Design and fabrication of smart street lighting

4.1 Research methodology

The methodology adopted in this study encompasses a comprehensive approach to developing a fully functional smart street lighting system. The process begins with a critical review of existing systems to identify areas for improvement.

Table 2 Comparative study of LED streetlighting innovations featuring IoT, LoRaWAN, and energy-saving technologies

Study reference	Street light-ing technol-ogy	IoT Platform	LoRaWAN	Controller	Powered	Energy efficiency measures	Network topol-ogy	Control meth-odology	Sensors used	Real imple-mentation	User interface
[34]	LED	✓	✓	Arduino UNO	Solar	Auto-dimming and auto turn on/off	LoRa	Environmental monitoring sensors and a smart display	PIR and LDR		LCD Display
[5]	LEDs			Arduino Uno	Solar	Automatic switching based on LDR		Operates based on sensor detection	LDR and PIR	✓	
[27]	LED			Microcontroller	Solar	Auto-dimming features and turns on or off automatically at dusk and dawn		Motion detec-tion and ambient light levels	Infrared sensors (IR) and LDR	✓	
[35]	LED	✓	✓	Arduino Mega micro-controller, modules, and sensors	Solar		LoRa	Embedded sensors and actuators	Various sen-sors and modules are used, such as temperature, humidity, and voltage/cur-rent sensors	✓	web-based monitoring system
LoRaWAN-IoT-SSLS	LED	✓	✓	Arduino Uno	Solar	Automatic switching based on LDR and PIR	LoRa/LoRaWAN	Multi-sensors-based Auto-mation and localisation	PIR, LDR and GPS	✓	Web-dashboard and Mobile GUI

Following this, the project progresses through a series of structured phases as outlined in Fig. 1. Subsequent stages include the meticulous design and modelling of the smart lamppost unit, incorporating components such as LEDs, PIR and LDR sensors, GPS modules, and a control circuit.

Initially, the project undertakes the selection of components to establish a prototype, utilising software for design and modelling. A preliminary understanding of the system's principles is achieved before proceeding to the design phase of the control circuit. Simulation tests are conducted on the control system; if unsuccessful, redesign and retesting are performed to ensure functionality.

Once the control circuit proves successful in simulations, a breadboard test is conducted to confirm operational performance. Components of the actual prototype are then fabricated in a workshop setting, including implementation of the circuit. The system undergoes continuous enhancement and optimisation, particularly focusing on programming code development through rigorous testing. The refined circuit is subsequently soldered and assembled into a prototype model. Further testing evaluates system operation, troubleshooting any malfunctions to optimise performance and ensure the product meets the project's objectives. Upon satisfactory functioning, comprehensive analyses are undertaken, and the system's performance is methodically evaluated.

In the final stages, the development of the coding underpins the system's workflow, followed by the design and assembly of the sensor node enclosures. Multiple prototype nodes are then fabricated to form a smart testbed, gathering data on the street lighting conditions and relaying updates to the cloud. Verification and validation of the network are conducted, with improvements made as required to ensure the system's functionality and effectiveness. The testing phase is iterative until the system is ready for practical deployment. Upon demonstrating the system's effectiveness through the testbed, the final product is completed. A series of experiments on the final prototype commences, aiming to evaluate its performance comprehensively and analyse the data to articulate the key findings of the research.

4.2 System architecture

The proposed system unfolds an architecture that meticulously orchestrates component functionality to create an energy-efficient, intelligent street lighting solution as shown in Fig. 2. Solar panels, coupled with a solar charger shield, constitute the system's sustainable energy harvesting unit. This charger shield optimises the charging process, thereby extending the Li-ion battery's lifespan and ensuring responsible energy management.

Fig. 1 Flowchart of research activities
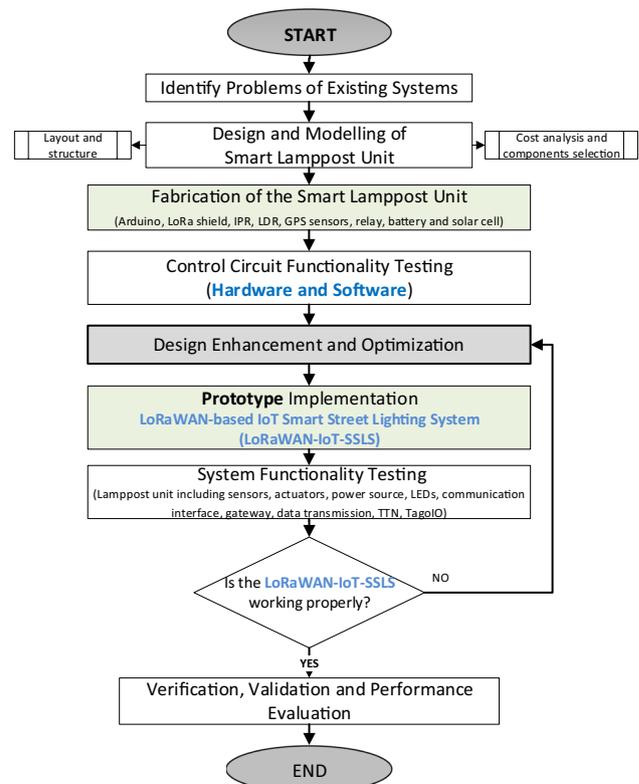
The core of the system's intelligent lighting control hinges on the PIR and LDR sensors. These sensors provide real-time inputs to an Arduino board, which in turn commands the relay—a crucial switching component—to toggle the LED lights on or off based on detected motion and ambient light levels. The inclusion of a GPS module within the LoRa shield enhances the system with precise location tracking capabilities for each streetlamp, adding a layer of spatial data critical for efficient monitoring and maintenance. Communication is pivotal within the system, achieved through the LoRa shield affixed to the Arduino UNO, which acts as a transmitter. This shield, endowed with GPS, not only facilitates the geolocation but also the transmission of sensor data to the LoRa gateway. Subsequently, data is relayed to The Things Network (TTN) server and stored in the cloud. The system allows users to access live data through the TTN server's internet interface. In addition to light intensity and motion, users can observe the geographic positioning of lamps. The TagoIO application serves as the user interface for system management, offering an intuitive platform for overseeing the smart street lighting system. This integration of solar energy, intelligent sensors, GPS tracking, and interactive applications showcases the system's holistic approach to smart city infrastructure, leveraging IoT to its fullest potential.

4.3 Components selection

The initiation of this project involves a strategic selection of components to establish the foundation for a prototype, which is subsequently modelled using sophisticated software tools. The chosen architecture for this system incorporates genuine, high-quality components to ensure reliability and functionality in real-world applications.

Central to the system's hardware is a LoRa shield, which facilitates communication between the sensors and the Arduino UNO microcontroller board. The LDR sensor plays a pivotal role in detecting ambient light levels, while the PIR sensor activates the LED lighting when motion is detected nearby, ensuring energy is conserved by only illuminating the streetlight as needed. Upon detection, the sensor signals are processed by the Arduino UNO and relayed via the LoRa shield. The subsequent action of the 5v relay activates the LED light. All collected data are transmitted to the Dragino LoRa Gateway, where they are consolidated and managed.

The hardware components selected for this project form a comprehensive suite designed to ensure robust functionality and efficiency in our smart street lighting system. The central processing unit is managed by an Arduino UNO, which orchestrates the system's operations. Motion detection is handled by a PIR Sensor, which activates lighting when movement is detected, while an LDR monitors ambient light levels to automatically adjust lighting conditions. Network communication is managed through a Dragino LoRa Gateway, with a Dragino LoRa/GPS Shield providing additional location tracking and data transmission capabilities. Energy harvesting is achieved via a monocrystalline solar panel, which powers the system in conjunction with a 5v relay for switching the LED light on or off, and an 18,650 Li-ion rechargeable battery ensures that the system remains powered. Additionally, a Solar Charger Shield v2.2 is used for efficient energy management. The lighting itself is provided by LED lights, known for their energy efficiency and durability.

Alongside the hardware, the project incorporates several software components essential for its development and operation. Proteus Simulations are utilised for testing and validating the circuit design, ensuring that all electronic components function correctly before physical assembly. Nx Modelling Software aids in the 3D modelling of the system,
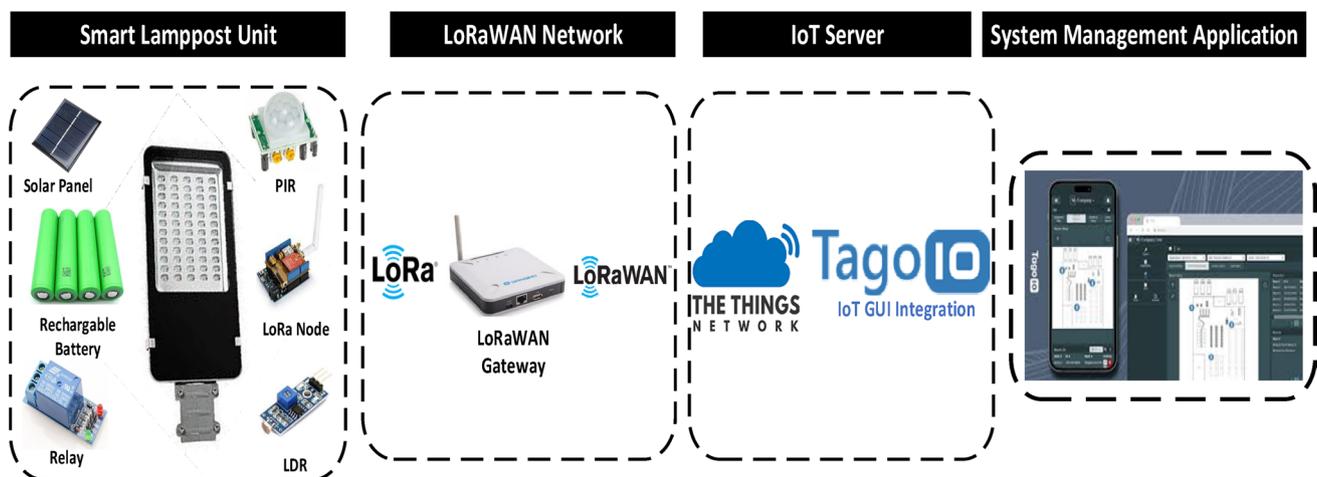

Fig. 2 Overall system architecture

allowing for precise and detailed construction of the hardware's physical structure. The programming of the Arduino UNO, which acts as the central processing unit of the system, is carried out using Arduino IDE Software, providing a versatile platform for coding the device's operational logic. Additionally, Fritzing Software is employed to create detailed wiring diagrams and PCB layouts, facilitating clear and accurate assembly and troubleshooting of the hardware setup. These software tools collectively enhance the design, simulation, and implementation processes, contributing to the system's overall functionality and efficiency.

Upon the meticulous selection and procurement of these components, the project moves into the design and fabrication phase, where each element is integrated to form a cohesive and functional prototype. This process encapsulates the synthesis of hardware and software, leading to a system that exemplifies innovation in smart street lighting technology.

4.4 ISPSL design

The design phase of Intelligent Solar-Powered Street Lamp is a critical step in product development. Our design process commenced with the use of 3D modelling software to prepare detailed digital representations of the device, facilitating the subsequent use of 3D printing for prototype creation. Utilising NX Modelling software, the design of the intelligent solar-powered streetlamp was conceptualized, focusing on modular components for ease of assembly and maintenance. The lamp design is showcased in Fig. 3, with all dimensions specified in millimetres.

The prototype's design is bifurcated into two primary sections: the upper and lower bodies. This segmentation is essential; the body must shield the internal components from environmental elements such as sunlight and water ingress. Additionally, this enclosure serves as a centralized repository for all mechanical parts, enhancing the maintainability of the system. Due to the limitations of the 3D printer's build volume, which is 200 mm × 200 mm × 200 mm, the body is constructed in two distinct segments for assembly post-printing.

The upper section of the body houses the PIR sensor and an LED light, as shown in Fig. 3. Conversely, the lower section, depicted in Fig. 4, accommodates the Arduino UNO, LoRa/GPS shield, LDR sensor, additional LED lights, batteries, and other mechanical elements. The design ensures all printed areas are oriented to face downwards to facilitate water runoff, while voids are positioned upwards to minimise material use and enhance structural integrity.

A solar panel is strategically positioned atop the prototype, functioning as a protective cover for the entire assembly, further detailed in Fig. 5. The solar panel not only prevents water penetration but also serves as the primary energy source for the system. The incorporation of a 'gate' design, illustrated in Fig. 5, provides a visual inspection point to verify the proper placement and security of components when the system is sealed by the solar panel. Lastly, the design includes a dedicated PIR sensor holder integrated into the upper body's circular section, ensuring optimal sensor function and protection. The holder's design and placement are highlighted in Fig. 6. Accompanying these figures, the documentation includes tabulated information delineating the key components and their respective designs, providing a clear blueprint for the intelligent solar-powered streetlamp's physical construction.

Upon the completion of the body design of ISPSL, the next crucial element is the mounting mechanism—termed a 'handler'—which secures the prototype to a street pole, as depicted in Fig. 7. The design of this handler is paramount, taking into account the shape of the pole, as well as gravitational and tensional forces, along with local weather conditions. Given that street poles in Malaysia typically have a cylindrical form, the mounting design incorporates a circular clamp equipped with screws to counteract gravitational forces securely. The interface between the prototype and the clamp also considers tension and gravitational forces. To enhance the durability and stability of the mount, we use a steel bracket positioned vertically. This design choice not only increases the handling strength over a smaller contact area but also accounts for Malaysia's tropical climate, which is characterised by rain rather than snow. The

Fig. 3 Upper part design of prototype. **A** This is a space for placing LED light. **B** This screw hole is for screw and holds the lower part together. **C** This circular design space is used to place the PIR sensor with a handle. Besides that, the small gaps on the circular design provide the PIR sensor to become adjustable in angle
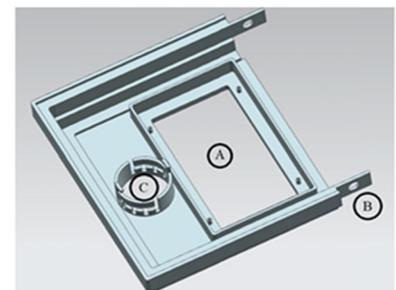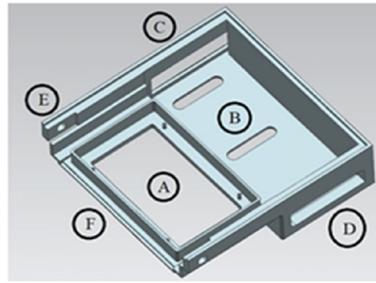
Fig. 4 Lower part design of prototype. **A** This is a space for placing LED light. **B** A space to store almost all the components and batteries. There are three long shape gaps which face downward are used to dissipate the heat. **C** An empty space to install a gate. **D** An empty space to let the antenna of Lora/GPS shield and LED sensor explore outside. **E** This screw hole is for screw and holds the upper part together. **F** A ladder shape design is used to prevent the upper part back fall and also become more stable when upper part and lower part is combining together

Fig. 5 Gate
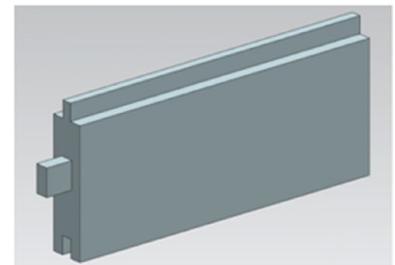
Fig. 6 PIR sensor holder. **A** A hole for 5 mm of screw which can provide tension force to the circular design. **B** These screw holes is for screw and hold the three pieces together and also link with three pieces. **C** A part that screw PIR sensor together which can turn along X-axis
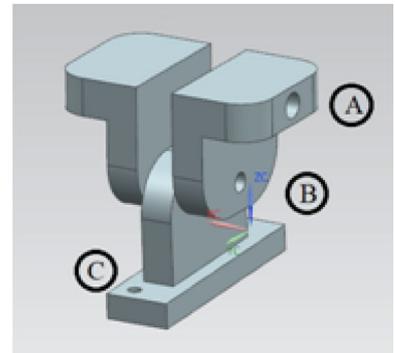
Fig. 7 The clamp. **A** Parts connect with body. Dimension (length, width, height) mm: 160×40×5. **B** Part connects with part A and part C. Dimension (length, width, height) mm: 65×40×5. **C** Circular Part. Dimension (length, width, height) mm: 320×40×5
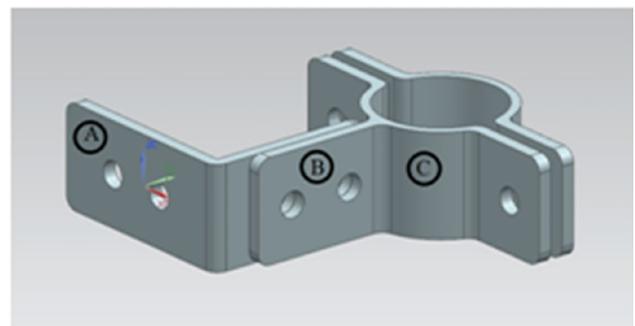
vertical orientation of the connector is advantageous in that it minimises the surface area, thereby reducing the likelihood of rain accumulation that could potentially add to the load. Figure 8 illustrates the complete assembly design, encompassing the entire body of the streetlamp coupled with its mounting clamp. The top of the assembly

is seamlessly integrated with a solar panel, which forms a protective covering. This design not only ensures the efficient harvesting of solar energy to power the lamp but also shields the internal components from environmental elements. The strategic placement of the solar panel serves a dual function, acting as a sustainable power source while also contributing to the overall robustness and weather resistance of the unit.

4.5 ISPSL fabrication

The assembly and fabrication of the ISPSL are complex processes that combine precision engineering with meticulous craftsmanship. The procedure begins with the preparation of detailed shop drawings that specify exact dimensions for each component. Following the planning stage, the actual assembly takes place, culminating in the installation of the final product.

Material selection was approached with a focus on functionality, ease of fabrication, and cost-effectiveness during the prototyping phase. Polylactic Acid (PLA) was selected for 3D printing the lamp's body components, gate, and PIR holder because of its good printability, dimensional accuracy, and sufficient mechanical strength for short-term experimental use. PLA offered a practical balance of affordability and ease of handling, enabling rapid fabrication of intricate designs required for the prototype. However, we acknowledge that PLA, being biodegradable and sensitive to prolonged UV exposure and environmental factors, is not optimal for long-term outdoor deployment. For real-world applications, more durable materials such as ABS, PETG, or weather-resistant composites would be recommended to ensure robustness and longevity in diverse environmental conditions. The use of 3D printing in this project nonetheless provided substantial advantages during development, including reduced costs, time efficiency, and the ability to produce complex geometries with precision.

In fabricating the clamp, stainless steel of 5 mm thickness was utilised for its superior resistance to corrosion from air and water exposure. This ensures the clamp's durability, even in adverse weather conditions. The production involved a series of machine operations, including cutting, pressing, grinding, sanding, and welding, to shape and refine the stainless-steel parts.

Sanding was particularly crucial in smoothing the surface of the cut steel, removing any imperfections resulting from the cutting process. The bending of various components required specific tools and techniques. A flat surface bronze-head hammer was employed for precision bending, maintaining a perfect surface even under significant force. The pressing machine allowed for the creation of a perfect circular shape to match the typical diameter of street light poles.

The assembly of the stainless-steel parts involved drilling precise holes for mounting and attachment. A hand drill machine was used in conjunction with a table clamp to ensure accurate placement of these holes. Following the shaping and hole-making processes, the parts were meticulously prepped for welding by sanding and cleaning with acetone to eliminate contaminants. Welding fused the components securely, with careful attention to cooling times and post-welding cleanup to ensure a smooth finish. Lastly, the application of red paint provided a protective coating, enhancing the clamp's lifespan and completing the fabrication process.

The completion of this streetlamp represents not just the physical assembly of parts but the embodiment of an innovative approach to sustainable urban lighting, integrating advanced materials and fabrication techniques to create a robust, eco-friendly product ready for deployment in the smart cities of the future. Figure 9 illustrates the streetlight fabrication process, showcasing the array of tools and techniques employed in the construction of the intelligent solar-powered streetlamp.

Fig. 8 Complete assembly of ISPSL unit with clamping mechanism, topped by a solar panel
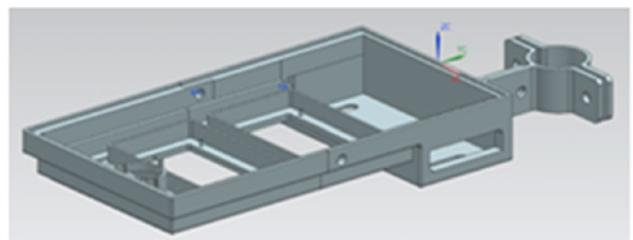
5 System development and implementation

5.1 System design

The design of the LoRaWAN-IoT-SSLS seamlessly integrates the innovative components and fabrication techniques outlined in the ISPSL design and fabrication sub-sections. Utilising the advanced design principles and materials selected for the ISPSL, this system harnesses solar energy through strategically positioned solar panels, which convert sunlight into electrical power stored in a Li-ion battery. This battery energises the microcontrollers and the relay, which are central to the operation of the LED lighting.

Key to this system is the PIR and LDR sensors, whose roles in detecting human presence and ambient light intensity, respectively, were solidified during the ISPSL's design phase. The information captured by these sensors is processed by an Arduino board, detailed in the fabrication subsection, which determines the optimal lighting conditions and actuates the LED lights accordingly.

The inclusion of the Dragino LoRa/GPS Shield, a decision born out of the component selection and design stages, extends the Arduino's functionality to enable long-range communication via LoRa and precise geolocation tracking. This shield ensures that data from the sensors are transmitted efficiently to the LoRa gateway for processing and storage.

Fig. 9 ISPSL fabrication process and tools used

(a) PLA Filament

(b) 3D Printer

(c) Cutting Machine

(d) Sanding Machine

(e) Pressing Machine

(f) Stick Welding Machine

In configuring the LoRaWAN network, critical transmission parameters were set to ensure compliance with regional duty cycle regulations and to optimise system performance. The LoRa module was configured with a bandwidth of 125 kHz, a spreading factor (SF) of 7, a coding rate of 4/5 and a transmission power output of 14 dBm. The LoRaWAN-IoT-SSLS system transmits a 10-byte payload in each packet to encapsulate the essential sensor readings and system states. The payload is structured as follows: bytes 0–2 carry the latitude data (24-bit), bytes 3–5 contain the longitude data (24-bit), bytes 6–7 encode the light intensity ("darkness") as a 16-bit value, and bytes 8–9 represent the motion detection and lamppost status, respectively, each as 8-bit values. This compact format ensures efficient data transmission within LoRaWAN's limited packet size, enabling real-time updates of geolocation, environmental conditions, and system status. The payload is unpacked at the server side to reconstruct full sensor readings and device location for remote monitoring. These settings provide a balanced trade-off between communication range, reliability, and data rate, suitable for the urban environment of our deployment. The time on air (ToA) for each transmitted data packet, which includes light intensity, motion status, and GPS coordinates, was approximately 56 ms. To maintain compliance with the 1% duty cycle regulation, the system was programmed to transmit data every 5 min, allowing for 12 transmissions per hour and approximately 288 transmissions per day per node. This configuration ensures efficient, reliable, and regulation-compliant operation while providing near real-time monitoring and control of the smart street lighting system.

Accessible operational data, such as light intensity and detected motion, is made available to users through TTN server cloud. System monitoring and management are further enhanced by the TagoIO app, a tool introduced as part of the holistic system development to provide a comprehensive overview of the ISPSL's performance.

Electrical connections, meticulously planned in the design phase, ensure that the PIR sensor, relay, and LDR sensor are appropriately powered and linked to the Arduino, allowing for the intelligent control of the LED lights based on the environmental data collected. This strategy emphasizes the seamless integration of the ISPSL design principles into the broader LoRaWAN-IoT-SSLS architecture.

The system's energy autonomy is guaranteed by the solar panel, a feature underscored in the ISPSL fabrication process, confirming the project's commitment to sustainability and efficiency. This approach not only demonstrates the continuity between the ISPSL design and fabrication efforts and the comprehensive LoRaWAN-IoT-SSLS but also highlights the project's innovative contribution to smart urban infrastructure development.

The circuit diagram depicted in Fig. 10 has been designed using Fritzing Software, which provides a visual representation of the physical connections between various electronic components. At the heart of the circuit is a microcontroller board, which is interfaced with a relay module to control an external LED light source. It is worth noting that the current system utilises a relay for ON/OFF switching of the LED lamp, without implementing dynamic dimming. While this effectively demonstrates automated control, future enhancements could integrate protocols such as DALI or PWM dimming to allow for more precise luminous flux regulation, enabling advanced adaptive lighting capabilities.

The microcontroller also connects to a pair of sensors: a PIR motion sensor and an LDR for ambient light detection. The PIR sensor's output is linked to one of the microcontroller's digital input pins, allowing it to trigger a response when motion is detected. Similarly, the LDR is connected to an analogue input pin to measure light intensity. This setup enables the microcontroller to make decisions about when to activate the LED light based on sensors readings, thus demonstrating an intelligent light control system. The relay acts as a switch, toggling the LED light in response to the microcontroller's signals. The diagram shows a clear layout of power connections, groundings, and signal pathways that are essential for the functioning of this smart lighting system.

Fig. 10 LoRaWAN-IoT-SSLS control circuit
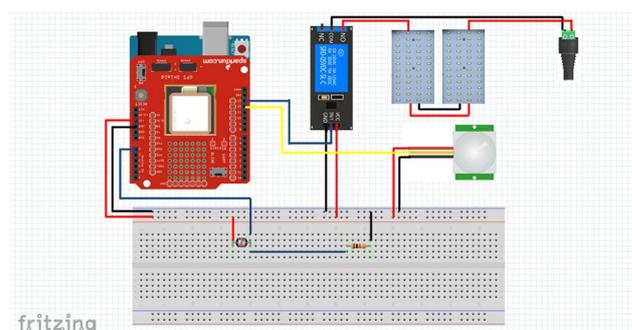
5.2 System implementation

The core contribution of this research is the development and real-time implementation of the LoRaWAN-IoT-SSLS, an innovative and market-ready street lighting solution that enables remote and continuous monitoring and control of street light operation. The system leverages light intensity and motion detection data, accessible via the internet at any time and from any location.

LoRa technology is selected for its long-range, low-power, and cost-effective connectivity, which is optimal for the expansive reach of urban street lighting networks. Its high network capacity, capable of supporting up to a thousand end-nodes per gateway, and the global interoperability assured by the standardization of LoRaWAN, are also key factors in its adoption. Critical to the functioning of the system are sensors such as LDRs for light sensing and PIRs for motion detection. The Dragino LoRa/GPS Shield is integrated for location tracking of each streetlight, enhancing the system's ability to deliver location-specific lighting solutions. Preliminary testing of individual sensors and actuators is carried out on a breadboard, ensuring their performance before moving on to the final system assembly.

The LoRaWAN-IoT-SSLS is designed with the intention of reducing energy consumption and lowering maintenance costs. Its simplicity is one of its greatest advantages, requiring only a few essential components and straightforward wiring for implementation. The use of connectors facilitates a plug-and-play approach, as illustrated in Fig. 11, which demonstrates the microcontroller interacting seamlessly with sensors and the relay within the system.

Post-assembly, the IoT-Enabled Smart Street Lighting System is installed within a lamppost prototype and subjected to further testing to evaluate hardware performance. The system undergoes continuous refinement to rectify any errors, ensuring it operates flawlessly as intended. On the software front, code is developed to enable monitoring and control functions of the street lighting system. This code supports the use of The Things Network and TagoIO, with the latter offering a smartphone-compatible interface. These platforms display real-time data from the sensors, allowing for comprehensive monitoring and responsive lighting management that aligns with smart city goals.

5.3 Functionality testing and enhancement

The hardware system of the LoRaWAN-IoT-SSLS prototype is subject to rigorous functionality testing to ensure it performs to the highest standard. This phase is critical for enhancing system performance and identifying any errors. Through an iterative process, issues detected in previous stages are addressed and resolved, which is vital for the progressive optimisation of the system.

For instance, LED bulbs are initially employed as stand-ins for actuators during early testing to confirm sensor operation. Post-programming, the full suite of actuators, including buzzers and relay modules, are introduced for comprehensive breadboard testing. All connections are meticulously examined using a multimeter, with wires carefully marked

Fig. 11 LoRaWAN-IoT-SSLS prototype control circuit

Fig. 12 Integration of sensors and actuators on the breadboard for system testing
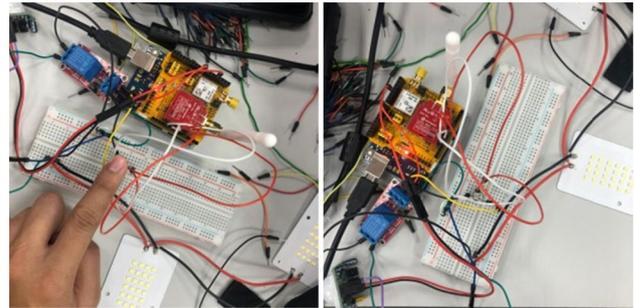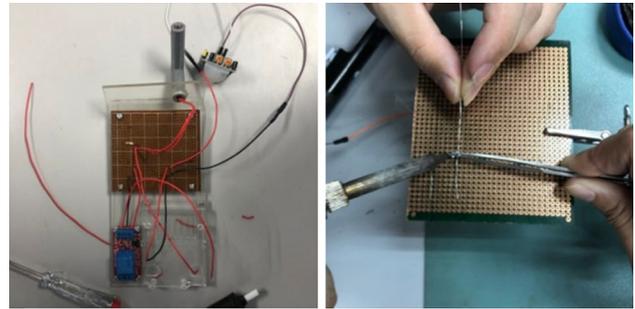

Fig. 13 Soldering process of sensors and actuators onto the donut board

and labelled to aid in the clear identification of each part of the system's circuitry. Moreover, for enhanced safety and organisation, all wires are insulated and neatly bundled with protective black tape.

Prior to assembly, individual testing of each component is mandatory, employing multimeter set to correct ranges and the Arduino UNO to validate functionality. This involves ensuring each channel is properly powered and grounded while monitoring the Serial Monitor output for consistency.

Following the establishment of all connections, troubleshooting is undertaken to iron out any issues, solidifying the foundation for a fully operational LoRaWAN-IoT-SSLS prototype. As detailed in Fig. 12, the initial system testing phase involved the integration of sensors and actuators on the breadboard, which was crucial for evaluating the circuit functionality prior to final implementation.

Following the refinement and optimisation phase, essential components were methodically soldered onto a donut board. Figure 13 illustrates the meticulous soldering of sensors and actuators onto the donut board, a key step in assembling the durable and reliable hardware for the LoRaWAN-IoT-SSLS prototype. For modular flexibility and ease of maintenance, female headers were soldered to accommodate the microcontroller, allowing for its straightforward removal and replacement if necessary. To enable the PIR and LDR sensors to accurately record ambient measurements from outside the board, extensions were created from the microcontroller pins using female headers.

Each connection on the donut board was meticulously crafted. The female header pins of the microcontroller were connected to the corresponding extended pins, and every junction was subsequently tested with a digital multimeter. This step was crucial to confirm electrical continuity and to avoid any potential short circuits between pins.

The soldering process was executed with precision, with careful attention to avoid any unintended contact with the donut board that might result in damage. Wires were arranged neatly to facilitate easy identification and troubleshooting of any future issues. This attention to detail in the soldering phase is integral to the reliability and longevity of the LoRaWAN-IoT-SSLS prototype, ensuring that each component maintains a secure and functional connection within the system.

5.4 System operational procedure

Streetlights typically operate for 12 h each night, often emitting full brightness unnecessarily during periods of low pedestrian and vehicular traffic. To enhance efficiency and conserve energy, a smart control system incorporating Light Dependent Resistors (LDR) and Passive Infrared (PIR) sensors has been developed. This system dynamically adjusts the illumination of streetlights based on the ambient light intensity and detected motion, turning them on or off as needed. The system harnesses solar energy using photovoltaic panels to generate electricity, which is stored in

rechargeable batteries that power the LED lights after dusk. The LDR measures ambient light levels, communicating this data to an Arduino microcontroller. If the LDR detects low light levels—below a user-defined threshold (settable between 0 and 1023, with a typical nighttime setting of 500)—the Arduino activates the streetlights via relays. Conversely, if the ambient light exceeds the threshold, indicating daylight, the LEDs remain off.

Additionally, the PIR sensor detects movement, enabling the streetlights to respond adaptively by illuminating when vehicles or pedestrians are present and turning off shortly after they pass, further reducing energy consumption. The system's LoRa shield transmits real-time data to a LoRa gateway, which then updates the operational status and sensor readings to an IoT cloud platform, The Things Network. This data can be accessed remotely via the TagoIO server on various smart devices, including PCs, laptops, and smartphones, allowing for remote monitoring and management of the street lighting system. This integrated approach not only significantly reduces energy waste but also enhances the adaptability and responsiveness of urban street lighting, representing a considerable advancement in smart city technology.

The latency of the system from motion detection to the LED activation was also tested. On average, the system demonstrated a switching response time of approximately 300 ms, which is considered satisfactory for real-time street lighting applications. Energy consumption of the system was measured to estimate its operational efficiency. The Arduino UNO and LoRa shield together consume approximately 70–80 mA during active transmission, while the LED lighting draws about 120 mA when illuminated. During idle conditions, the system's current draw drops to below 20 mA. The solar panel (5W) and 18,650 Li-ion battery (3.7V, 2600mAh) were sufficient to power the system continuously during outdoor testing, confirming its viability for self-sustained operation (Fig. 14). Although no calibrated luminance sensor was used, the LDR was programmed to respond at an empirically derived threshold corresponding to approximately 500 lx. This threshold was used to distinguish between day and night conditions for lighting control purposes (Table 3).
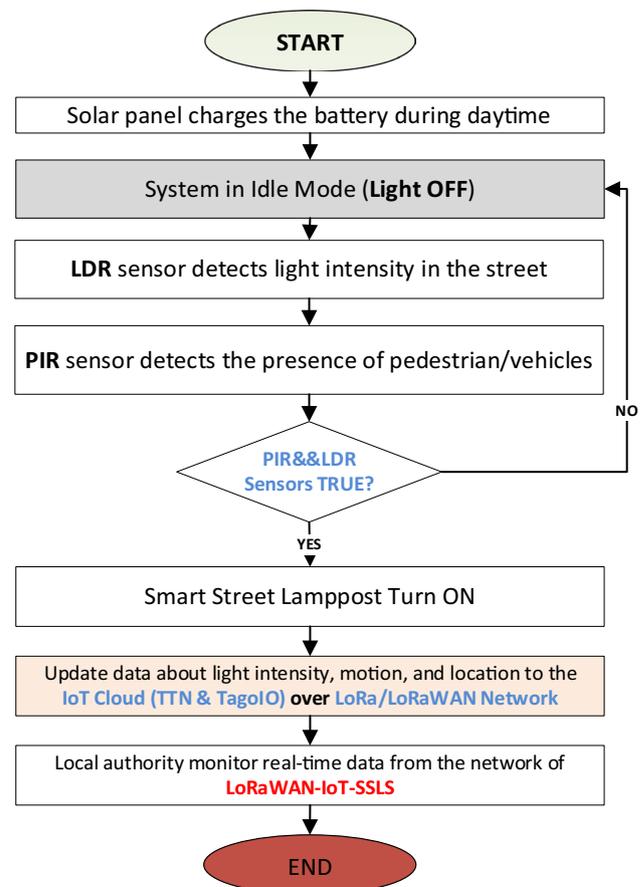
Fig. 14 System operation flowchart

Table 3 Comparative analysis of LED street lighting response based on IoT and LoRaWAN technologies

	Light intensity detected by LDR sensor	Motion detected by PIR sensor	Condition of LED
1	More than 500 lx	LOW	OFF
2	More than 500 lx	HIGH	OFF
3	Less than 500 lx	LOW	OFF
4	Less than 500 lx	HIGH	ON

Algorithm 1 Smart Street Lighting System based on LoRaWAN

```
Require: Activate street lighting based on ambient light and motion during
nighttime
Ensure: Real-time environmental monitoring using light intensity and motion
sensors.
1: Install LoRaWAN Gateway & connect to the Internet
2: Register the Gateway in the TTN Console (GW ID, Frequency Plan, router, GW
key)
3: Create LoRaWAN-IoT-SSLS Application in the TTN Console (App. ID, App. EUI,
TTN-Handler)
4: Register LoRa Node under LoRaWAN-IoT-SSLS Application (Dev. ID, Dev. EUI,
App Key, App EUI)
5: Define Device Activation Method (ABP)
6: Get Network Session Key & App Session Key & Device Address
7: Define Libraries for multi-sensor smart LoRa node & TTN
8: Define LoRa-Node pin mapping ➲ For sensors & LoRa connection
9: Set LoRa configuration parameters
10: L ← Light intensity value ➲ LDR sensor
11: M← Motion value ➲ PIR Sensor
12: C ← GPS coordinate value ➲ GPS sensor
13: Initialize oT-SSLS-LoRaWAN ➲ System Powered ON at t = 0
14: for each round do
15:   Get L, M, C
16:   if L < 500 lux then:
17:     if M is true (motion detected)
18:       Switch ON lights (activate relay)
19:     else
20:       Switch OFF lights (deactivate relay)
21:   else
22:     Maintain current light state
23: Establish a connection between LoRa Node & LoRaWAN GW
24: Update status of the node in TTN Server (online)
25: Send data to LoRaWAN GW
26: Upload data to TTN Server over the Internet
27: Decode the received Payloads to retrieve original sensors readings
28: Integrate data into TagoIO Web-based dashboard
29: Synchronize data with TagoIO mobile App. using Smartphone
30: Authority Monitor lighting status and location in real-time
31: END
```

6 Results and validation

The LoRaWAN-IoT-SSLS, now fully operational, represents the culmination of its design, fabrication, and testing phases, as illustrated in the accompanying figures. Programmed via the Arduino IDE, the system dynamically adjusts street lighting based on real-time input from the LDR and PIR sensors, ensuring responsiveness to specific environmental conditions.

The validation phase focuses on confirming the accuracy, responsiveness, and reliability of the data collected by the SSLS. As illustrated in Fig. 15, the system activates under predefined conditions, utilising both LDR and PIR sensors to manage lighting intelligently. Sensor data is transmitted in real time through the LoRaWAN gateway to The Things Network (TTN), enabling remote monitoring and instantaneous updates. This architecture ensures that lighting levels adjust automatically based on detected light intensity and motion, optimising both illumination quality and energy efficiency.

The following sections detail the system's performance across various operational scenarios, highlighting its effectiveness under different combinations of light and motion conditions.

Fig. 15 Sensor-driven lighting control scenarios: **a** Morning time with no motion (Lighting OFF), **b** Morning time with motion (Lighting OFF), **c** Night time with no motion (Lighting OFF), **d** Night time with motion (Lighting ON)
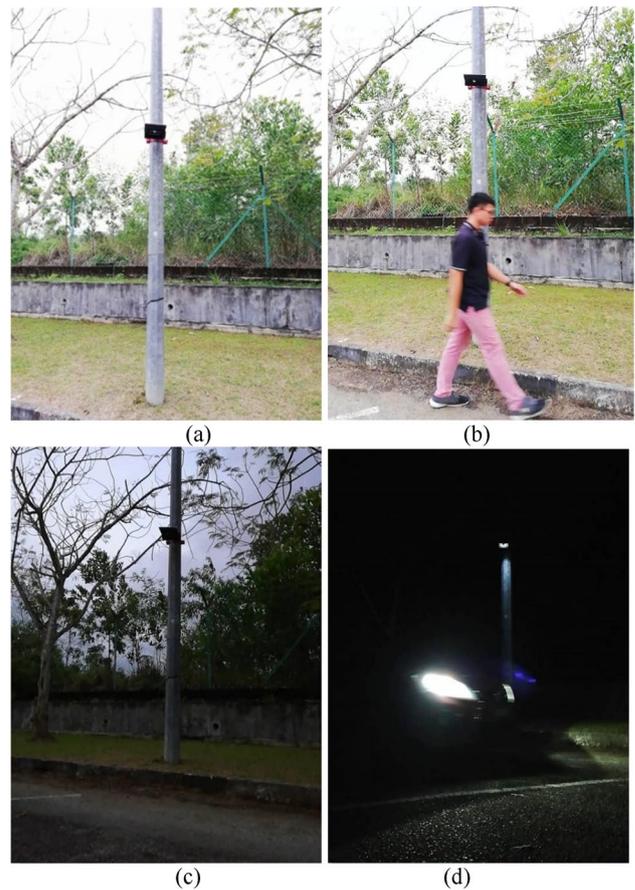
First scenario: During high light conditions (over 500 lx, indicative of daytime) with no detected motion, the system conservatively keeps the streetlight off to save energy, as shown in Fig. 15a.

Second scenario: Similarly, when motion is detected under high light conditions, the system determines no need for artificial lighting, maintaining the streetlight in the off-position Fig. 15b.

Third scenario: In scenarios where, ambient light is low (below 500 lx, typical of nighttime) and no motion is detected, the streetlight remains off, optimising energy use Fig. 15c.

Fourth scenario: Importantly, in scenarios with low ambient light and detected motion, such as a vehicle passing, the streetlight is activated to enhance safety and visibility. Following the detection of motion, the light remains on for an additional 10 s before automatically shutting off to conserve energy, as shown in Fig. 15d. This 10-s duration is used for testing purposes and can be adjusted according to street activity levels, which may vary between urban, suburban, and rural environments.

6.1 Advanced data monitoring and system management

The LoRaWAN-IoT-SSLS system's connectivity framework utilises The Things Network (TTN) to transmit sensor data, including light intensity, motion detection, and, critically, GPS coordinates captured by the integrated GPS sensor within each streetlamp. This data is channelled through the Dragino LoRa Shield to a LoRaWAN gateway, enabling dynamic, real-time monitoring and control. The incorporation of GPS data provides precise geolocation of each lamp post, which is invaluable for streamlined maintenance, asset tracking, and operational management. Additionally, the TagoIO platform is employed to enhance data visualisation and user interaction, offering an intuitive interface for monitoring and analysing system performance remotely.

Figure 16 details TagoIO's user interface, accessible via https://tago.io/, which facilitates comprehensive device management, data storage, analytics, and service integration within a user-friendly application environment. This sophisticated management system allows city officials and maintenance teams to access real-time information and control the street lighting infrastructure efficiently from any smart device, significantly enhancing urban lighting solutions and

Fig. 16 User interface using TagoIO

contributing to the smart city paradigm. In addition to these indicators, TagoIO maps out the GPS coordinates of each streetlight, offering a geographical overlay that shows real-time locations and statuses. This geolocation feature is further supported by live data streams showing latitude and longitude, and a clock marking data receipt times. Detailed transmission metrics such as frequency and signal-to-noise ratios are crucial for understanding and optimizing the communication range of the LoRa Shield.

Light Intensity and Motion: Visual indicators on TagoIO include a light bulb icon that shifts from red to blue based on the time of day, and a car icon that toggles between blue and red depending on motion activity.

Lamppost Status: Represented by a moon icon that switches from black to yellow based on the lamp's operational state.

Figures 17 and 18 illustrate the dynamic data visualisation capabilities of the TagoIO platform for the IoT-Enabled Smart Street Lighting System. These figures demonstrate how the system interprets and responds to varying environmental conditions, specifically variations in light intensity and motion detection.

Figure 17 (High Light Intensity, No Motion Detected): This scenario, shown in the first screenshot, records a light intensity of 966 lx—well above the predefined threshold for daytime operation. As expected, no motion is detected, and the streetlight remains off to conserve energy. The light bulb icon appears in red, indicating high ambient light levels, while the car icon is also red, confirming no detected motion. The lamppost icon stays black, signifying that the streetlight is inactive, demonstrating the system's appropriate response under high-light, no-motion conditions.

Fig. 17 Condition when high intensity but no motion
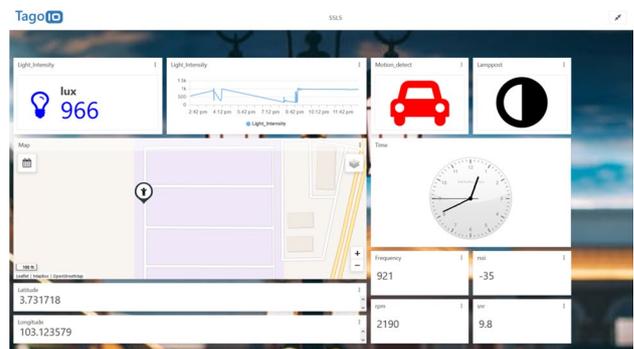

Fig. 18 Condition when high intensity and motion detected
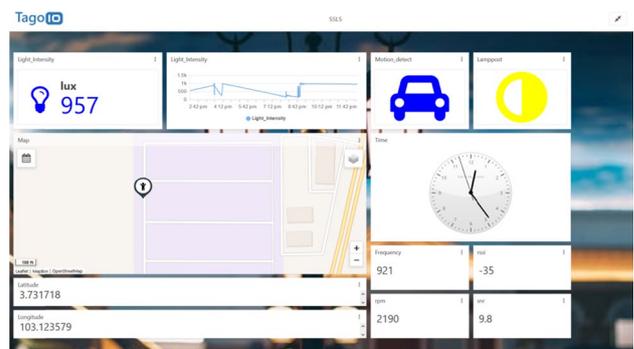
Figure 18 (High Light Intensity, Motion Detected): In this scenario, the light intensity is measured at 957 lx, confirming daytime conditions. Simultaneously, motion is detected, as indicated by the blue car icon on the dashboard. According to the system's programmed logic, despite the high ambient light levels, the detection of motion triggers a conditional response, activating the streetlight (lamp icon switches to yellow). This behaviour, while generally conservative for energy saving, is designed to provide additional illumination during unusual or unexpected motion events, enhancing safety and visibility in cases where heightened awareness is beneficial—such as during adverse weather conditions or in zones with mixed pedestrian and vehicular traffic.

Both figures provide a comprehensive demonstration of the system's responsiveness, displaying not only the dynamic status of light intensity and motion detection but also the GPS coordinates for precise geolocation of each streetlamp. Additionally, real-time timestamps ensure accurate data logging, which is essential for operational tracking and auditability. This detailed information equips urban administrators with actionable insights to monitor, manage, and optimise the street lighting network effectively, thereby enhancing energy efficiency and public safety. The TagoIO interface, coupled with its seamless synchronisation to mobile applications, offers an intuitive and accessible platform for real-time system supervision and control, making it well-suited for scalable deployment in smart city environments.

6.2 LoRa/LoRaWAN connectivity analysis

In this sub-section, we examine the connectivity and communication quality between the LoRa node of our Intelligent Solar-Powered Street Lighting System and the centrally installed LoRaWAN gateway on the university campus. The primary focus is on how the Signal-to-Noise Ratio (SNR) and Received Signal Strength Indicator (RSSI) vary with distances ranging from 200 to 1000 m. To realistically simulate varied urban street configurations, SSLS nodes were installed at increasing distances up to 1 km from the nearest LoRaWAN gateway. Over a 12-h testing period, RSSI and SNR values were logged and averaged to assess the system under different traffic patterns and environmental conditions, including peak hours and late-night scenarios. The values were extracted as real-time instantaneous readings from both The Things Network and the TagoIO dashboard at each measurement point. Given that the current testing was limited to a single node in a controlled setup focused on point-to-point performance validation, the results are presented as averaged values rather than full statistical distributions. This approach was deemed sufficient for demonstrating baseline feasibility. However, we acknowledge that future large-scale deployments will benefit from more extensive statistical analyses, including distribution evaluations, to further validate system robustness across broader conditions.

Figure 19 illustrates that the SNR values begin at approximately 10 dB at a distance of 200 metresand gradually decline to around 3.5 dB at 1000 m. This trend confirms the expected degradation in signal quality with increasing distance, affecting the system's ability to effectively separate the transmitted signal from background noise. Notably, the communication remained reliable throughout the tested range of up to 1000 m, although further distances may necessitate advanced error correction protocols to preserve data integrity. It is important to mention that these results were obtained using an indoor LoRaWAN gateway, which likely contributed to the observed attenuation; deploying outdoor gateways could further optimise performance.

Figure 20 shows the RSSI values decreasing from approximately − 35 dBm at 200 metresto − 95.3 dBm at 1000 m, reflecting significant signal attenuation due to environmental factors, urban obstructions, and the inherent characteristics of RF propagation. As the RSSI nears the receiver's sensitivity threshold, the potential for packet loss increases, underscoring the importance of network enhancements such as increasing transmission power, optimising antenna placement, and deploying additional gateways to maintain robust connectivity across larger urban areas.

Overall, the connectivity analysis underscores the critical role of SNR and RSSI metrics in evaluating LoRaWAN network performance within urban environments. These findings demonstrate the current system's capability to maintain stable

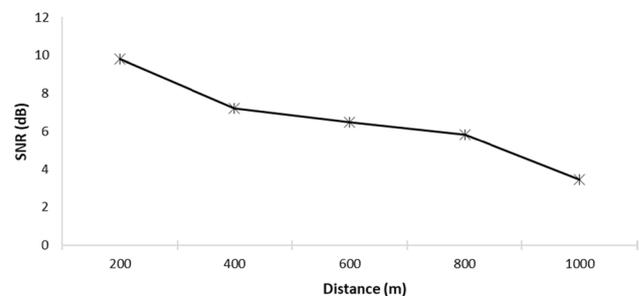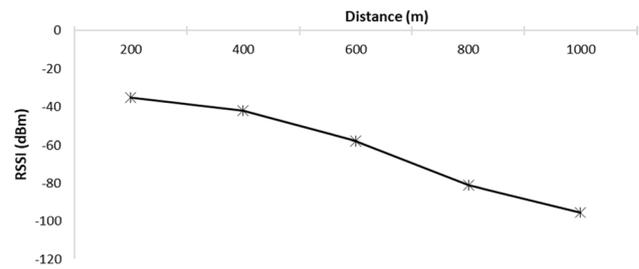**Fig. 19** SNR vs. Distance for a single ISPSL node

Fig. 20 RSSI vs. Distance for a single ISPSL node

operation within a 1 km radius and offer practical insights for optimising network configuration. This ensures that smart street lighting systems remain reliable and efficient, even under challenging urban conditions, thus supporting the broader objectives of smart city infrastructure for sustainable and resilient urban development.

It is important to note that the current implementation involved testing a single ISPSL node at distances up to 1000 m from the LoRaWAN gateway. Across these tests, we observed a 100% packet delivery ratio (PDR) with no packet loss detected within this range. Therefore, packet loss ratio (PLR) analysis was not prioritised for this specific deployment scenario. However, we acknowledge that in larger-scale deployments involving multiple nodes and longer-term monitoring, PLR is a critical performance indicator. We plan to incorporate comprehensive PLR evaluations in future studies to further validate the system's robustness and scalability.

6.3 Enhancements for practical implementation

The findings from our connectivity analysis of the ISPSL prototype deployed at the university campus provide crucial insights into the communication capabilities and constraints of the system. The need for a robust connection between the LoRa nodes integrated within streetlamps and the centrally located LoRaWAN gateway is evident, especially to enable real-time monitoring and control of the lighting system. These insights are instrumental in informing decisions on the strategic placement of streetlamps relative to the gateway and may prompt adjustments in the network configuration to optimise both performance and reliability.

To effectively address the challenges identified for full-scale urban deployment of our system, we propose several strategic enhancements. Firstly, the implementation of outdoor LoRaWAN gateways is anticipated to significantly improve SNR and RSSI. By situating gateways outdoors, we can reduce obstructions and minimize the distance that signals need to travel, thereby enhancing both the reliability and quality of network communications. Secondly, to ensure comprehensive coverage and maintain network integrity, it is advisable to increase the density of gateways across the urban landscape. Deploying multiple gateways would provide overlapping coverage and create a redundancy system, safeguarding against connectivity issues that might arise with any single gateway. These enhancements are crucial for supporting the robust, city-wide deployment of the intelligent street lighting system.

As the deployment of the ISPSL expands to encompass a broader array of urban settings, several critical factors need to be addressed to ensure scalability and operational efficiency. Firstly, network design plays a crucial role as effective data transmission across an increasingly extensive network of streetlamps necessitates meticulous planning to ensure optimal distribution of gateways. This is essential for maintaining consistent communication across the network. Secondly, data management capabilities must be enhanced to manage the growing volumes of data generated by multiple ISPSL units. A robust backend infrastructure is vital for efficient system monitoring and management, ensuring that data can be processed and acted upon in real time. Additionally, antenna and frequency configuration require careful optimization to adapt to the unique challenges presented by complex urban topographies, where signal propagation may be hindered by buildings and other structures. Lastly, the environmental adaptability of the system's components is paramount. The ISPSL must be engineered to withstand a variety of environmental conditions, ensuring reliable and consistent operation across diverse weather scenarios. By addressing these considerations, the ISPSL can be effectively scaled up, enhancing urban infrastructure with a reliable, efficient, and adaptive lighting solution.

The preliminary tests have laid a foundational understanding of the network's operational capabilities and limitations. By incorporating these enhancements and continuously monitoring system performance, the ISPSL is poised for effective scaling and broader urban implementation. This strategic approach not only improves the reliability and efficiency of the street lighting system but also integrates seamlessly into the broader smart city infrastructure, enhancing energy management and improving urban living conditions.

While the proposed LoRaWAN-IoT-SSLS system demonstrates promising results in terms of energy efficiency, scalability, and real-time monitoring, several limitations must be acknowledged. First, the current prototype uses PLA for the lamp housing, which, despite its initial suitability for prototyping, is not optimal for long-term outdoor exposure without protective coatings. Second, the system's performance is constrained by the placement and density of LoRaWAN gateways; signal strength and reliability may degrade in highly obstructed or densely built environments. Third, the testing was conducted within a university campus with a limited number of deployed units, which may not fully represent the complexities of large-scale urban deployments. Additionally, while GPS integration allows for precise location tracking, signal acquisition can be affected by extreme weather conditions or dense urban canopies. Future work will focus on enhancing material durability, expanding large-scale field trials, and integrating advanced algorithms for predictive maintenance and further optimisation of network performance.

7 Conclusions and future work

In conclusion, the IoT-Enabled Smart Street Lighting System presented in this paper represents a sustainable and energy-efficient approach to urban lighting, harnessing the power of LEDs and solar panels. The integration of these technologies not only contributes significantly to reducing energy consumption compared to traditional street lighting—but also offers enhanced longevity and environmentally friendly attributes associated with LED lighting. LEDs do not emit heat or contain toxic materials and are capable of quick switching, making them ideal for dynamic street lighting systems. A critical advancement in this project is the development of a new control and monitoring system utilizing LoRa wireless technology, which supports long-range communication up to 15 km. This feature allows for the remote monitoring of streetlights through the IoT platform, the TTN, which facilitates real-time data access and system management without the need for physical inspection. Furthermore, the integration of the TagoIO interface enhances user interaction, providing a convenient platform for accessing system data on both computers and mobile devices, thus ensuring operational flexibility and ease of monitoring.

The system's automation is driven by advanced sensor technologies, including light-dependent sensors and passive infrared motion sensors. These sensors automatically adjust lighting based on detected ambient light levels and movement, thereby optimizing energy use and reducing operational costs. The light-dependent sensor effectively measures light intensity to control the lamp post's activation and deactivation in response to natural light conditions, while the motion sensor enhances safety and energy efficiency by responding to movement in its vicinity.

Looking ahead, there are several areas where further research and development could augment the capabilities of the ISPSL:

- Enhanced Sensor Integration: Exploring the integration of additional environmental sensors, such as weather or pollution sensors, could provide more data-driven insights to optimise lighting conditions further and contribute to broader smart city initiatives.
- Machine Learning Algorithms: Implementing machine learning algorithms could enable predictive maintenance and adaptive lighting control based on user behaviours and environmental changes, increasing the system's efficiency and responsiveness.
- Scalability Tests: More extensive testing across multiple urban environments would help refine the system's scalability and effectiveness, ensuring its adaptability to different geographic and climatic conditions.
- Energy Storage Solutions: Investigating more advanced energy storage solutions could enhance the efficiency and reliability of the solar-powered supply system, particularly in regions with less consistent sunlight.
- Incorporation of detailed Packet Loss Ratio (PLR) analysis in future multi-node deployments to evaluate network reliability and identify areas for optimisation under large-scale and high-traffic scenarios.
- Integration of advanced dimming control protocols (e.g., DALI or PWM) to enable dynamic regulation of luminous flux, allowing more adaptive and energy-efficient street lighting compared to the current ON/OFF relay-based control.

By continuing to develop and refine these elements, the ISPSL can play a pivotal role in shaping the future of urban lighting, driving forward the integration of smart technologies into everyday infrastructure to create more sustainable, efficient, and adaptable urban environments.

Data availability The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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