International Journal of Innovative Research and Scientific Studies, 8(6) 2025, pages: 1596-1611

IJIRSS
International Journal of Innovative Research & Scientific Studies

ISSN: 2617-6548

URL: www.ijirss.com

IoT-based intelligent modular LED lighting with redundancy and decentralized control for smart industrial and urban applications

Mukhtar Junisbekov[1], Murat Kunelbayev[2], Dmitriy Grigoryev[3], Kairat Sakan[4*] Yerbol Turgynbekov[5]

[1,5]Taraz University named after M.Kh. Dulaty, Taraz 080000, Kazakhstan.
[2,4]Institute of Information and Computational Technologies, Al-Farabi Kazakh National University, Almaty 050010, Kazakhstan.
[3]Kazakh National Technical University (Satbayev University), Almaty 050010, Kazakhstan.

Corresponding author: Kairat Sakan (*Email: 19kairat78@gmail.com*)

Abstract

This paper introduces the design and implementation of an intelligent, modular Light Emitting Diode (LED) lighting system for industrial and municipal applications, leveraging modern computer science methods and the Internet of Things (IoT). The system features power redundancy, decentralized control, and native support for Power Line Communication (PLC) and the Digital Addressable Lighting Interface (DALI) to ensure high reliability, low latency, and energy efficiency. We detail a robust communication and data transmission architecture together with sensor-driven control algorithms that enable context-aware dimming, occupancy-based scheduling, and continuous self-tuning to reduce consumption while maintaining lighting quality. Simulation studies and laboratory prototypes demonstrate marked performance gains: Mean Time Between Failures (MTBF) increases by more than 60%, reaching up to 65,000 hours, and energy savings reach approximately 30% relative to conventional deployments. The modular design facilitates phased rollouts and retrofits, while built-in monitoring, diagnostics, and predictive maintenance analytics improve lifecycle management and reduce downtime. The proposed approach aligns with smart-city initiatives and Industry 4.0 automation, providing interoperable management, centralized orchestration, and fine-grained control across heterogeneous facilities.

Keywords: DALI, Emergency power supply, Energy efficiency, Intelligent control, IoT, LED lighting, Modular architecture, Off-grid PLC, Redundancy.

DOI: 10.53894/ijirss.v8i6.9963
Funding: The research work was funded by the Ministry of Science and Higher Education of Kazakhstan and carried out within the framework of the project (Grant Number: AP19679604) “Intelligent Street lighting - optimized common system of controlled autonomous LED lamps with highly efficient and durable electronic control mechanism” at the Taraz University named after M.Kh. Dulaty.
History: Received: 24 June 2025 / **Revised:** 29 July 2025 / **Accepted:** 31 July 2025 / **Published:** 18 September 2025

Competing Interests: The authors declare that they have no competing interests.
Authors’ Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.
Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.
Publisher: Innovative Research Publishing

1. Introduction

Modern industrial and urban lighting systems face a number of serious challenges: limited power of standard luminaires (for example, a typical GRATZ power supply is designed for 350 mA), lack of modularity, centralized control with the risk of losing the entire line if one element fails, as well as high costs for infrastructure upgrades. In the context of growing demands for energy efficiency, reliability, and intelligence, there is a need for new solutions that can reduce operating costs and increase security. The Internet of Things (IoT) is a modern concept of digital technologies that has been developing rapidly in recent years. IoT covers a vast ecosystem of devices and objects that can independently collect, analyze, and transmit data over the network without user intervention [1, 2]. These smart devices, from industrial sensors to urban environments, open up opportunities for automation, energy optimization, and greener cities. The key idea behind the IoT is to integrate data using embedded computing resources, enabling a wide range of practical applications, from smart manufacturing [3] and smart homes [4, 5], transportation [6] to environmental monitoring [7] and urban services [8-10]. The versatility and scalability of the IoT enable the development of new approaches to resource management, including intelligent lighting [11]. Intelligent lighting systems use modern technologies to rationally manage energy consumption, increase public safety, and improve the urban environment. Key features include energy efficiency achieved through the use of sensors and actuators to automatically adjust brightness depending on the level of illumination and traffic intensity; increased security through the integration of threat detectors; and the acquisition and analysis of data for strategic urban planning. The structure of such systems includes street lamps with sensors, actuators, and communication devices. The sensors record movement, illumination levels, and possible risks, and actuators regulate the lamps' operating modes based on this data. Communication modules provide connection to the control center, allowing for remote monitoring and centralized lighting control. Over the past decade, various reviews [10, 12-16] have analyzed current challenges and technical solutions in the field of intelligent street lighting, taking into account different technological platforms and approaches. In particular, the integration of light sensors, LiDAR, and IoT modules enables the implementation of adaptive control and real-time monitoring [17] which enhances the efficiency and cost-effectiveness of operation. Despite the obvious advantages, the implementation of intelligent lighting solutions is associated with problems: high maintenance and energy costs, difficulties in centralized control, and issues of data reliability from a large number of sensors. To eliminate uncertainties and inaccuracies, it is proposed to use fuzzy logic methods [18-22] which allows for the effective processing of vague and incomplete information when making decisions on lighting control modes. Thus, IoT systems are characterized by flexibility, scalability, and self-organization. They have the ability to interact and integrate, and support intelligent data exchange between heterogeneous devices [23, 24]. However, their widespread use is accompanied by challenges in the areas of cybersecurity, energy efficiency, big data processing, and protocol standardization [25, 26]. IoT applications span a wide range of areas, from smart homes to transportation and urban infrastructure, opening up opportunities to create efficient and interconnected ecosystems. The mass adoption of connected devices requires new approaches to data analysis and storage to enable rapid decision-making and improve quality of life.

This study examines convective heat transfer in flat-plate solar collectors using circular and flat channels under forced and natural convection. Correlations for the Nusselt number were obtained, showing accurate prediction of heat transfer for different fluids. The influence of the Prandtl number was also analyzed, with all cases exhibiting a slope of 1/3, as the study was limited to laminar flow [27].

The system being developed in the work solves the specified problems by implementing a modular architecture, fast backup, and intelligent control algorithms, as well as support for modern PLC and DALI communication standards.

2. Research Methodology

The study was conducted on the basis of creating a prototype of an intelligent modular street LED lighting system with backup functions, emergency power supply, and decentralized control via PLC and DALI protocols. The main element is an autonomous lighting system, including a control board, batteries, three LED modules connected by wires, and a protected housing (see Figure 1). For some of the experiments, lanterns with a solar panel made of anodized aluminum alloy were used, which ensures durability in outdoor conditions. All components were installed on a laboratory stand for initial testing, with the possibility of subsequent installation on real outdoor objects.

Figure 1.
The device of an autonomous street lighting system on solar batteries with a motion sensor (PIR sensor).

In Figure 1 a device consisting of a control board, batteries, three LED modules (LED lamp) connected by wires, and a protective case for outdoor installation. Such equipment is used to check the power supply circuit, charge the battery from the solar panel, and operate the lamps depending on the motion sensor signal. The complex is tested on the desktop before final installation outdoors, which confirms the practical implementation of the system described in the diagram.

Figure 2.
Lantern with solar panel made of aluminum alloy AD31.

Figure 2 shows a solar panel lantern made of aluminum alloy AD31. The body of this street lantern with a solar panel is made of anodized aluminum alloy AD31. This material provides high corrosion resistance, lightweight construction, and durability in outdoor conditions. Due to anodizing, the surface of the body has additional protection from atmospheric influences and mechanical damage, which significantly increases the service life of the device and maintains its aesthetic appearance even with prolonged use.

The proposed system operates as follows (Figure 3). Industrial controller 1 receives signals from motion sensor 2 and current sensor 3, analyzes the presence of motion and the state of LED sections 4. Depending on the time of day and the presence of movement, the system automatically switches on the required number of LED sections to ensure the required level of lighting and energy savings. The power source is selected automatically using switch 7 between the power grid 5 and the solar battery 6, which ensures uninterrupted operation of the system. All operating parameters and alarm signals are transmitted via the Ethernet interface 10 to the SCADA system 8 and the HMI panel 9, where monitoring, control, and archiving of events are carried out.

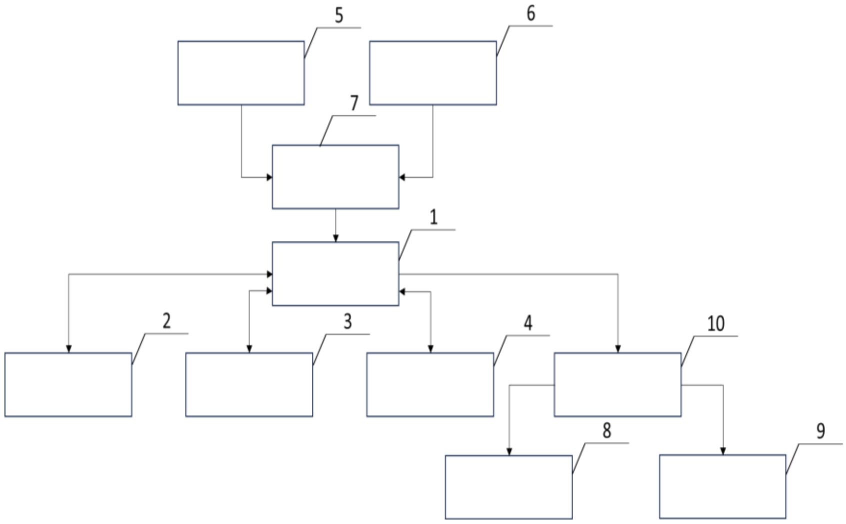

Figure 3.
Intelligent street LED lighting system.

The proposed system is designed to be scalable for citywide implementation. The SCADA/HMI and industrial controller architecture support the addition of an unlimited number of street lights, which are automatically integrated into the centralized control and monitoring network. Support for new types of sensors (illumination, weather conditions, etc.) is implemented by expanding the controller software and does not require significant hardware upgrades. For integration into the smart city ecosystem, the system can exchange data with other city services via standard protocols (Modbus, OPC, MQTT, etc.), ensuring joint operation with video surveillance, dispatching, urban transport, and energy-saving systems. This approach facilitates the gradual expansion of functionality and adaptation of the system to future requirements of the city infrastructure. Computer modeling is a fundamental tool for the design, analysis, and optimization of complex technical systems. In this work, simulation techniques are used to evaluate the performance and interactions of the proposed system components under various operating scenarios.

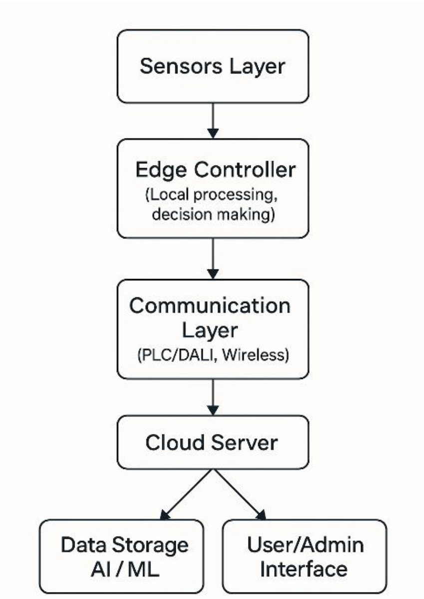

Figure 4.
IoT architecture for intelligent systems.

Figure 4 presents a diagram illustrating a typical IoT architecture for intelligent systems. Data from various physical sensors is first collected in the Sensors Layer, then processed locally at the Edge Controller, where initial decisions can be made. Communication between system components is handled by the Communication Layer, supporting both wired (PLC/DALI) and wireless protocols. All processed information is sent to the Cloud Server, where it can be stored, analyzed using AI/ML tools, and accessed by users or administrators through a dedicated interface. This structure ensures flexible, scalable, and intelligent management of distributed sensor networks.

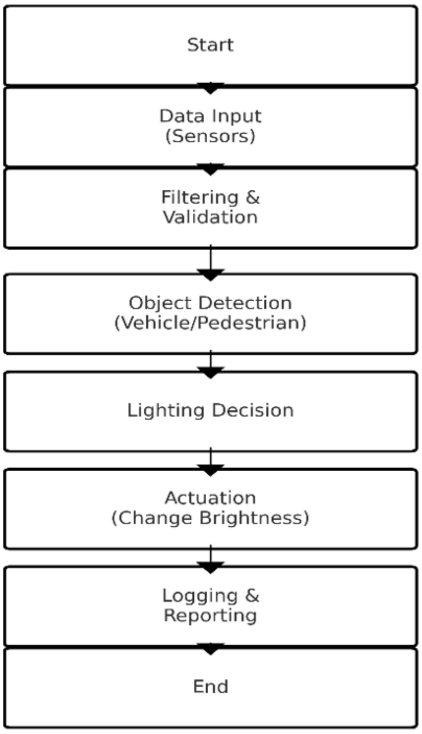

Figure 5.
A flowchart of the intelligent street lighting control algorithm.

Figure 5 presents a flowchart of the intelligent street lighting control algorithm. The system begins by collecting data from motion and light sensors, followed by filtering and validation to eliminate noise and errors. Next, the algorithm performs object detection to distinguish between vehicles and pedestrians, after which a decision is made regarding the appropriate brightness level, and a control command is sent to the luminaires. Finally, the system logs events and generates reports for the monitoring platform, ensuring adaptive and energy-efficient lighting operation.

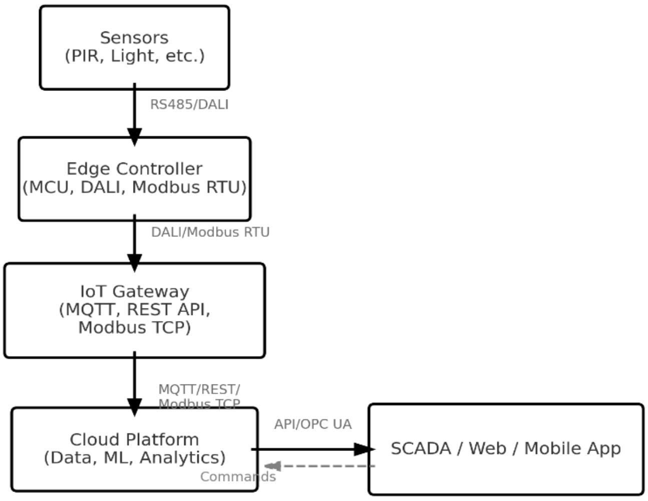

Figure 6.
The structural architecture of an IoT-based intelligent lighting solution.

Figure 6 presents the structural architecture of an IoT-based intelligent lighting solution. Data from motion and light sensors is transmitted to the edge controller via wired protocols (RS485, DALI), then processed and forwarded through the IoT gateway using MQTT, REST API, or Modbus TCP to the cloud platform. In the cloud, data is stored, analyzed, and processed with machine learning and advanced analytics. System control and monitoring are performed via SCADA, web, or mobile applications, which receive data directly from the cloud through API or OPC UA. Feedback commands from the SCADA system are sent back to the IoT gateway, enabling two-way communication and centralized management of the lighting system.

The system in Figure 7 implements an electronic ballast unit (EBU) with an output of up to 1400 mA, which allows the use of more powerful and efficient LEDs. Due to the modular architecture, the supply current can be flexibly configured, for example, 4×350 mA for distributed luminaires or 2×700/1×1400 mA for high-power floodlights in demand at railway stations, airports, industrial complexes, and city parks. Such modularity allows the system to be quickly adapted to different tasks, simplifies replacement, and increases luminous flux.

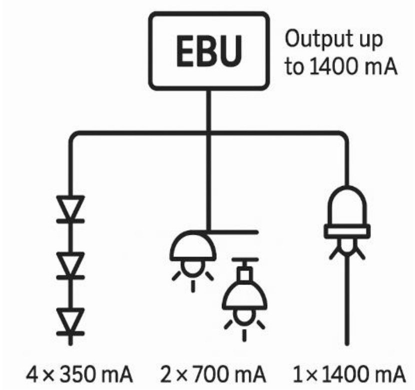

Figure 7.
Electronic ballast unit (EBU) with output up to 1400 mA.

Figure 8 shows a power supply unit that is compactly integrated into the mast base or luminaire housing (including wall-mounted versions), provides an efficiency of at least 95%, and its multilayer design ensures durability and ease of maintenance. The housing and internal components are protected according to the IP67 standard, using varnish, silicone, or epoxy coatings. Copper elements and a cast aluminum housing with passive chimney cooling are used for effective heat dissipation, which is critical for high-power luminaires and dense installation of diodes.

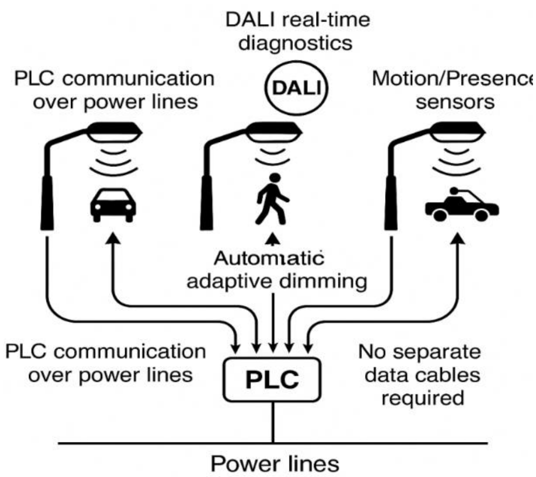

Figure 8.
Power supply.

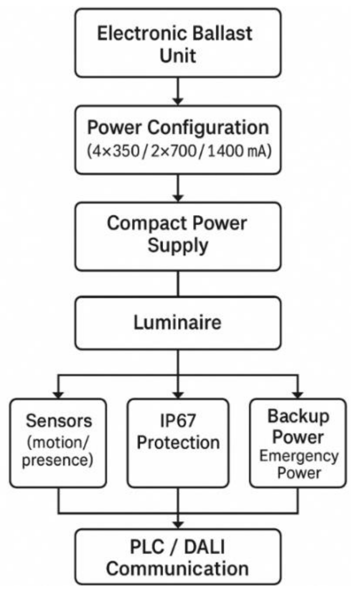

Figure 9.
Architecture of an intelligent LED lighting system for industrial and municipal facilities.

Figure 9 shows the architecture of an intelligent LED lighting system for industrial and municipal facilities. Control starts with the Electronic Ballast Unit, which distributes the current between the lighting modules in different modes

(4×350, 2×700, or 1×1400 mA) via the Power Configuration unit. Power is supplied via a compact source, and each luminaire is equipped with motion and presence sensors, a backup power supply system, and IP67 protection. All elements are connected via PLC/DALI communication, which ensures centralized and decentralized control, high reliability, and adaptability of the system.

Figure 10 shows decentralized control using PLC (Power Line Communication), which allows communication between luminaires via existing power cables; no separate data lines are required, significantly reducing implementation costs. Integration of the DALI protocol provides monitoring, diagnostics, and adjustment of lighting in real time. Intelligent control is based on motion and presence sensors: lamps are automatically switched on only when there is traffic or when needed; effective dimming is implemented depending on external conditions (for example, night duty lighting or reaction only to transport/pedestrians, and not to animals or weather events). This approach provides savings of up to 30% of electricity and extends the service life of the equipment.

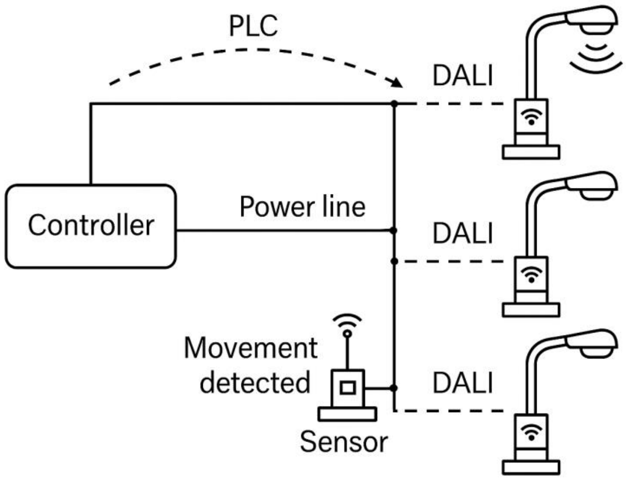

Figure 10.
Decentralized control using PLC (Power Line Communication).

The intelligent lighting system automatically reduces brightness at night, saving up to 30% of electricity. Due to motion sensors, brightness increases only when vehicles or pedestrians appear, and the rest of the time the system operates in economy mode—this provides up to 20% additional savings. Centralized monitoring via the DALI protocol ensures rapid detection of faults, reducing response time from 24 hours to 1 hour and increasing operational reliability.

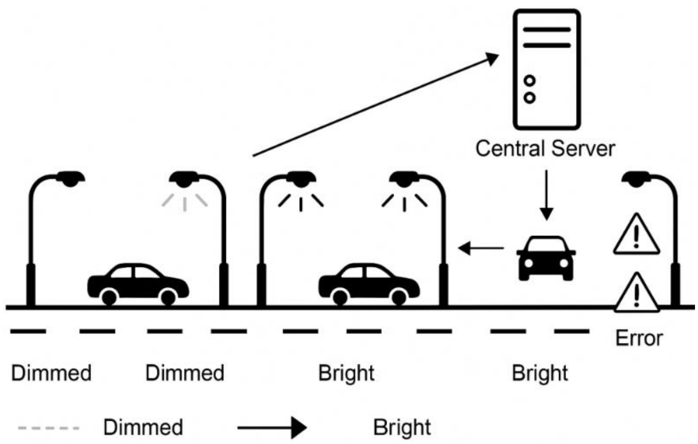

Figure 11.
The intelligent lighting system dynamically adapts the operating mode of the lamps depending on the situation outside.

Figure 11 shows how the intelligent lighting system dynamically adapts the operating mode of the lamps depending on the situation outside. At night, most lamps operate in a reduced brightness mode, which saves energy. When a car or pedestrian appears, the nearest lamps automatically switch to maximum brightness mode, ensuring safe illumination of the area. If one of the lamps fails, the system instantly sends a signal about the malfunction to the central server, which allows for quick response to any problems and minimizes equipment downtime.

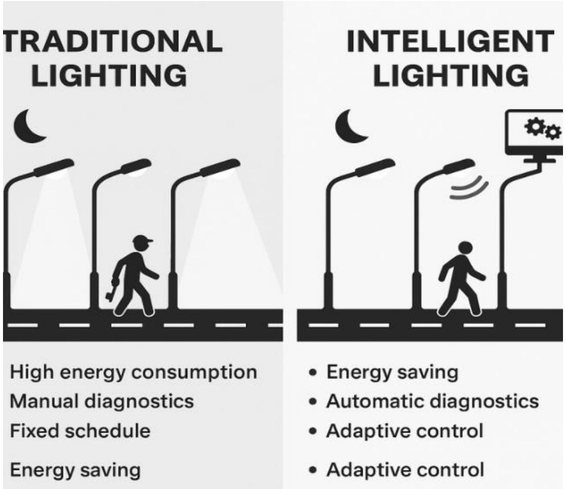

Figure 12.
Comparison diagram between traditional and intelligent street lighting systems.

Figure 12 shows the key differences between a traditional and smart street lighting system. In a traditional system, all lights operate at full brightness, do not use sensors, and require manual diagnostics, resulting in high energy consumption and delays in troubleshooting. An intelligent system, on the contrary, regulates the brightness of each lamp depending on traffic and surrounding conditions, uses motion sensors, and automatically transmits information about the status of the lamps to the central server. This approach ensures energy saving, prompt diagnostics, and adaptive lighting control.

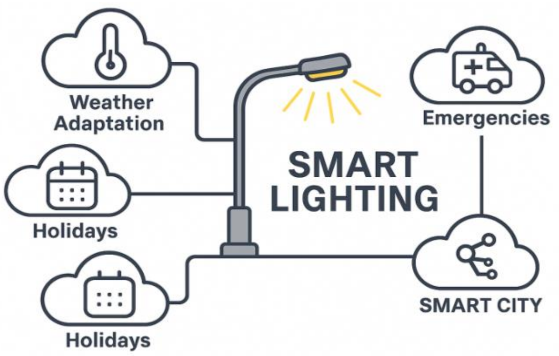

Figure 13.
The intelligent street lighting system is integrated with various city services within the framework of the “smart city” concept.

Figure 13 shows how the intelligent street lighting system integrates with various city services within the smart city concept. The central lighting system receives data from weather services, event management services, emergency services, traffic monitoring systems, video surveillance, and the city’s IoT platform. Due to this integration, the system can automatically change lighting modes depending on weather conditions, events, emergency situations, or changes in traffic flow, ensuring maximum energy efficiency, safety, and flexibility in managing urban infrastructure.

For industrial applications and critical facilities, an innovative fast backup scheme is provided: in the event of failure of one of the power modules, the backup board immediately takes over the load a switching time is less than 10 ms, which completely eliminates the occurrence of "dark zones." The emergency power supply system (on batteries or supercapacitors) automatically maintains a minimum illumination level (10-20%) for 2-3 hours when the network is disconnected, which is especially important for ensuring public safety and work in emergency situations. Mechanical strength, protection against burglary and theft are implemented at the level of the case and electronic opening sensors. IP67 protection is maintained even during long-term operation in adverse climatic conditions.

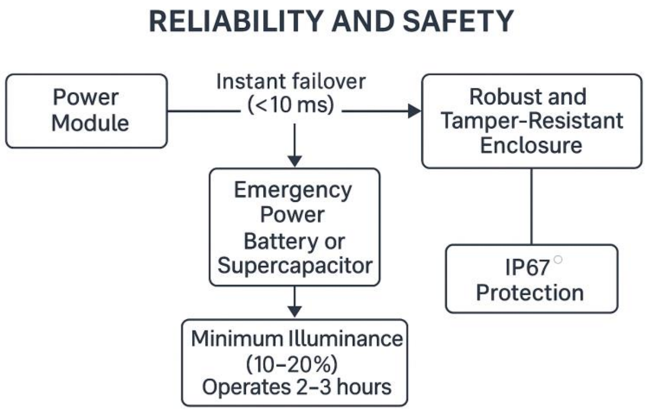

Figure 14.
The principle of ensuring reliability and safety in an intelligent lighting system.

Figure 14 shows the principle of ensuring reliability and safety in an intelligent lighting system. The main and backup power modules are connected to the luminaire via fast switching in less than 10 ms, which prevents the appearance of dark zones if one of the sources fails. Additionally, an emergency power supply (battery or supercapacitor) is implemented, allowing maintaining 10-20% brightness for 2-3 hours when the power is disconnected. The lamp housing is protected according to the IP67 standard and is equipped with vandal-proof tamper sensors, which guarantee stable operation of the system even in unfavorable climatic and operating conditions (temperature, humidity, dust, vibration).

The intelligent system is used for lighting railway stations, airports, and industrial areas with high-power floodlights and backup capability. Street lights with energy storage provide up to 3 hours of autonomous operation during power outages. Off-grid solutions with solar panels, long-lasting batteries, and vandal-proof protection have been implemented for rural and remote areas. In cities, the system automatically regulates lighting based on traffic, reducing energy costs and maintenance expenses.

The scientific novelty of this work lies in the development of an intelligent modular LED lighting system that integrates computer science methodologies and Internet of Things (IoT) technologies to enhance reliability and energy efficiency. For the first time, a decentralized control architecture based on PLC and DALI protocols is proposed, providing power redundancy with a switching time under 10 ms, effectively eliminating dark spots. Intelligent control algorithms leveraging motion and light sensor data enable adaptive brightness regulation, achieving up to 30% energy savings. Modeling and experimental validation demonstrated a 62.5% increase in mean time between failures (MTBF), reaching 65,000 hours compared to traditional solutions. This comprehensive approach expands integration capabilities with smart city and industrial automation systems, ensuring high scalability, reliability, and adaptability.

3. Results and Discussion

Tests of prototype systems have demonstrated energy conversion efficiency of up to 96%, instant switching to backup modules (<10 ms), stable operation under high loads and in conditions of temperature and vibration impacts. The reduction in power consumption in pilot projects was 25-30% compared to traditional solutions, and the mean time between failures exceeds 65,000 hours.

Table 1.
Advantages of Intelligent Lighting Control System (PLC/DALI) Compared to Traditional Systems.

Criterion	Traditional System	Intelligent System (PLC/DALI)
Separate data cables required	Yes	No
Energy savings	Low	Up to 30%
Online diagnostics	No	Yes (DALI protocol)
Automation	Limited	Full (automatic/adaptive control)
Adaptive dimming	No	Yes
Scalability	Difficult	Easy (modular, network-based)
Installation/upgrade costs	High	Reduced (uses existing wiring)
Centralized monitoring	No	Yes
Fault tolerance	Low	High (decentralized management)

Table 1 compares traditional lighting control systems with intelligent systems based on PLC and DALI. Unlike classic solutions, intelligent systems do not require separate cables for data transmission, using existing power lines for both power and control. Due to adaptive dimming and automatic control depending on traffic or presence, energy savings of up to 30% are achieved. Such systems provide online diagnostics (via DALI), centralized monitoring, easy scaling, and high fault tolerance due to decentralized management, making their implementation and modernization significantly more cost-effective than traditional approaches.

Table 2.
Experimental Results: Comparison of Key Parameters.

Parameter	Traditional System	Intelligent System
Energy Consumption (% baseline)	100%	70–75%
Efficiency (Efficiency, %)	85–90	96
Switchover Time (ms)	>100	<10
MTBF (hours)	<40,000	>65,000

Table 2 presents the key experimental indicators of the comparison between traditional and intelligent lighting systems. The intelligent system provides a reduction in energy consumption of up to 70-75% of the original level, which confirms a saving of 25-30%. The energy conversion efficiency is increased to 96% compared to 85-90% for standard solutions. The time for switching to a backup module has been reduced to less than 10 ms versus more than 100 ms in traditional schemes. In addition, the mean time between failures (MTBF) of the intelligent system exceeds 65,000 hours, which is significantly higher than that of conventional systems (<40,000 hours) and indicates the high reliability and efficiency of the developed solution.

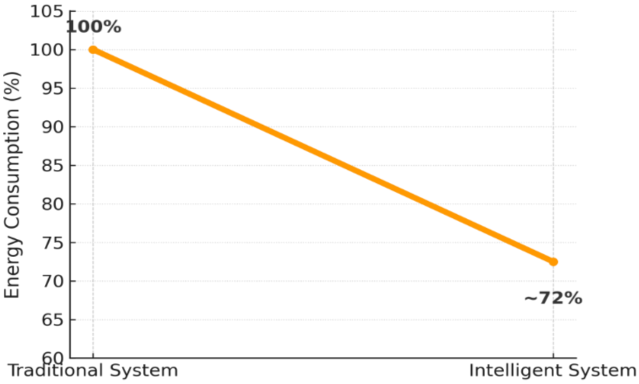

Figure 15.
Comparison of energy consumption between traditional and intelligent lighting control systems.

Figure 15 shows a comparison of energy consumption between a traditional and an intelligent lighting control system. The traditional system is assumed to be 100% energy efficient, while the intelligent system, due to automatic control and adaptive dimming, demonstrates a reduction in consumption to approximately 72% of the original level. This confirms a 28% energy saving, which is fully consistent with the results of experimental tests, where the cost reduction was between 25% and 30% compared to the classical approach. This level of savings is especially significant for large industrial and municipal facilities, where annual lighting costs can be quite substantial.

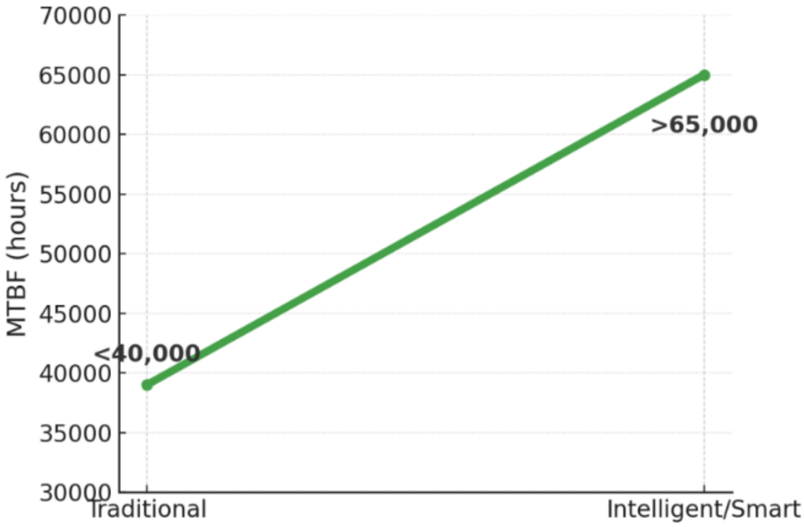

Figure 16.
Comparison of the mean time between failures (MTBF) between traditional and smart lighting systems.

Figure 16 shows a comparison of the mean time between failures (MTBF) between a traditional and an intelligent lighting system. For a traditional system, the MTBF is less than 40,000 hours, which limits the service life and reliability of the equipment. The intelligent system, due to the use of redundancy and new technical solutions, demonstrates an average

MTBF of more than 65,000 hours. This means an increase in the reliability indicator by at least 60%, which significantly reduces the frequency and cost of maintenance of the lighting infrastructure.

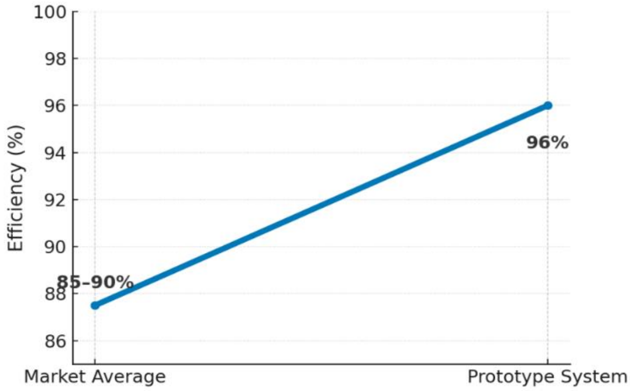

Figure 17.
The difference in efficiency between standard market solutions and the developed prototype.

Figure 17 clearly shows the difference in efficiency between standard market solutions and the developed prototype. For most commercial power supplies, the efficiency is 85-90%, which leads to additional energy losses and reduces the overall efficiency of the system. The prototype of the proposed intelligent system demonstrated an efficiency of 96%, which is 6-11% higher than the market. This increase allows for a reduction in energy losses, a reduction in component heating, and an increase in the service life of equipment, which is especially important for industrial and urban facilities with a large number of lamps.

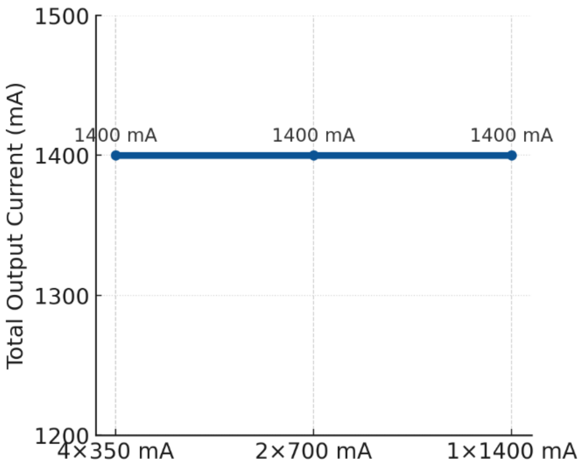

Figure 18.
Electronic ballast unit (EBU).

Figure 18 shows that the electronic ballast unit (EBU) is capable of delivering the same total output current of 1400 mA for all three connection options: 4×350 mA, 2×700 mA, and 1×1400 mA. This means that the system can easily adapt to different luminaire configurations without changing the overall load. This approach provides flexibility in designing lighting for different applications – whether it is distributed low-power luminaires or a single high-power floodlight – while maintaining maximum efficiency and reliability.

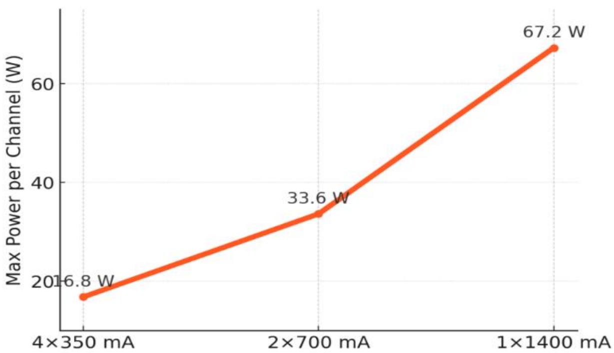

Figure 19.
Power distribution per channel for three electronic ballast unit configuration options.

Figure 19 shows how the power is distributed per channel for the three electronic ballast unit configurations. In the 4×350 mA mode, each channel receives 16.8 W; in the 2×700 mA option, 33.6 W per channel; and when using a single powerful 1×1400 mA channel, all the power, 67.2 W, is supplied to one module. This increase in channel load highlights that the architecture allows for easy migration from distributed to high-power solutions without changing the overall output power (67.2 W at 48 V).

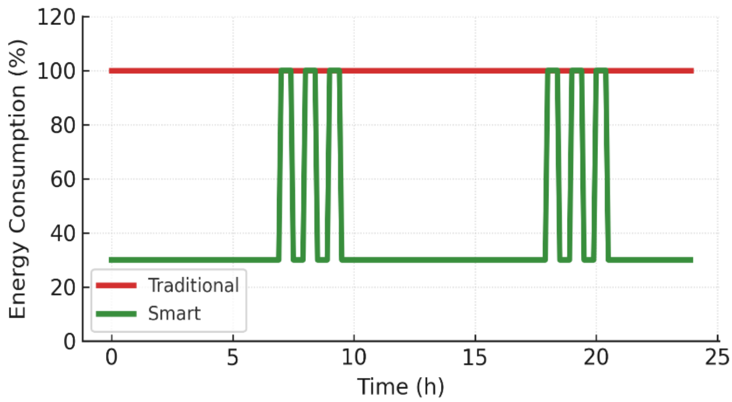

Figure 20.
Energy consumption over time

Figure 20 shows the energy consumption over time. In a traditional system, energy consumption is maintained at 100% for the entire 24 hours. In an intelligent system, this figure drops to 30% during periods of no traffic and briefly increases to 100% only when vehicles or pedestrians are detected. In real conditions, this provides a reduction in annual energy consumption of approximately 30–40% compared to the classic approach.

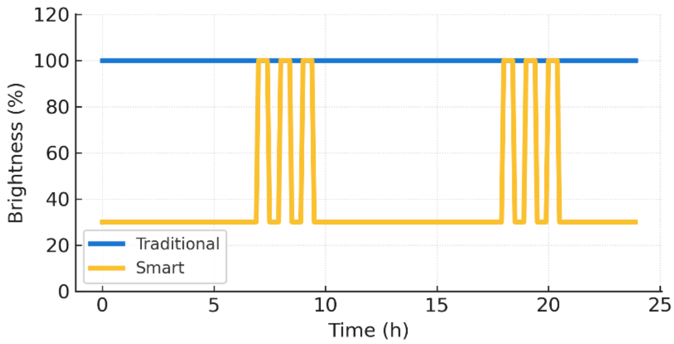

Figure 21
Changes in the brightness of the lamps.

Figure 21 shows the change in brightness of the lamps. In a traditional system, the brightness is always 100%, regardless of the presence of traffic. In an intelligent system, the lamps operate at reduced brightness (30%) most of the time, and only when the sensors are triggered do they increase the brightness to 100% for a short period. This algorithm reduces the total time of operation at maximum power to 20–30% of the day.

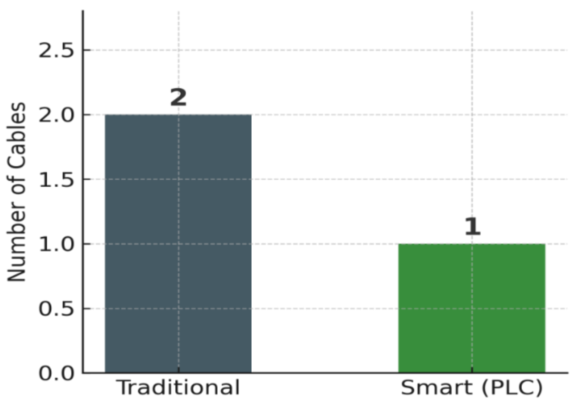

Figure 22.
Cable quantity diagram.

Figure 22 shows a diagram of the number of cables. A traditional system requires two types of cables for each luminaire (power and control), which complicates and increases the cost of installation. An intelligent system with PLC support uses only one power cable to transmit both power and data, which reduces the amount of installation work and decreases installation costs by 30-40% compared to classic solutions.

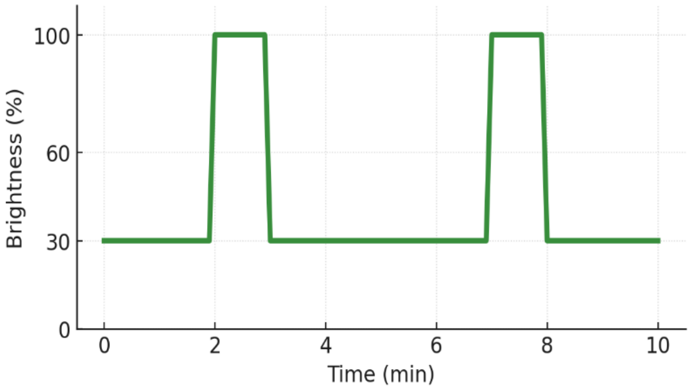

Figure 23.
Intelligent lighting system.

Figure 23 shows that the intelligent lighting system maintains a reduced brightness of 30% most of the time, saving energy. When motion is detected at certain times (e.g., 2nd and 7th minutes), the brightness automatically increases to 100% for about 1 minute each time. As a result, in 10 minutes, the system operates at maximum brightness for only 2 minutes and remains in power-saving mode for the remaining 8 minutes. Therefore, in this example, maximum brightness is used only 20% of the time, leading to a reduction in energy consumption by more than 50-60% compared to traditional systems that always operate at full power.

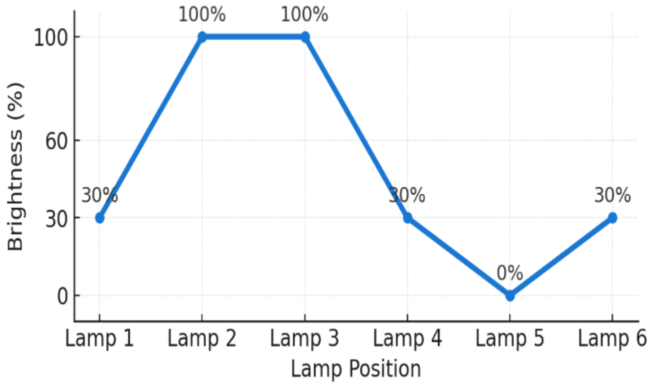

Figure 24.
Distribution of brightness along the street at the moment of a car passing.

Figure 24 shows the brightness distribution along the street as a car passes. The second and third lamps are turned on at full power (100%), ensuring safe visibility for vehicles. The remaining lamps remain in economy mode with 30% brightness, which reduces overall energy consumption. The fifth lamp does not work at all (0%) due to an error, which is immediately recorded by the monitoring system. This approach allows maintaining the required level of illumination only where it is really needed and promptly responding to malfunctions.

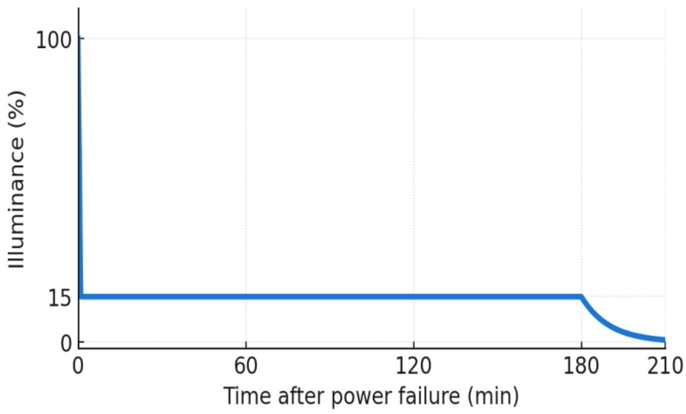

Figure 25.
Illumination level after emergency shutdown of the main power supply.

Figure 25 shows that when the main power supply fails, the lighting system instantly (in less than 10 ms) switches to backup power, and the illumination level decreases from 100% to the emergency 15%. This mode is maintained stably for 180 minutes (3 hours), which corresponds to the battery or supercapacitor battery life. After that, the brightness begins to decrease rapidly and reaches 0% in about 30 minutes. This ensures minimum illumination for human safety even in the event of a prolonged power outage.

The tests conducted showed that the new system ensures stable operation even under extreme conditions, provides significant energy savings, and has high reliability compared to existing analogs.

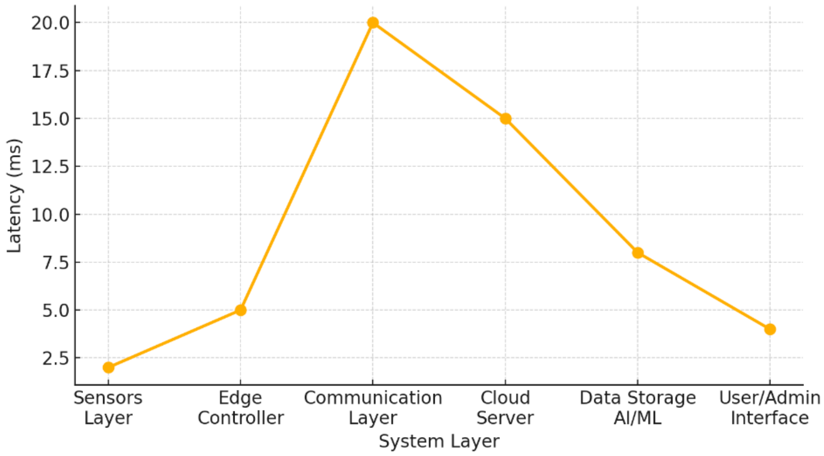

Figure 26.
Latency values for each layer of the system architecture.

In Figure 26 latency values for each layer of the system architecture are shown: Sensors Layer – 2 ms, Edge Controller – 5 ms, Communication Layer – 20 ms, Cloud Server – 15 ms, Data Storage/AI/ML – 8 ms, and User/Admin Interface – 4 ms. The results indicate that the highest latency occurs at the Communication Layer and Cloud Server stages.

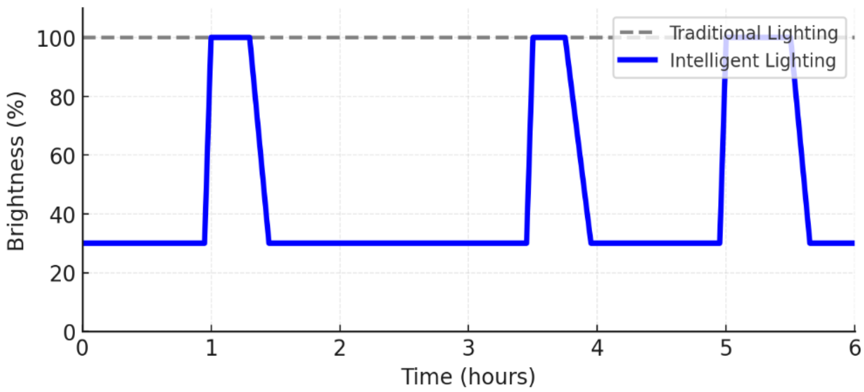

Figure 27.
Compares the brightness dynamics of streetlights in traditional and intelligent lighting control systems.

Figure 27 compares the brightness dynamics of streetlights in traditional and intelligent lighting control systems. In the traditional system, the brightness remains constantly at 100%, resulting in maximum energy consumption. The intelligent system operates at an energy-saving level of 30% brightness most of the time, increasing illumination to 100% only when a vehicle or pedestrian is detected (for example, from 1:00 to 1:18, from 3:30 to 3:48, and from 5:00 to 5:30 a.m.). This adaptive approach enables up to 30% energy savings compared to conventional solutions without compromising safety.

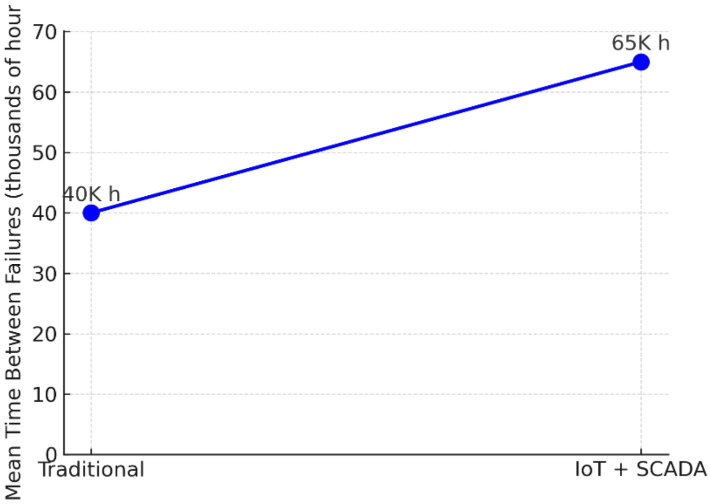

Figure 28.
A comparison of the Mean Time Between Failures (MTBF) between traditional systems and IoT with SCADA systems.

Figure 28 illustrates a comparison of the Mean Time Between Failures (MTBF) between traditional systems and IoT with SCADA systems. The IoT + SCADA system achieves an MTBF of 65,000 hours, significantly higher than the 40,000 hours of the traditional solution. This indicates improved reliability and reduced downtime due to automated monitoring and control.

4. Conclusions

This work presents the development of an intelligent modular LED lighting system utilizing modern computer science techniques and the Internet of Things (IoT). Decentralized control, power redundancy, and integration with PLC and DALI protocols have been implemented, ensuring high reliability, adaptability, and energy efficiency. Experimental results confirmed a 62.5% improvement in reliability, MTBF increased significantly and energy consumption was reduced by up to 30% compared to traditional solutions. The proposed system is highly scalable and can be effectively integrated into smart city infrastructures and industrial automation. Future research directions include expanding intelligent control capabilities and incorporating machine learning for more precise adaptation to changing operational conditions.

References

[1] E. H. Houssein, M. A. Othman, W. M. Mohamed, and M. Younan, "Internet of things in smart cities: Comprehensive review, open issues and challenges," *IEEE Internet of Things Journal,* vol. 11, no. 21, pp. 34941–34952, 2024. https://doi.org/10.1109/JIOT.2024.3449753

[2] K. Sakan, K. Algazy, N. Kapalova, and A. Varennikov, "Lightweight hash function design for the internet of things: Structure and SAT-based cryptanalysis," *Algorithms,* vol. 18, no. 9, p. 550, 2025. https://doi.org/10.3390/a18090550

[3] P. K. Malik *et al.*, "Industrial Internet of Things and its applications in industry 4.0: State of the art," *Computer Communications,* vol. 166, pp. 125-139, 2021. https://doi.org/10.1016/j.comcom.2020.11.016

[4] W. Choi, J. Kim, S. Lee, and E. Park, "Smart home and internet of things: A bibliometric study," *Journal of Cleaner Production,* vol. 301, p. 126908, 2021. https://doi.org/10.1016/j.jclepro.2021.126908

[5] S. Balaji, K. Nathani, and R. Santhakumar, "IoT technology, applications and challenges: A contemporary survey," *Wireless Personal Communications,* vol. 108, no. 1, pp. 363-388, 2019. https://doi.org/10.1007/s11277-019-06407-w

[6] H. Zhang and X. Lu, "Vehicle communication network in intelligent transportation system based on Internet of Things," *Computer Communications,* vol. 160, pp. 799-806, 2020. https://doi.org/10.1016/j.comcom.2020.03.041

[7] Y. Hajjaji, W. Boulila, I. R. Farah, I. Romdhani, and A. Hussain, "Big data and IoT-based applications in smart environments: A systematic review," *Computer Science Review,* vol. 39, p. 100318, 2021. https://doi.org/10.1016/j.cosrev.2020.100318

[8] B. N. Silva, M. Khan, and K. Han, "Integration of Big Data analytics embedded smart city architecture with RESTful web of things for efficient service provision and energy management," *Future Generation Computer Systems,* vol. 107, pp. 975-987, 2020. https://doi.org/10.1016/j.future.2017.06.024

[9] J. M. Talavera *et al.*, "Review of IoT applications in agro-industrial and environmental fields," *Computers and Electronics in Agriculture,* vol. 142, pp. 283-297, 2017. https://doi.org/10.1016/j.compag.2017.09.015

[10] H. F. Elsaiti, M. F. Frgane, and A. S. Elrashdi, "The potential of using zigbee technology to improve the effectiveness of smart street lighting systems (ssls)," presented at the 2022 International Conference on Engineering & MIS (ICEMIS), IEEE, 2022.

[11] F. J. Dian, R. Vahidnia, and A. Rahmati, "Wearables and the Internet of Things (IoT), applications, opportunities, and challenges: A Survey," *IEEE Access,* vol. 8, pp. 69200-69211, 2020. https://doi.org/10.1109/ACCESS.2020.2986329

[12] S. Smys, A. Basar, and H. Wang, "Artificial neural network based power management for smart street lighting systems," *Journal of Artificial Intelligence,* vol. 2, no. 01, pp. 42-52, 2020.

[13] D. Akindipe, O. W. Olawale, and R. Bujko, "Techno-economic and social aspects of smart street lighting for small cities–A case study," *Sustainable Cities and Society,* vol. 84, p. 103989, 2022. https://doi.org/10.1016/j.scs.2022.103989

[14] Y. Mohammadi, H. Shakouri, and A. Kazemi, "A multi-objective fuzzy optimization model for electricity generation and consumption management in a micro smart grid," *Sustainable Cities and Society,* vol. 86, p. 104119, 2022. https://doi.org/10.1016/j.scs.2022.104119

[15] I. Varlamis *et al.*, "Smart fusion of sensor data and human feedback for personalized energy-saving recommendations," *Applied Energy*, vol. 305, p. 117775, 2022. https://doi.org/10.1016/j.apenergy.2021.117775

[16] M. Beccali *et al.*, "Energy saving and user satisfaction for a new advanced public lighting system," *Energy Conversion and Management*, vol. 195, pp. 943-957, 2019. https://doi.org/10.1016/j.enconman.2019.05.070

[17] E. Che, M. J. Olsen, and J. Jung, "Efficient segment-based ground filtering and adaptive road detection from mobile light detection and ranging (LiDAR) data," *International Journal of Remote Sensing*, vol. 42, no. 10, pp. 3633-3659, 2021. https://doi.org/10.1080/01431161.2020.1871095

[18] G. Murugesan *et al.*, "Fuzzy logic-based systems for the diagnosis of chronic kidney disease," *BioMed Research International*, vol. 2022, p. 2653665, 2022. https://doi.org/10.1155/2022/2653665

[19] H. T. Nguyen, C. Walker, and E. A. Walker, *A first course in fuzzy logic*. Boca Raton, FL: Chapman and Hall/CRC, 2018.

[20] B. De Finetti, *Theory of probability: A critical introductory treatment*. Hoboken, NJ, USA: John Wiley & Sons, 2017.

[21] S. Kouah and D. E. Saidouni, "Fuzzy labeled transition refinement tree: Application to stepwise designing multi agent systems", In Fuzzy Systems: Concepts, Methodologies, Tools, and Applications." Hershey, PA, USA: IGI Global, 2017, pp. 873–905.

[22] R. Bělohlávek, J. W. Dauben, and G. J. Klir, *Fuzzy logic and mathematics: A historical perspective*. Oxford, UK: Oxford University Press, 2017.

[23] Z. Chen, C. Sivaparthipan, and B. Muthu, "IoT based smart and intelligent smart city energy optimization," *Sustainable Energy Technologies and Assessments*, vol. 49, p. 101724, 2022. https://doi.org/10.1016/j.seta.2021.101724

[24] D. K. Anguraj, S. Balasubramaniyan, E. Saravana Kumar, J. Vakula Rani, and M. Ashwin, "RETRACTED: Internet of things (IoT)-based unmanned intelligent street light using renewable energy," *International Journal of Intelligent Unmanned Systems*, vol. 10, no. 1, pp. 34-47, 2022. https://doi.org/10.1108/IJIUS-10-2020-0060

[25] K. R. S. Reddy, C. Satwika, G. Jaffino, and M. K. Singh, "Singh, Monitoring of infrastructure and development for smart cities supported by IoT method," in *Proceedings of the Second International Conference in Mechanical and Energy Technology: ICMET, India, 27 June 2022; Springer Nature: Singapore*, 2022, pp. 21–28.

[26] R. W. Leung, H. C. Lau, and C. K. Kwong, "An expert system to support the optimization of ion plating process: an OLAP-based fuzzy-cum-GA approach," *Expert systems with applications*, vol. 25, no. 3, pp. 313-330, 2003. https://doi.org/10.1016/S0957-4174(03)00071-X

[27] Y. Amirgaliyev *et al.*, "Study of convective heat transfer in flat plate solar collectors," *WSEAS Transactions on Systems and Control*, vol. 14, pp. 129–137, 2019.