A new airfield lighting system network architecture

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ABSTRACT

Airport navigation lights are essential for safe night and adverse weather flying. Airfield ground lighting (AGL) systems provide visual guidance during airport operations. These systems use multiple lamps connected in series with constant current regulators (CCRs) to provide power. Prompt detection and location of failed lamps are critical to airport efficiency and cost savings. Local area network (LAN) communication facilitates lamp monitoring and control, improving system performance and reducing maintenance costs. Effective transmission media are critical for system reliability and efficiency. This article presents a new network architecture for AGL systems that connects lamps and the control system using a new intelligent module; this architecture combines star and bus topologies in a hybrid intranet network. The obtained results show excellent networking performances by means of latency and throughput. This architecture improves operational efficiency and reduces maintenance for AGL systems.

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1. INTRODUCTION

Emerging trends in the aviation industry underscore the critical need to monitor and control airport lighting systems. Such efforts not only increase airport capacity but also improve operational efficiency, which has a profound impact on air traffic control and aircraft safety [1]–[5]. At the heart of this infrastructure are airfield ground lighting (AGL) systems, which play a central role in illuminating runways, providing critical speed indicators, and ensuring aircraft alignment during the critical phases of approach, landing, and taxiing [6], [7]. Among the array of AGL components, position lights, often referred to as beacons, stand out as indispensable fixtures. These beacons are meticulously installed within devices engineered to modulate the intensity, color, and directional emission of light. The sheer scale of these installations is staggering, ranging from approximately 500 in smaller airports to 3,000-4,000 in the largest ones, underlining the monumental maintenance and conservation efforts involved [8]–[12]. Detecting and rectifying faulty lamps within this extensive network represents a colossal and costly undertaking, further underscoring the magnitude of the challenges inherent in ensuring the seamless operation of airport lighting systems [13]–[17].

However, the process of locating a failed lamp requires physical intervention by preventive and corrective maintenance personnel. This requires personnel to physically move onto the runway to diagnose and, if necessary, repair the problem. During this entire intervention period, the runway must be taken out of service, disrupting airport operations. These tasks are particularly critical at the beacon locations along the runway. In addition, both the International Civil Aviation Organization (ICAO) [18], [19] and the Federal Aviation Administration (FAA) [7], [19] impose strict safety regulations, including limits on the maximum number of defective lights. As a result, runways often face significant downtime due to AGL system maintenance.

In light of these challenges and regulatory requirements, extensive research has been conducted over the past several decades to address the issue of locating failed lamps without the need for physical intervention. Innovative solutions have been explored, such as the use of wireless technologies and the use of power line communication (PLC) technology [20]–[22]. These efforts aim to streamline and expedite the detection and repair processes, thereby minimizing runway downtime and increasing operational efficiency. Consequently, this scenario has spurred the development of new technologies aimed at facilitating these essential maintenance tasks in line with the evolving needs and standards of the aviation industry. However, wireless technologies are often rejected due to the potential for interference with various radio navigation instruments. Conversely, PLC technology, while promising, has several limitations. The main problems arise from the attenuation of the carrier current along the high-voltage lines connected to the high-voltage (HV) transformer of the constant current regulator (CCR), as well as the myriad reflections and attenuations due to the considerable distance of the runway, and the resonance phenomenon in case of an open circuit on the secondary side of the isolation transformer [23]–[25].

In response to these challenges, local area network (LAN) communication systems over AGL are emerging as an attractive alternative. In particular, Ethernet technology is emerging as a robust LAN solution. Ethernet enables the seamless transfer of data between computers, printers, routers, and other network-connected devices. This technology uses either copper or fiber-optic cables to transmit data in the form of electrical or optical signals. Data is transmitted in packets, each carrying a unique media access control (MAC) address assigned to each device connected to the network. In particular, Ethernet offers a wide range of transmission speeds, from 10 Mbps (10Base-T) to a staggering 100 Gbps (100GBase-T), enabling efficient and reliable communication within the AGL infrastructure [26].

2. DESCRIPTION OF THE AIRFIELD GROUND LIGHTING SYSTEM

Figure 1 shows the basic architecture of an airport lighting system [8]. A comprehensive specification of the airport's visual aids can be found in [18], while detailed information on the electrical systems can be found in [19]. Central to this infrastructure is the constant current regulators (CCR), which are strategically located in the control room, typically near the airport's power source. The primary function of the CCR is to provide a constant adjustable sinusoidal current to the primary power circuit. This capability provides precise control of the beacon brightness. Adjustment of the beacon brightness can be done either manually or remotely, facilitated by manipulating the control value that regulates the electrical current supplied by the CCR [27]. This sophisticated control mechanism not only allows fine-tuning of lighting levels but also increases operational flexibility and efficiency within the airport lighting system.

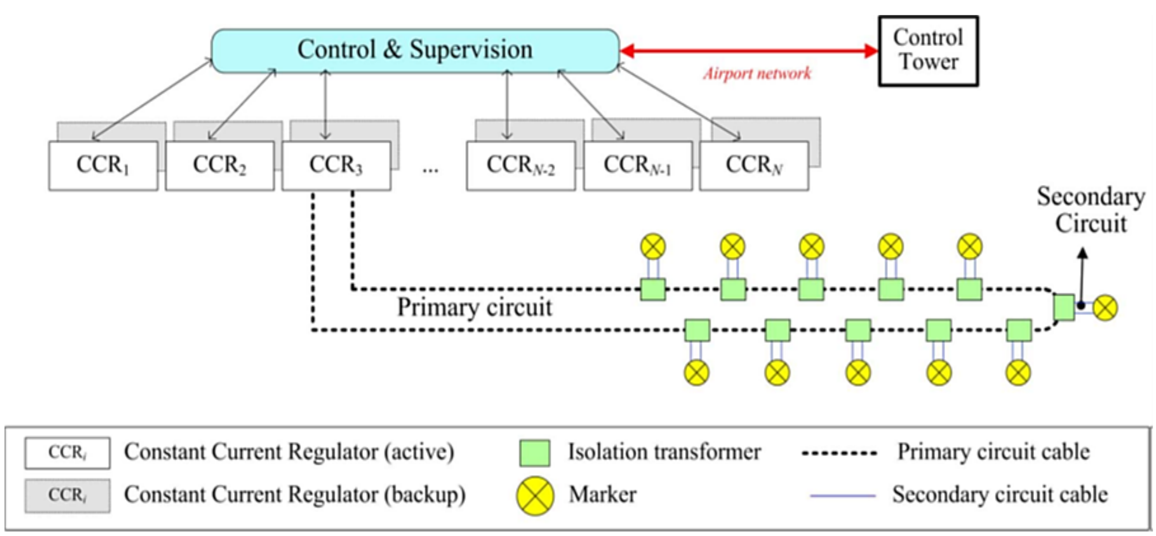

Figure 1. Airfield ground lighting system (AGL) [8]

The CCR is connected in series with a single-core cable, known as the primary circuit cable, which serves as the conduit for distributing the generated current to the lamps through the isolation transformer (IT). This arrangement ensures that the current flow remains uninterrupted even in the event of a lamp failure. The critical function of IT goes beyond simply maintaining continuity; it also serves to isolate high voltages within the primary circuit, protecting against potential electrical hazards. In addition, the secondary circuits use bipolar cables to make connections between the lamps and the ITs. This configuration allows the secondary circuit to efficiently transfer power from the IT to the lamps while maintaining appropriate voltage levels. By using bipolar cables, the secondary circuits ensure optimal performance and reliability, reducing the risk of power fluctuations or interruptions that could compromise the effectiveness of the airport lighting system [28]–[30].

Different types of beacons within airport lighting systems serve different functions and can be grouped into several primary classifications. One primary category includes the approach lighting system (ALS) and the precision approach path indicator (PAPI). These systems play a critical role in providing pilots with critical information necessary to execute visual approaches. The ALS facilitates safe landing procedures by improving visibility during the approach phase, while the PAPI provides precise vertical guidance to help pilots maintain the correct glide path. Another important category is the runway lighting system (RLS), which includes a range of lighting components designed to delineate the critical areas of the runway. This includes lighting along the centerline, edges, and thresholds to ensure optimal visibility for aircraft during takeoff and landing operations. In addition, taxiway and apron lights and guidance signs are integral components of the RLS. These elements are critical in assisting pilots during taxiing maneuvers by providing clear visual cues and guidance within the airport environment. The full integration of these beacon categories into the airport lighting system underscores their collective role in enhancing aviation safety and operational efficiency [18], [19]. By providing pilots with essential visual aids and guidance cues, these systems contribute significantly to the seamless flow of air traffic and the overall safety of airport operations.

3. NEW NETWORK ARCHITECTURE OF AIRFIELD LIGHTING SYSTEM

3.1. Basic network architecture topologies

Ethernet is an important technology in LANs, providing connectivity between devices via the carrier sense multiple access with collision detection (CSMA/CD) protocol. Ethernet LANs primarily use point-to-point or multipoint links, with the bus topology being a simple variant. In a bus topology as shown in Figure 2, data transmitted over the network can cause access contention, which is addressed by defining access policies. Despite contention issues, bus networks offer high-speed data transfer and flexibility for new station integration, ensuring uninterrupted network functionality. The star topology features a central node that acts as a hub for network connections in Figure 2, facilitating efficient communication among all nodes. This concentrator ensures that messages are routed only to their intended recipients, increasing the reliability of data transmission. Although decentralized, the network is vulnerable to failure of the central node, requiring redundancy measures to prevent widespread disruption. Despite this risk, the star topology provides high-performance inter-node communication and robustness against individual node failures. The ring topology connects each node in a unidirectional loop in Figure 2, enabling high-speed data transmission suitable for long distances. Each station receives and regenerates messages, copying them as needed. However, it is sensitive to loop breaks, which can interrupt network communications. Implementing a double-ring configuration provides redundancy, increasing fault tolerance and ensuring uninterrupted operation [26].

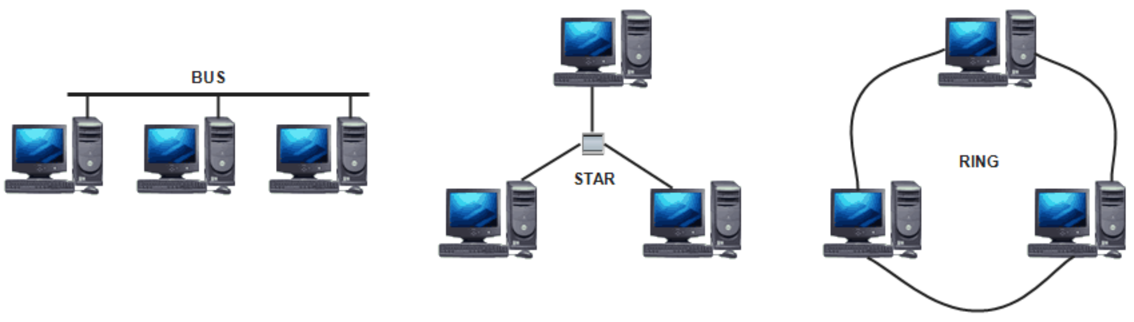

Figure 2. Basic topologies

3.2. Proposed network architecture of airfield lighting system

The architecture of the proposed airfield lighting system is illustrated in Figure 3. The new system is based on Ethernet technology for communication between the different intelligent modules. The smart modules are interconnected using Ethernet cables in a bus topology, where each smart module is equipped with two RJ45 ports. These smart modules are linked to each other in a bus configuration. Additionally, on each side, the smart module loops are connected to a central data collector in a star topology. On the other hand, the main role of the data collector component is to establish communication with the control/SCADA system located in both maintenance and tower posts.

The new network architecture of the lighting system is essentially based on a hybrid intranet network topology, which concatenates both star and bus configurations. This hybrid approach serves dual purposes. Firstly, it ensures effective communication among the various modules within the proposed system. Secondly, using this configuration, we can easily avoid the signal attenuation introduced by the distance that separates the central switch and the last intelligent module on the AGL system. The use of a bus topology among smart modules allows them to communicate efficiently with each other. Simultaneously, the star topology that links smart module loops to the data collector, can significantly enhance the overall reliability and centralization of the system. This hybrid configuration is a strategic choice to optimize both communication effectiveness and the practical constraints associated with the spatial distribution of intelligent modules along the runway.

In summary, the proposed architecture combines the main features of a bus topology (for smart modules) and a star topology (to ensure the communication between smart modules and the central data collector). This hybrid intranet network topology is designed to address the specific needs of the airfield lighting system, ensuring seamless communication while overcoming challenges related to distance within the system.

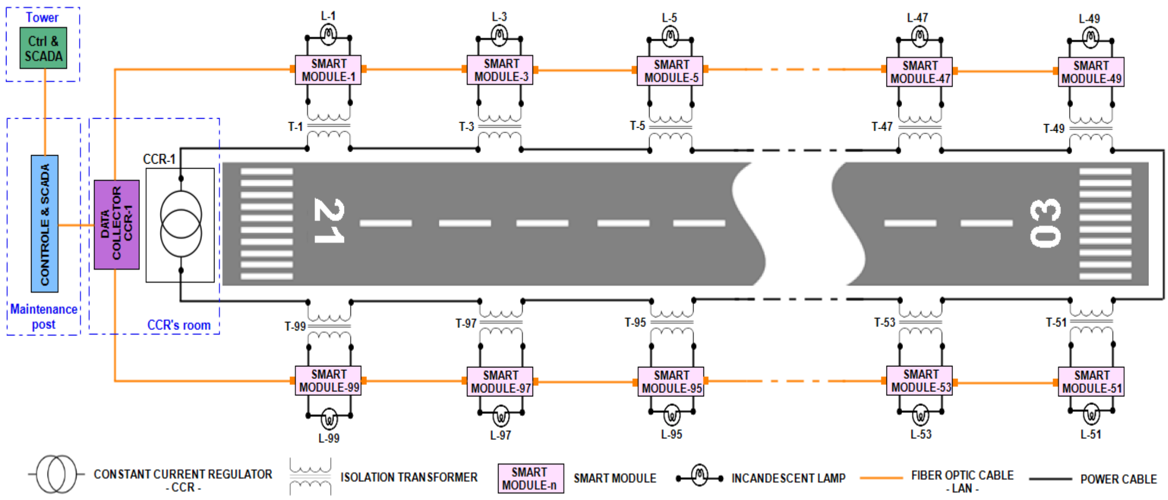

Figure 3. Architecture of the proposed airfield lighting system

The new smart module used in the architecture of the proposed airfield lighting system is essential for monitoring the operating status of the lamp, whether it is operational or defective. Basically, the new smart module shown in Figure 4 consists of four main units which are:

a. Power supply unit: the role of the power supply in our intelligent module is to provide a continuous and stable voltage source to power the various components of the module. It is responsible for converting the AC voltage at the lamp terminals into the appropriate DC voltage for the needs of the electronic circuits.
b. Measurement unit: the role of this unit is to provide a precise indication of the values of these electrical parameters (current, voltage). This function is essential in our system, as it allows, among other things, the monitoring of the operation of each lamp.
c. Processing unit: it is a microcontroller-based unit consisting of an integrated circuit combining a processor (CPU), memory, I/O, and communication peripherals. The microcontroller is set up to perform specific tasks, such as reading and scaling the electrical quantities (current, voltage) measured by the measuring unit in order to use the final values in a fault light detection algorithm and is parameterized to ensure the exchange of data through the link with the communication unit.

d. Communication unit: is based on a serial peripheral interface (SPI) module, which is a high-speed synchronous serial communication interface used to connect the processing unit (microcontroller) or intelligent module to the lighting system's local area network (LAN) by transferring binary data sequentially on a common clock. The communication unit is capable of processing data at transfer rates of up to several megabits per second, making it a fast and efficient communication interface for our system, which requires high-speed data transfers.

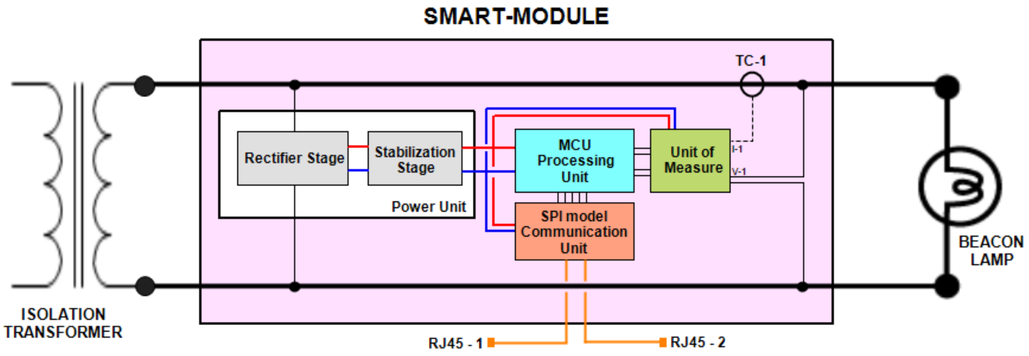

Figure 4. Block diagram of the proposed smart module

4. RESULTS AND DISCUSSION

This study is all about understanding how the AGL system's network works. We will have a close look at its monitoring interface and its performance. By doing this, we hope to find out if the system is good enough to be used in different situations. That way we can see how useful it could be in real applications.

4.1. Monitoring interface

The monitoring interface of the proposed system is shown in Figure 5. This interface allows operators to control and monitor the status of various lighting elements on the AGL, such as runway lights, taxiway lights, and approach lights. In addition, the system provides real-time monitoring of the airfield lighting equipment, including ensuring proper operation, checking for faults, and addressing any problems on time. For example, in the screenshot shown in Figure 5, we can see that runway lights ID09-R1 and ID37-R1, taxiway lights ID15-T1, and approach lights ID48-A2 are defective.

Figure 5. General synoptic of the runway

On the other hand, the proposed interface includes other key features, including automation, integration, and safety compliance. The automation feature is necessary to optimize the use of lighting based on parameters such as time of day and weather conditions. In addition, the proposed interface can be integrated with other airport systems and air traffic control infrastructure to ensure seamless communication and coordination. Furthermore, in terms of safety compliance, the proposed AGL can contribute to meeting safety standards and regulations for airfield lighting, thereby enhancing overall aviation safety.

4.2. Network performances analysis

In this paper, our focus is on the study of how well a network works by looking at its performance. We do this by looking at things like how fast data travels (latency) and how much data it can handle at one time (throughput). By focusing on these two factors, we can get a good idea of how efficient and reliable the network is overall. This helps us better understand its strengths and weaknesses.

4.2.1. Latency performance

Figure 6 shows the latency over one minute (60 s) of three lamps of the proposed AGL which are: lamp N°1, lamp N°15, and lamp N°27 as shown in Figure 5. The first lamp is placed at ~800 meters from the data collector, while the 15th lamp is placed at ~1640 meters, and the 27th lamp is placed at ~3,680 meters. For the first lamp, the upload and download latencies are simulated. This figure shows that the upload latency (↑) is about 30 ms and the download latency (↓) is about 40 ms for the first lamp. In contrast, the 15th lamp has a latency of about 160 ms and the 27th lamp has a latency of about 260 ms. As can be seen, the further away the lamp is from the data collector, the greater the latency. However, since the maximum latency recorded by the proposed AGL is 260 ms, which corresponds to the lamp farthest from the runway (about 3.7 km from the data collector), the proposed AGL achieves excellent latency performance.

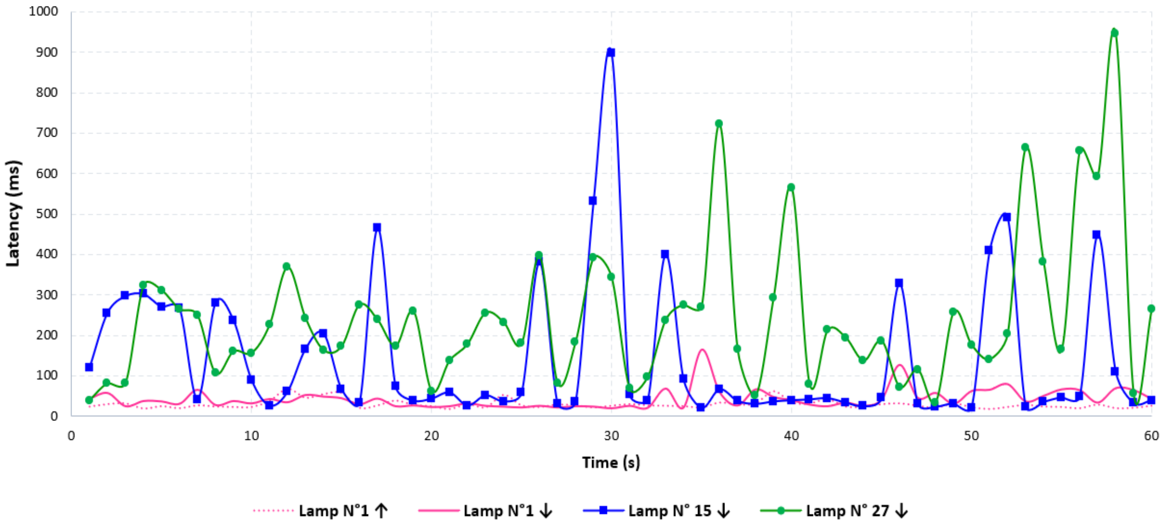

Figure 6. Latency simulation of the proposed AGL

4.2.2. Throughput performance

On the other hand, throughput refers to the rate at which data/signal is successfully transmitted over a communication channel within a defined period of time. This metric quantifies the actual amount of data that is seamlessly transferred from one point to another in a network. Throughput serves as a key indicator when evaluating the efficiency of a network, providing insight into the network's ability to deliver data without encountering errors or experiencing delays. However, it is different from bandwidth, which is the maximum capacity of a communication channel. While bandwidth is the upper limit, throughput reflects the actual speed at which data is transferred over a network. Figure 7 shows the throughput simulation of the proposed AGL over a bandwidth of 100 Mbps. From this figure, we can see that the obtained throughput is around 95 Mbps, which confirms the excellent network performance. Comparing the present work with similar contemporary state-of-the-art AGL communication networks [20], [21], as mentioned in Table 1. We can observe that the proposed AGL system exhibits excellent networking performance in terms of latency and throughput as well as interference-free and impenetrable, especially in intranet configuration.

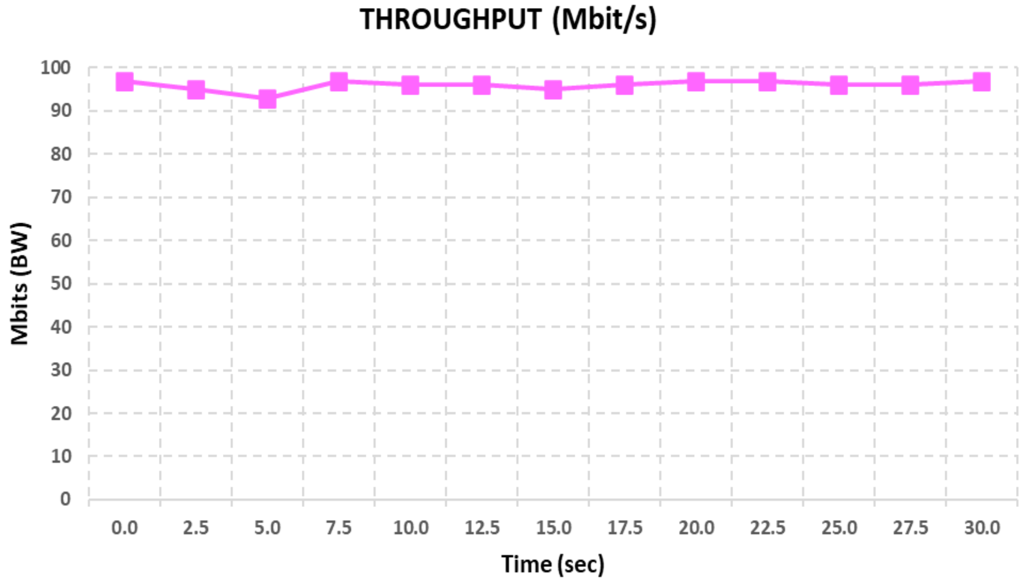

Figure 7. Throughput simulation of the proposed AGL

Table 1. Comparison between different types of communication technology

	Latency	Throughput	Interference	Security
PLC [20]	4.5 s	48 Mbps	Sensitive	High security
Wireless [21]	70 ms	86 Mbps	Sensitive	Low security
Ethernet (this work)	30 ms	95 Mbps	Not sensitive	High security

5. CONCLUSION AND PERSPECTIVES

In this article, an overview of a new aerodrome ground lighting (AGL) system network architecture is introduced. The said system is based on a new smart module that ensures the power supply of each AGL component as well as the measurement, processing, and communication of each component's status with the data collector. The proposed AGL is implemented on a hybrid network topology that includes star and bus configurations. On the other hand, to guarantee a real-time monitoring dashboard, an interface is developed to enable operators to control and monitor different lighting elements. This interface fulfills various key features such as automation, integration, and safety compliance.

The proposed network topology shows excellent performances in terms of latency and throughput, which leads to seamless communication and efficient real-time monitoring. Instead, the proposed work highlights the importance of enabling connectivity between lamps and the LAN of the SCADA system to reach the design specifications. This will be achieved through the design and realization of the new smart module, intentionally positioned between each current transformer and lamp. Future publications will include a detailed description of the smart module, indicating a commitment to sharing the technical intricacies and advancements associated with this novel technology. Overall, the proposed enhancements aim to improve safety measures for aircraft operations and ensure the cost-effectiveness of maintenance and operation within the AGL system.

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