INTEGRATION OF WIRELESS COMMUNICATION TECHNOLOGIES IN SMART STREET LIGHTING SYSTEMS FOR FUTURE SMART CITIES

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Annotation: *This paper explores the integration of wireless communication technologies-specifically LoRaWAN, Sigfox, and mesh network protocols such as IEEE 802.15.4 and Bluetooth-into modern smart street lighting systems. These technologies enable efficient, low-power, and long-range data transmission between lighting fixtures and IoT devices across urban environments. The study highlights how streetlights are evolving from simple illumination units into multifunctional nodes that collect, process, and exchange data within citywide networks. Furthermore, it discusses the architectural similarities between LoRa-based systems and cellular networks, emphasizing the advantages of privately owned infrastructure in reducing operational costs and enhancing flexibility. The paper concludes that smart lighting systems, when combined with IoT-based wireless technologies, can form the backbone of future smart city communication networks, supporting scalable, cost-effective, and energy-efficient connectivity.*

Keywords: *Smart lighting, LoRaWAN, Sigfox, mesh network, IEEE 802.15.4, Bluetooth, IoT, smart city, wireless communication, energy efficiency.*

In a standard wired smart lighting setup, as depicted in Fig.1, communication between each lighting fixture and the electrical cabinet (or segment controller) is established via low-voltage power lines. The electrical cabinet then connects to the central control unit through either a high-speed wired network, such as fiber optics, or a wireless wide-area network (WAN), including cellular or LPWAN technologies. This hierarchical network design ensures reliable data exchange and centralized management, allowing for real-time monitoring and control of the lighting system. Globally, this architecture has been widely adopted due to its robustness and scalability. Traditional street lighting systems have reached a high level of technological maturity, with numerous manufacturers offering turnkey solutions for decades. Nevertheless, the emergence of the Internet of Things (IoT) has transformed the role of street lighting. Modern systems are no longer limited to illumination; they are evolving into multi-functional platforms capable of supporting various location-based services, environmental sensing, and data-driven urban applications. Consequently, smart street lighting now represents a cornerstone for the development of intelligent urban infrastructures, providing both energy efficiency and a foundation for the interconnected services that define future smart cities.

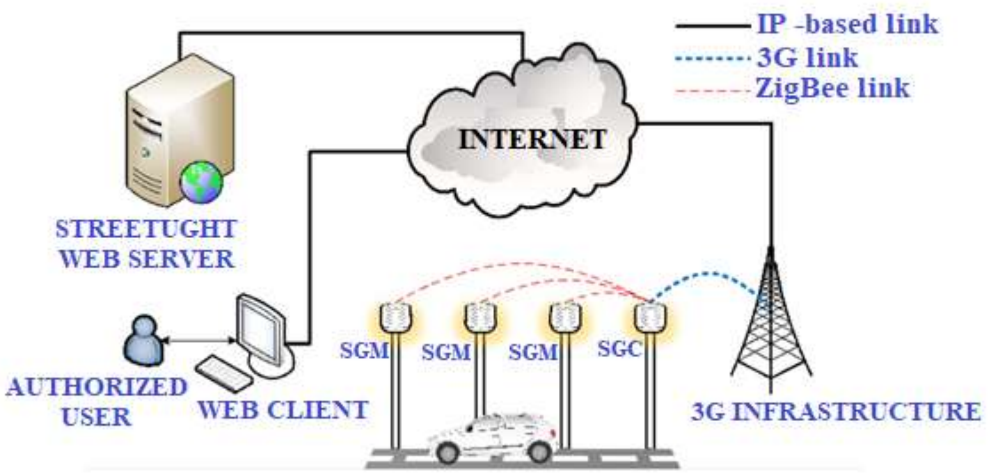

Fig.1. Architecture of a wired smart lighting system

Indeed, future streetlights will undoubtedly be equipped with advanced wireless communication technologies, designed not only to provide illumination but also to collect, process, and exchange real-time data with a diverse array of surrounding IoT devices. These devices may include environmental sensors, smart bicycles, connected vehicles, parking management systems, and waste bins, among others. Such integration positions streetlights as multifunctional nodes within the urban IoT ecosystem. From this perspective, leveraging the same wireless network infrastructure to simultaneously support both smart lighting operations and broader IoT services becomes highly efficient, reducing the need for dedicated networks solely for street lighting management [1-3]. This convergence can lead to substantial cost savings, simplified maintenance, and improved scalability for future urban infrastructure. Recognizing the increasingly intertwined nature of IoT wireless services and smart lighting in forthcoming smart city deployments, multiple street lighting system manufacturers have been motivated to enhance their products to natively accommodate IoT wireless protocols. Modern smart street lighting systems are thus evolving from purely illumination-focused devices to sophisticated communication hubs. In such systems, the primary functionality still revolves around transmitting operational data between the electrical cabinet and individual lighting fixtures to enable centralized control, energy optimization, and fault detection. Simultaneously, an additional radio frequency (RF) network-typically established via compact wireless modules integrated into each streetlight-is deployed to facilitate seamless communication with nearby IoT devices. This network can also enable device-to-device communication when required, creating a decentralized mesh that enhances the robustness and responsiveness of the overall smart city infrastructure. Consequently, future streetlights are expected to serve not only as sources of light but also as critical enablers of urban intelligence, environmental monitoring, and real-time service coordination.

The LoRa Wide Area Network (LoRaWAN) represents a point-to-multipoint communication protocol specifically designed for wide-area network (WAN) applications in the Internet of Things (IoT) ecosystem. As an open standard, LoRaWAN provides a compelling combination of long-range connectivity and ultra-low power consumption, making it particularly suitable for battery-operated devices that transmit small amounts of data intermittently. In rural environments, LoRaWAN can achieve transmission distances exceeding 10 kilometers, while in urban settings, the range typically varies between 2 to 5 kilometers depending on environmental factors, such as building density, interference, and terrain. This capability enables the deployment of large-scale sensor networks for applications including environmental monitoring, smart agriculture, utility metering, and smart city infrastructure. From a network architecture perspective, LoRaWAN is commonly deployed using a star topology. In this configuration, and devices-such as sensors, actuators, or smart streetlights-communicate directly with a central node, typically referred to as a gateway, which serves as a bridge between the end devices and the network server. The gateway aggregates the data transmitted by multiple end devices, forwards it to the network server for processing, and, if necessary, relays control commands back to the devices. This star topology ensures simple network management, reduces device complexity, and allows end devices to operate in low-power modes for extended periods.

Fig.2 illustrates a typical LoRaWAN deployment, highlighting the communication flow from numerous geographically distributed IoT nodes to a single gateway, which then interfaces with the cloud or central management platform. Moreover, LoRaWAN incorporates adaptive data rate mechanisms and robust security features, including end-to-end encryption, to optimize network performance and protect transmitted data. The combination of long-range coverage, minimal energy requirements, and scalable architecture makes LoRaWAN a foundational technology for enabling sustainable, low-maintenance IoT networks in both urban and remote areas.

Fig.2. Architecture of a smart lighting system based on LoRaWAN/Sigfox

It is evident that the resulting network architecture of LoRa-based smart lighting systems closely resembles that of a conventional cellular network. LoRa gateways, distributed strategically across urban areas, perform functions analogous to cellular base stations (BS) by aggregating data from multiple end devices and relaying it to the central control system. The fundamental distinction lies in the ownership and management of the network: LoRa networks are typically private, meaning that the entity responsible for the smart lighting infrastructure also retains full control over this critical communication asset. In contrast, if a traditional cellular network is employed to link LoRa gateways to the control center, recurring service fees must be paid to the network operator. Nevertheless, given that only a relatively small number of gateways are required to cover a city, these operational costs remain modest compared to the overall infrastructure investment. Currently, multiple lighting fixture manufacturers have integrated LoRa and Sigfox technologies into their products. The decision to adopt one technology over the other primarily hinges on the infrastructure owner's preference for network management and associated costs. LoRa enables the creation of a privately managed network with minimal ongoing communication expenses, providing the owner with autonomy and potential revenue-generating opportunities through data services. On the other hand, Sigfox offers a fully managed network, allowing the infrastructure owner to avoid the complexities of deployment and maintenance; however, the communication service constitutes an operational expenditure that may escalate over time [4].

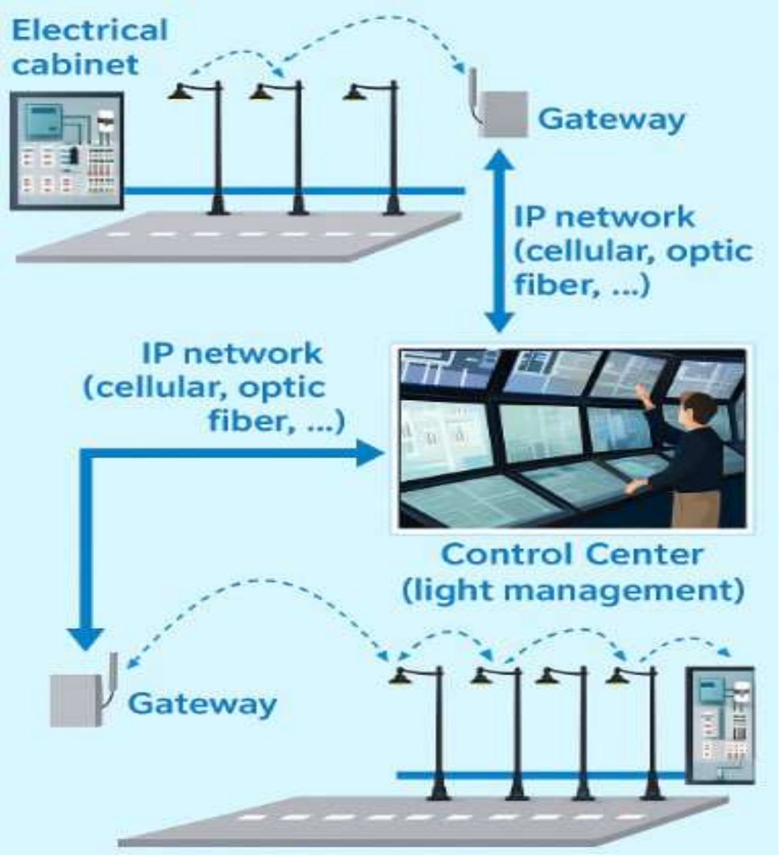

Fig.3. Smart lighting architecture based on Bluetooth/IEEE 802.15.4 mesh

Managing a private communication network entails direct responsibility for each connected streetlight, including maintenance, monitoring, and ensuring reliable data transmission. In the LoRa scenario, the infrastructure owner benefits from long-term cost efficiency and the ability to optimize network performance, while also potentially monetizing the data collected from IoT devices within the network. Conversely, in the managed network scenario, all communication costs are treated purely as operational expenses, reducing control but simplifying network management. This distinction underscores the strategic trade-offs between ownership, cost, and operational flexibility when designing and deploying smart street lighting systems in modern urban environments.

Notably, both LoRa and Sigfox technologies experience coverage challenges similar to those encountered in conventional cellular networks with comparable architectures. In mobile communication, users can often mitigate poor connectivity by moving to a location with better signal reception; however, streetlights are fixed infrastructure elements and cannot reposition themselves. As a result, static placement may occasionally lead to degraded communication quality in areas with signal obstructions or interference. Nevertheless, the impact of coverage issues in street lighting networks is generally less severe due to the close proximity of neighboring poles, which often allows for line-of-sight transmission conditions and enhanced signal reliability. Additionally, inter-pole communication within such networks does not require a subscription to a third-party network provider, nor does it incur recurring fees, since the ownership of the lighting infrastructure includes the inter-pole communication network. Fig.3 demonstrates two commonly used technologies for implementing mesh networks in smart lighting systems: IEEE 802.15.4 and Bluetooth. These mesh networks, primarily deployed within street lighting systems, function as dedicated communication infrastructures that are typically designed to support only smart lighting services. However, considering the rapid expansion of urban IoT ecosystems, where an increasing number of smart devices require connectivity for data exchange, deploying a network solely for a single service represents a significant underutilization of resources. Wireless networks, by contrast, are fundamental enablers of smart city and IoT applications, offering flexibility, wide coverage, and low deployment costs that make them ideal for supporting a diverse array of connected devices. Each streetlight in a smart lighting infrastructure could either operate as a standalone smart object-such as a sensor, meter, or environmental monitoring device-or function as an integral node within a broader citywide wireless network that provides connectivity for other smart devices [4-6]. This dual role emphasizes the strategic importance of designing smart street lighting systems not only for illumination and energy efficiency but also as critical communication infrastructure that can underpin future smart city services. By leveraging existing lighting poles as network nodes, municipalities can optimize infrastructure utilization, reduce deployment costs, and provide scalable, robust connectivity for emerging IoT applications, thereby transforming the street lighting network into a foundational element of the urban digital ecosystem. Transforming smart lighting infrastructure into a capillary, multifunctional citywide communication network-capable of transmitting data, collecting information, and delivering services to and from IoT devices-turns it into a dynamic platform for smart city development. In this scenario, public lighting infrastructure, instead of being merely a cost factor, becomes an asset that enables new services and revenue-generating opportunities.

Conclusion:

The integration of wireless communication technologies into street lighting systems represents a transformative step toward building smarter and more connected cities. LoRaWAN and Sigfox enable long-range and low-power connectivity, while mesh network technologies such as IEEE 802.15.4 and Bluetooth provide localized, reliable inter-pole communication. Compared to traditional cellular networks, LoRa-based architectures offer greater autonomy, cost efficiency, and scalability, especially when owned and managed privately.

Moreover, utilizing streetlights as network nodes not only enhances lighting control and maintenance but also creates a versatile communication infrastructure capable of supporting diverse IoT applications.

Consequently, future street lighting systems will play a crucial role in establishing intelligent urban environments, facilitating data-driven decision-making, and promoting sustainable city development.

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