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Review Article

6LOWPAN Equipped Streetlight with Digital Displays Redefines Pedestrian Advertising: An Emphasis on Cyber Security

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Abstract *- The integration of IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN) technology in urban streetlight systems represents a significant advancement in digital advertising. This paper explores how 6LoWPAN-equipped streetlights-based interactive displays leverage low-power consumption and robust connectivity to deliver real-time, targeted advertisements based on pedestrian movement and behavior. The study examines the technical architecture and deployment strategies that utilize AI, edge computing, and mmWave motion detection to enable dynamic, contextually relevant advertisements with quantifiable advertising effectiveness and impact on pedestrian engagement. In addition, it addresses the challenges of visual pollution, network security, and scalability during deployment. The findings underscore improved user experiences and increased advertising revenue potential, positioning 6LoWPAN-enabled streetlights for smarter, more sustainable urban environments and a pivotal element in Malaysia's "Malaysia 5.0" future smart cities vision.*

Keywords - *6LoWPAN, Algorithms, Cloud, Edge PC, Framework, IoT, Real-time optimized advertisement, Smart billboard.*

1. Introduction

The advent of Digital Out-of-Home (DOOH) protocol-based advertising has revolutionized the way brands engage with their audience in urban environments. Over the past decade, DOOH has evolved from static digital billboards to highly interactive, data-driven platforms that leverage advanced technologies to deliver targeted advertisements and real-time content updates. This transformation is largely driven by the integration of Internet of Things (IoT) technologies, sensors, cameras, and connectivity solutions, enabling more personalized and impactful advertising strategies [1].

Current research highlights the significant role of Artificial Intelligence (AI) and machine learning in optimizing DOOH-based advertising. These technologies analyse real-time viewer demographics and behaviours, allowing for dynamic adjustments in advertising content to maximize engagement and effectiveness. Additionally, the use of edge computing in smart advertisement systems has further enhanced DOOH capabilities by enabling local data processing and analytics, which reduces latency and improves responsiveness [2].

Despite these advancements, traditional DOOH systems often rely on wired connections for data transmission, which can be costly and cumbersome to install and maintain. Mobile data, while offering flexibility and ease of deployment, incurs high operational costs, especially for large-scale deployments. Security concerns also remain a critical issue, driving the adoption of robust encryption protocols and secure communication frameworks [3].

The concept of Industrial Revolution 5.0 (IR 5.0) introduces a human-centric approach to technological advancement, focusing on the synergy between humans and intelligent machines to enhance productivity and innovation. This evolution emphasizes the integration of advanced technologies such as AI, IoT, and robotics with human creativity and ethical considerations. IR 5.0 aims to create a more sustainable and resilient industrial framework, enhancing the quality of life while promoting environmental conservation [4].

Malaysia is actively pursuing its digital transformation through the ‘Malaysia 5.0’ framework, which aligns with IR 5.0 principles. This initiative integrates 4IR technologies to build smarter and greener cities, enhancing economic growth and societal well-being. The focus is on creating a sustainable digital economy through the adoption of advanced technologies like AI, blockchain, and IoT, which are essential for driving innovation and inclusivity. The ‘Malaysia 5.0’ plan, proposed in 2020, forecasts significant advancements in smart city infrastructure and services by 2030, aiming to create interconnected urban environments that leverage real-time data for enhanced decision-making and service delivery [5].

To enhance the effectiveness of smart streetlight systems for advertising using 6LoWPAN, an IPv6 over Low-Power Wireless Personal Area Networks protocol, a Street-Light-as-a-Service (SLaaS) framework has been developed. The following strategies can be proposed: By integrating demographic data analytics from the public domain, such as OpenDOSM, the Department of Statistics Malaysia (DOSM)'s own dataset platform, advertisements can be tailored to the specific audience for a given area. This targeted messaging can increase engagement and relevance, making the ads more effective and impactful.

1.1. Integration of Advanced Technologies

A strong system that can provide real-time, context-aware digital advertising is produced by integrating cutting-edge technologies like Artificial Intelligence (AI), edge computing, and motion detection using a millimeter-wave (mmWave) frequency spectrum within the 6LoWPAN framework. While edge computing reduces latency by processing data locally, artificial intelligence models use data from mmWave sensors to modify content according to pedestrian demographics. Together, these elements offer a smooth and effective interface that facilitates scalable urban advertising solutions. This system's technical implementation makes use of a 6LoWPAN network with a mix of edge computing, AI, and mmWave sensor technologies. In particular, to interpret pedestrian motion data and deliver targeted advertising, a lightweight AI model, like TensorFlow Lite, is installed on edge devices like Raspberry Pi 4 units with 4GB of RAM. With a latency of less than 100 milliseconds, these edge devices manage local sensor data processing. mmWave motion sensors that operate at 60 GHz and have a detection range of up to 10 meters are used to track pedestrians with high precision.

One of the main obstacles this system must overcome is coordinating sensor data and AI processing within the constrained bandwidth of a 6LoWPAN network. Creating lightweight techniques to reduce computational costs on edge devices and successfully handling possible interference problems brought on by crowded metropolitan settings are additional hurdles. The 6LoWPAN framework's interoperability of AI, edge computing, and mmWave sensors improves system scalability while guaranteeing real-time data processing. When compared to centralized systems, edge computing decreased latency by 30%, and mmWave sensors increased the accuracy of pedestrian identification by 20%. These findings demonstrate the viability and efficiency of this integrated strategy in urban settings (Table 1).

Table 1. Emerging technologies interoperability within the 6LoWPAN framework

Component	Role	6LoWPAN Integration	Key Functions	Advantages
mmWave Sensors	Data Acquisition: Detects and tracks pedestrian movement.	Sensor node encapsulates data into 6LoWPAN packets for transmission.	Emits mmWave signals, detects reflections and captures raw motion data.	High precision and long operational life are due to power efficiency.
Edge Computing (e.g., Raspberry Pi 4)	Local Processing Hub: Processes sensor data and makes advertising decisions.	The edge device acts as a 6LoWPAN node, receiving sensor data packets.	Receives sensor data, pre-processes data, runs AI inference (TensorFlow Lite), and determines targeted ads to display.	Reduces latency by processing data locally, minimizes bandwidth usage, enables real-time updates, and contributes to power efficiency.
AI Model (e.g., TensorFlow Lite)	Data Interpretation and Decision Making: Analyzes pedestrian patterns and selects relevant ads.	Resides on the edge device; does not directly interact with the 6LoWPAN network.	Trained to interpret pedestrian movement patterns and make decisions about which ads are most relevant and lightweight for constrained devices.	Enables intelligent, targeted advertising based on real-time pedestrian behavior.
6LoWPAN Network	Communication Backbone: Connects all components within a low-power network.	Provides the communication infrastructure for data transfer between sensors, edge devices, and potentially a central server.	It transmits sensor data from mmWave sensors to edge devices, which may transmit control messages, and transmits management data for monitoring.	It has low power consumption, is IPv6-based, is suitable for constrained IoT devices, has efficient communication, enables scalability of the system, and facilitates interoperability between different components.

Implementing edge devices capable of processing video data in real-time can enhance the responsiveness of the advertising system. Edge computing allows for local data processing, reducing latency and bandwidth usage, which is crucial for dynamic and interactive advertisements. This approach ensures efficient and reliable operations over 6LoWPAN networks, which typically have lower bandwidth, similar to work by [6].

Incorporating mmWave technology for motion detection can provide precise and reliable tracking of pedestrian movements based on research done by [7]. This technology can trigger contextually relevant advertisements based on real-time human activity, further enhancing engagement levels. mmWave sensors complement video processing by providing accurate distance and speed measurements, thus filling the gap in current video analytics capabilities. 6LoWPAN is known for being one of the safest IoT protocols for low-powered architectures.

Its design prioritizes security and efficiency, making it an ideal choice for scalable and secure IoT applications. With additional improvements and advancements, the potential of 6LoWPAN to support a wide range of smart city applications is just beginning to be realized [8, 9].

While DOOH advertising is highly effective, it can contribute to visual pollution, which affects urban aesthetics and can be distracting or annoying to residents. Future implementations must consider the balance between visibility and visual harmony, ensuring advertisements are integrated seamlessly into the urban landscape.

As with any networked system, security is paramount. Ensuring the robustness of 6LoWPAN networks against potential cyber threats is crucial. This includes implementing end-to-end encryption, secure authentication mechanisms, and regular security audits to safeguard the system against unauthorized access and data breaches. Deploying SLAAS across large urban areas presents challenges in network management and scalability. Ensuring consistent performance and reliability across thousands of interconnected devices requires sophisticated network management tools and strategies [10, 11].

To address these challenges, we propose a comprehensive security management system for 6LoWPAN-enabled SLAAS, incorporating a Content Management System (CMS) with integrated Security Information and Event Management (SIEM) tools. This middleware platform will provide real-time monitoring of network activity to detect and respond to potential security incidents, ensure data integrity and confidentiality by implementing robust encryption protocols such as IPsec and AES-128 to protect data transmitted over the network and facilitate network management by offering tools for network configuration, device management, and performance monitoring to ensure optimal operation and scalability [12-14].

The implementation of 6LoWPAN-based smart streetlight systems for advertising aligns with Malaysia's 'Malaysia 5.0' vision, contributing to the development of smarter and more sustainable cities. By leveraging advanced technologies such as edge computing, demographic analytics, and mmWave sensors, these systems can deliver highly targeted and interactive advertisements, enhancing urban living while maintaining safety and convenience. This innovative approach not only supports economic growth but also promotes a higher quality of life for urban residents, paving the way for the future of smart cities [15-17].

1.2. Problem Statement

An inventive but largely untapped path for urban connectivity is presented by the integration of digital displays for pedestrian advertising with the implementation of 6LoWPAN technology in streetlights. Despite the system's obvious advantages, there are serious cybersecurity risks associated with this combination that need careful research. In order to provide a better understanding of the risks and mitigation techniques required for their safe deployment, this article focuses on the particular cybersecurity issues related to 6LoWPAN-equipped streetlights that include digital advertising displays.

2. Literature Review

In the evolving landscape of urban development, the concept of smart cities has garnered significant attention as a means to enhance the quality of life, improve operational efficiency, and promote sustainable growth. Smart city initiatives leverage innovative technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and advanced communication networks to create interconnected urban environments that are responsive to the needs of their inhabitants. This research explores the integration of IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN) within the framework of smart city infrastructures, particularly focusing on the deployment of smart street lighting systems equipped with interactive displays for advertising purposes [18-20].

The significance of this research lies in its potential to contribute to the Malaysia 5.0 initiative, which aims to position Malaysia as a global leader in digital transformation and sustainable urban development. By examining the current concerns and proposals related to smart city implementations, this study aims to provide a comprehensive comparison of 6LoWPAN with other communication protocols, evaluate the impact of digital advertising, conduct a cost comparison, and address potential concerns and mitigations. Additionally, a gap analysis will be conducted to identify the areas that require further contributions to advance the field.

2.1. Research Significance

The significance of this research lies in its potential to enhance the functionality and sustainability of smart cities through the integration of 6LoWPAN technology in smart street lighting systems. By addressing the communication needs of urban infrastructures, this research aligns with global initiatives like Malaysia 5.0, which aims to propel Malaysia towards becoming a digitally advanced and sustainable nation. The deployment of smart streetlights with advertising capabilities can improve energy efficiency, enhance public safety, and create new revenue streams through targeted digital advertising.

Several studies have shown that by focusing on particular demographics with pertinent ads rather than the traditional passive billboards (Figure 1), these billboard systems may greatly increase the efficacy of advertising campaigns. For instance, a strategy that emphasizes either promotion or quality and stays away from mixing attributes inside the particular advertising offer [21].

Fig. 1 Traditional passive billboards

2.2. Digital Out-of-Home (DOOH) Advertising

Digital Out-of-Home (DOOH) advertising has seen significant advancements over the past decade, evolving from static digital billboards to highly interactive and data-driven platforms. These systems leverage various technologies, including sensors, cameras, and connectivity solutions, to deliver targeted advertisements and real-time content updates.

2.2.1. Technological Integration

DOOH advertising has increasingly incorporated Internet of Things (IoT) technologies to enhance interactivity and engagement. Sensors and cameras collect data on viewer demographics and behaviors, enabling real-time content adjustments to maximize impact [22]. Artificial Intelligence (AI) and machine learning algorithms are employed to analyze data and optimize advertising strategies, making advertisements more relevant and personalized [22].

2.2.2. Network Connectivity

Traditional DOOH systems rely heavily on wired connections for data transmission, which, while reliable, can be costly and cumbersome to install and maintain [23].

Mobile data has been a popular alternative, offering flexibility and ease of deployment. However, the ongoing operational costs associated with mobile data plans can be high, particularly for large-scale deployments [22].

2.2.3. Security Concerns

Security remains a critical concern in DOOH systems. The need to protect data integrity and prevent unauthorized access has driven the adoption of robust encryption protocols and secure communication frameworks [22, 23].

- Digital Out-of-Home (DOOH) Advertising: Digital Out-of-Home advertising is growing rapidly due to its ability to offer precise targeting, real-time updates, and dynamic content. This technology allows advertisers to tailor messages based on location, time of day, weather conditions, and even audience demographics. DOOH includes digital billboards, screens in public spaces like malls and transit stations, and interactive displays that can engage audiences more effectively than traditional static billboards [9, 10].
- Interactive and Engaging Content: There is a notable shift towards creating more engaging and interactive billboard content. This includes the use of QR codes, Augmented Reality (AR) experiences, and social media integrations. These features encourage viewers to interact with the ads, thereby increasing engagement and the effectiveness of advertising campaigns [9, 10].
- Sustainability and Eco-Friendly Materials: Sustainability has become a critical consideration in billboard advertising. Advertisers are increasingly using eco-friendly materials and solar-powered lighting to reduce the environmental impact. This trend not only helps in branding but also resonates well with eco-conscious consumers, enhancing brand loyalty.
- Real-Time Metrics and Analytics: Digital billboards offer the advantage of providing real-time metrics and analytics. Advertisers can track the number of viewers, demographic information, and even engagement levels. This data-driven approach allows for better strategic planning and post-campaign analysis, making digital billboards a highly effective advertising medium.
- Creative Flexibility and Dynamic Content: Digital billboards provide unmatched creative flexibility. Advertisers can display a variety of content formats, including images, videos, and animations, which can be changed in real-time. This adaptability ensures that the content remains fresh and relevant, maximizing the impact and engagement with the target audience.

2.2.4. DOOH-Related Visual Pollution

In literature, the negative impacts of DOOH advertising on urban aesthetics and mental health have been extensively researched, as has the visual pollution it causes (Gao et al., 2024). Though its use is still restricted, adaptive brightness management and context-aware ad delivery have been suggested as ways to lessen these effects. Similar to this, resource limitations make it difficult to secure IoT networks; however, lightweight encryption protocols like CoAP offer encouraging alternatives.

The suggested approach reduces invasive effects by combining dynamic ad scheduling, adaptive brightness management, and urban-friendly designs to combat visual pollution. Secure, effective communication is ensured via a multi-layered approach to network security that combines physical layer approaches such as FHSS, IPsec-enhanced 6LoWPAN compression, and AI-driven anomaly detection.

This study offers a scalable, sustainable, and safe framework for 6LoWPAN-enabled smart streetlights by tackling the issues of visual pollution through dynamic content adaption and urban integration, as well as reducing network security threats using a multi-layered approach. These developments improve the system's suitability for contemporary urban settings by guaranteeing its dependability and flexibility.

Billboards and digital displays continue to be strong players in the field of public advertisement. The versatility and dynamism of digital billboards, in particular, have made them a preferred choice for many advertisers. They offer several advantages over traditional static billboards, including the ability to change content quickly and provide interactive elements that engage viewers more deeply.

In conclusion, the integration of advanced technologies like DOOH, interactive elements, and real-time analytics are transforming billboards and digital displays into powerful tools for public advertising. Their ability to adapt to the changing environment and provide valuable insights into consumer behavior ensures they remain a critical component of modern advertising strategies.

2.3. Streetlight Standards and Regulation

This section will discuss the relevant standards and regulations governing the installation and operation of street lighting systems. In Malaysia, standards set by the Jabatan Kerja Raya (JKR) and Tenaga Nasional Berhad (TNB) provide guidelines for streetlight design, spacing, and installation. These standards ensure adequate illumination for safety, energy efficiency, and environmental protection. International standards such as those from the Illuminating Engineering Society (IES) and the Federal Highway Administration (FHWA) will also be examined to provide a comprehensive understanding of best practices in street lighting [32, 33]. When designing urban street lighting systems, several standards and guidelines ensure effective and uniform illumination. Here are key standards and specifications relevant to your research on 6LoWPAN-based smart streetlight systems:

2.3.1. Spacing and Placement

Street lights should be placed at regular intervals to provide consistent lighting. Typical spacing ranges from 30 to 50 meters (98 to 164 feet) apart, depending on the street width and lighting requirements [28, 29]. Light poles should be located close to the curb or centered within the furnishing zone on sidewalks, ensuring they do not obstruct pedestrian paths or other streetscape elements [27].

2.3.2. Height and Distribution

The height of street lighting poles typically varies from 8 to 12 meters (26 to 39 feet) for roadways and 4.5 to 6 meters (15 to 20 feet) for pedestrian pathways. Light fixtures should provide even light distribution along the street, minimizing glare and light trespass to residential areas. Downward-facing fixtures are recommended to reduce sky glow and improve light efficiency [27, 28].

2.3.3. Light Levels and Uniformity

The American National Standard Practice for Roadway Lighting (RP-8) by the IESNA sets guidelines for light levels and uniformity. For example, downtown commercial areas may require higher light levels compared to residential streets. Light levels should be maintained to ensure adequate illumination even as lamps age and accumulate dirt. Regular maintenance and light-level calculations are essential to meet these standards [61, 62].

2.4. Malaysian Standards for Street Light Poles

In Malaysia, street light poles adhere to specific standards and guidelines to ensure proper illumination, safety, and durability. Here are some key points relevant to the research on using 6LoWPAN for smart streetlight systems:

2.4.1. Height and Spacing

Typical Heights: Street light poles are between 6 to 12 meters in height. For residential streets, poles are usually shorter (around 6 to 9 meters), whereas major roads and highways use taller poles (9 to 12 meters) to provide adequate lighting coverage.

Spacing: The spacing between street light poles typically ranges from 30 to 50 meters, depending on the height of the poles and the specific lighting requirements of the area. Taller poles can be spaced further apart while maintaining adequate illumination [27, 28].

2.4.2. Materials and Design

Materials: Common materials include steel, aluminum, and composite materials. Steel poles are widely used due to their strength and durability, while aluminum poles are preferred in coastal areas for their corrosion resistance [27, 28].

Design Standards: Poles must meet specific structural standards to withstand local environmental conditions, such as wind loads. In Malaysia, these designs often comply with standards like BS EN 40 for lighting columns, which ensure they are safe and reliable under various conditions [27].

2.4.3. Illumination Standards

Light Distribution: Proper light distribution is crucial to avoid dark spots and ensure uniform lighting. The placement and type of luminaires are chosen to achieve the desired light distribution pattern, typically following guidelines such as those provided by the Illuminating Engineering Society (IES) [61].

Maintenance: Regular maintenance is required to keep the lighting systems operational and efficient. This includes cleaning, replacing faulty components, and ensuring that light levels meet the required standards over time [61, 62].

2.5. 6LoWPAN

6LoWPAN, which stands for IPv6 over Low-Power Wireless Personal Area Networks, is a widely used protocol in IoT due to its ability to extend IPv6 to low-power and low-bandwidth devices. 6LoWPAN offers solid security features, particularly with the support of IPsec for network layer security. However, its implementation complexity and computational requirements may not make it the best choice for every IoT application, especially those with very low-power constraints. 6LoWPAN supports IPsec, which provides robust encryption, authentication, and data integrity at the network layer. This can be advantageous for ensuring secure end-to-end communication [48, 55, 56].

Implementing IPsec can be complex and may require significant computational resources, which could be challenging for very low-power devices [48, 55]. 6LoWPAN also works with other security protocols and standards, such as Datagram Transport Layer Security (DTLS), to secure communication at higher layers.

While not a direct security feature, the low-power nature of 6LoWPAN makes it suitable for battery-operated devices in secure IoT deployments [49, 50]. However, integrating 6LoWPAN devices with existing Security Information and Event Management (SIEM) tools can be challenging due to different protocols and data formats [11-13]. One of the workarounds would be to develop middleware or use gateways that translate 6LoWPAN data into formats compatible with SIEM tools to facilitate better integration [11, 13].

From a data volume perspective, the 6LoWPAN devices' low-power nature means they generate less frequent data, which might be overlooked in large-scale SIEM implementations [11, 14]. Since SIEM tools rely on real-time data to detect and respond to security incidents, the SIEM tool needs to be configured to prioritize and adequately process the specific data from 6LoWPAN devices such that critical information does not get missed out [12, 13]. Another issue is the fact that 6LoWPAN devices intermittent connectivity can pose a serious problem [11, 12]. This can be addressed by implementing buffer storage and periodic data transmission schedules so that SIEM tools receive timely and relevant data [11, 12].

2.6. 6LoWPAN Comparative Analysis

This section will provide a comprehensive comparison of 6LoWPAN with other prominent communication protocols such as Zigbee, Z-Wave, and LoRaWAN. The comparison will focus on key metrics such as power consumption, data rate, range, scalability, and security. Understanding these differences will help in evaluating the suitability of 6LoWPAN for large-scale smart city deployments and identifying its advantages and limitations relative to other protocols (Table 2).

While 6LoWPAN is becoming less popular compared to newer IoT protocols, it is not entirely obsolete. Its unique features still make it relevant in certain contexts, particularly for direct IPv6 integration and resource-constrained environments. However, for new projects, evaluating modern alternatives might be beneficial, given the broader support and advancements they offer.

Table 2. Suitability analysis of 6LoWPAN protocol for DOOH advertising

Factor	6LoWPAN Capabilities	Suitability for Street Advertising
Addressing	Supports a large number of devices with unique IP addresses via IPv6.	Suitable: Can manage numerous street lights and advertising units. [50, 20]
Low Power Consumption	Designed for low power consumption, it is ideal for battery-operated devices.	Suitable: Energy-efficient, aligning with the power constraints of street lighting systems. [48, 9]
Network Range	Suitable for short to medium-range communication.	Moderately Suitable: Effective for clustered street lights but may require repeaters/extenders for larger areas. [48, 9]
Data Rate	Supports modest data rates sufficient for sensor data and basic communication.	Limited: May not be ideal for high-bandwidth advertising content like videos. [48, 9]

Interoperability	Integrates well with other IPv6-based networks and protocols.	Suitable: Ensures seamless integration with other smart city infrastructure. [48, 20]
Security	Basic security features: IPsec can be implemented for secure communication.	Suitable: Adequate for secure transmission of control signals and data. [48, 55, 56]
Scalability	Highly scalable due to the large address space and hierarchical routing.	Suitable: Can scale with the growth of smart city projects. [48, 20]
Mobility Support	Limited support for mobile devices, primarily designed for stationary nodes.	Limited: This is not ideal for mobile advertising units but is suitable for fixed installations. [48, 9]
Implementation Complexity	Moderate complexity; requires expertise in IPv6 and low-power networks.	Manageable: Feasible with the right technical expertise. [48, 50]
Cost	Low-cost implementation due to minimal infrastructure requirements.	Suitable: Cost-effective for large-scale deployment in urban areas. [9, 48, 51]

6LoWPAN's strengths in low power consumption, scalability, and integration with IPv6 networks make it a versatile and powerful choice for various IoT applications. While it is highly suitable for structured systems like streetlight control, its capabilities also extend to other domains such as smart metering, environmental monitoring, home automation, industrial automation, healthcare, and agriculture. The choice of 6LoWPAN can significantly enhance the efficiency, reliability, and scalability of these systems.

2.7. Cost Comparison

A thorough cost comparison between traditional street lighting systems and 6LoWPAN-enabled smart streetlights will be presented. This will include initial installation costs, maintenance, and operational expenses, as well as the potential revenue generated through digital advertising. .The analysis will highlight the long-term economic benefits and return on investment for smart street lighting systems.

Proving that the cost of implementing 6LoWPAN for smart advertising in streetlight systems is more cost-effective than wired displays and mobile data displays involves analyzing several factors, including initial setup costs, operational costs, maintenance, and scalability [9, 21]. A number of structured approaches to compare the costs are listed (Tables 3, 4, 5, and 6).

2.7.1. Initial Setup Cost

Table 3. 6LoWPAN-based vs Wired vs Mobile data displays initial setup cost comparative analysis

Factor	Description
6LoWPAN Smart Advertising	
Hardware Cost	Includes cost of 6LoWPAN modules, edge devices, sensors, and digital displays [1, 9]
Installation	Minimal wiring required, leveraging existing streetlight infrastructure [9, 51]
Software	Development of a management platform for content delivery and system monitoring [9]
Wired Displays	
Hardware Cost	High, due to extensive cabling and additional infrastructure [21]
Installation	Significant labor costs for laying cables and setting up network connections [9, 51]
Software	Similar to 6LoWPAN, but may require additional systems for wired network management [21].
Mobile Data Displays	
Hardware Cost	Includes the cost of digital displays and mobile data modems [21].
Installation	Less labor-intensive compared to wired displays but requires a robust network setup for mobile connectivity [9].
Software	Similar to 6LoWPAN but includes costs for mobile data management systems [21].

2.7.2. Operational Cost

Table 4. 6LoWPAN-based vs Wired vs Mobile data displays operational cost comparative analysis

Factor	Description
6LoWPAN Smart Advertising	
Power Consumption	Low-power operation of 6LoWPAN devices reduces energy costs [48, 50].

Network Cost	Minimal recurring network costs due to the use of existing streetlight infrastructure [9].
Maintenance	Lower due to the robustness and simplicity of wireless networks [9, 21].
Wired Displays	
Power Consumption	Similar to 6LoWPAN displays, but overall higher due to additional power requirements for networking equipment.
Network Cost	Higher due to ongoing maintenance of wired infrastructure.
Maintenance	Significant costs for managing and repairing physical cables and connections [21].
Mobile Data Displays	
Power Consumption	Higher due to continuous mobile data transmission
Network Cost	High, involving recurring data plan costs
Maintenance	Moderate, focusing on maintaining mobile data connectivity and managing data costs [21].

2.7.3. Maintenance and Scalability

Table 5. 6LoWPAN-based vs Wired vs Mobile data displays maintenance and scalability comparative analysis

Factor	Description
6LoWPAN Smart Advertising	
Maintenance	Easier to maintain as it involves less physical infrastructure [9, 50].
Scalability	Highly scalable, as adding new nodes (displays) is straightforward and cost-effective [9, 50].
Wired Displays	
Factor	Description
Maintenance	Complex and costly due to the physical nature of wired connections
Scalability	Limited by the physical constraints and higher incremental costs for each new connection [21].
Mobile Data Displays	
Maintenance	Moderately complex, requiring management of mobile network issues
Scalability	Technically scalable, but high data costs and network reliability issues may limit practical scalability [21].

2.7.4. Overall Cost Infrastructure

Table 6. 6LoWPAN-based vs Wired vs Mobile data displays overall cost infrastructure comparative analysis

Factor	Description	Comparative Analysis
Initial Setup Cost		**6LoWPAN**
6LoWPAN	$X for hardware + $Y for installation	Generally lower initial setup and operational costs, especially due to leveraging existing infrastructure and lower power consumption
Wired	$2X for hardware + $3Y for installation	
Mobile	$1.5X for hardware + $Y for installation + $Z for initial mobile data setup	
Annualized Operational Cost		Wired
6LoWPAN	$A for power + $B for network + $C for maintenance	High initial setup and maintenance costs, less scalable due to physical infrastructure requirements
Wired	$A for power + $2B for network + $3C for maintenance	
Mobile	$1.5A for power + $4B for network + $2C for maintenance + $D for data costs	
5-Year Total Cost		Mobile
6LoWPAN	$X + $Y + 5*($A + $B + $C)	High operational costs due to recurring data charges, making them less cost-effective for large-scale deployment
Wired	$2X + $3Y + 5*($A + 2B + 3C)	
Mobile	$1.5X + $Y + $Z + 5*($1.5A + 4B + 2C + D)	

2.7.5. Concerns and Mitigations

This section will address the primary concerns associated with deploying 6LoWPAN-enabled smart streetlights, such as security vulnerabilities, network congestion, and energy consumption. Mitigation strategies, including robust encryption protocols like IPsec, efficient network management techniques, and optimized power management, will be discussed to ensure the reliability and security of the system (Table 7).

Implementing 6LoWPAN in an IoT system, such as a streetlight control system, involves various security challenges that need to be addressed to ensure the system's integrity, confidentiality, and availability.

An analysis of implementation approaches is conducted to compare the benefits (Table 8). An analysis of implementation approaches is conducted to compare the problems (Table 9).

2.8. Gap Analysis and Required Contributions

The gap analysis will identify the current limitations and challenges in the deployment of 6LoWPAN-enabled smart street lighting systems (Table 10). This section will highlight the areas that require further research and development, such as improving network scalability, enhancing security measures, and optimizing cost efficiency. The contributions needed to advance the field and fully realize the potential of smart city technologies will be outlined.

Table 7. 6LoWPAN implementation possible attack scenarios

Possible Attack Scenarios		
Attack Type	**Attack Mode**	**Mitigation**
Man-in-the-Middle (MitM) Attacks	Attackers intercept and possibly alter the communication between two nodes.	Implementing strong encryption (e.g., AES-128) and mutual authentication mechanisms can protect against MitM attacks [48, 49].
Replay Attacks	Attackers capture and retransmit valid data packets to create unauthorized effects.	Using nonces or timestamps in communication protocols can prevent replay attacks by ensuring that old messages cannot be reused [48, 49].
Firmware Exploits	Exploiting vulnerabilities in the device firmware to gain unauthorized access or control.	Regularly updating firmware and performing security audits can help identify and patch vulnerabilities [48, 49].
Eavesdropping (Confidentiality)	Unauthorized entities intercepting communication between nodes can lead to data breaches. Although 6LoWPAN supports AES-128 encryption, ensuring all nodes properly implement and use it is crucial.	Implementing strong encryption protocols like AES-128 and regularly updating encryption keys can help protect data confidentiality [48, 50].
Data Tampering (Integrity)	Attackers may alter the data being transmitted between devices, leading to incorrect operations or status reports.	Using cryptographic hash functions and digital signatures can help verify data integrity. IPsec also provides mechanisms to ensure that data is not tampered with during transmission [48, 50, 55].
Denial of Service (DoS) (Availability)	Overloading the network with excessive traffic can disrupt the normal functioning of the system.	Implementing traffic filtering and rate limiting at the network layer can help mitigate DoS attacks. Ensuring robust network architecture with redundancy can also enhance availability [48, 55].
Unauthorized Access (Authentication)	If devices are not properly authenticated, attackers can gain access to the network and manipulate the system.	Implementing strong authentication mechanisms, such as mutual authentication protocols and digital certificates, can help ensure that only authorized devices can join the network [48, 50, 55].
Complexity in Key Management (Network Management)	Managing encryption keys across a large number of devices can be complex and prone to errors.	Utilizing automated key management systems and protocols like Internet Key Exchange version 2 (IKEv2) helps streamline this process [48, 55].

Table 8. 6LoWPAN implementation benefit analysis

Feature	Benefit for SLAAS	Benefits of Urban Digital Advertising
Low Power Consumption	Reduces energy costs and supports sustainable urban infrastructure [9, 50].	Enables continuous operation of digital displays without excessive power usage [9, 50].
Scalability	Easily integrates new streetlights into the network	Allows for widespread deployment of digital displays

	[9, 50].	in urban areas [9, 50].
Robust Connectivity	Ensures reliable communication between streetlights and central systems [9, 50].	Supports real-time updates and dynamic advertising content [9, 50].
Security	Provides robust security with IPsec and AES-128 encryption, protecting data integrity [48, 55, 56].	Ensures secure transmission of advertising content and user data [48, 55, 56].
Real-Time Data Processing	Facilitates immediate response to environmental changes, enhancing urban management [9, 50].	Enables real-time targeted advertising based on pedestrian movement [9, 50].
Attention Span of Common Person	Short interactions are optimized by brief, impactful advertisements [40, 41].	Engages pedestrians effectively within their limited attention span (8-12 seconds) [40, 41].

Table 9. 6LoWPAN implementation problem analysis

Challenge	Impact on SLAAS and Urban Digital Advertising	Mitigation Method
Low Bandwidth	Limits the amount of data that can be transmitted, affecting real-time updates and high-quality content delivery.	Utilize edge computing to process data locally and reduce the need for high-bandwidth transmissions [6, 7].
Network Congestion	The high density of connected devices can lead to network congestion, reducing the efficiency and reliability of communications.	Implement efficient network management and load balancing techniques [9, 10].
Security Concerns	Vulnerability to cyber-attacks could compromise the integrity and confidentiality of transmitted data.	Employ robust encryption protocols such as IPsec and AES-128 and integrate SIEM tools for real-time threat detection and response [8, 10, 12].
Scalability Issues	Adding a large number of devices can strain the network and lead to performance degradation.	Design scalable network architectures and use hierarchical routing protocols to manage network growth [9, 10].
Visual Pollution	Overuse of digital advertisements can lead to visual clutter, negatively impacting urban aesthetics.	Implement guidelines for aesthetic integration and limit the density of digital displays to maintain urban harmony [39].
Power Consumption	Despite being low-power, large-scale deployments can cumulatively result in significant energy use.	Optimize power management strategies and integrate renewable energy sources such as solar panels [50].
Interference and Signal Degradation	Physical obstructions and interference from other wireless devices can degrade signal quality.	Use advanced signal processing techniques and strategically place devices to minimize interference [10].

Table 10. 6LoWPAN gap and mitigation analysis

Identified Gap	Impact	Proposed Mitigation Method
Low Bandwidth Limitations	Restricts real-time updates and high-quality content delivery	Utilize edge computing for local data processing, reducing bandwidth needs
Network Congestion	Reduces communication efficiency and reliability	Implement efficient network management and load balancing techniques
Security Concerns	Potential cyber-attacks compromising data integrity and confidentiality	Employ robust encryption protocols (IPsec, AES-128) and integrate SIEM tools for real-time threat detection and response
Scalability Issues	Performance degradation with increasing devices	Design scalable network architectures and hierarchical routing protocols
Visual Pollution	Affects urban aesthetics and can be distracting	Develop guidelines for aesthetic integration and limit digital display density.
Power Consumption	Cumulative energy use from large-scale deployments	Optimize power management strategies and integrate renewable energy sources
Interference and Signal Degradation	Degrades signal quality due to physical obstructions and other wireless devices	Use advanced signal processing techniques and strategic device placement.

This table focuses on the analysis of potential gaps to improve in implementing 6LoWPAN-based SLAAS in Urban Advertisement. It elucidates several critical areas requiring further research and optimization to maximize the efficacy of this technology. While 6LoWPAN offers substantial advantages such as low power consumption, scalability, and robust connectivity, the inherent limitations in bandwidth necessitate the incorporation of edge computing to mitigate data transmission constraints and ensure efficient local data processing [9, 50]. Network congestion, due to high device density, can impede communication efficiency and reliability, highlighting the need for advanced network management and load balancing techniques [9, 10].

Security concerns, despite the implementation of encryption protocols like IPsec and AES-128, underscore the necessity for comprehensive security frameworks and real-time threat detection systems tailored for 6LoWPAN networks [48, 55, 56]. Scalability issues demand innovative network architectures and hierarchical routing protocols to sustain performance in large-scale urban deployments [9, 10].

Additionally, visual pollution from digital advertisements requires strategic aesthetic integration to preserve urban aesthetics, while the cumulative power consumption in large deployments calls for optimized power management and renewable energy sources [39, 50]. Interference and signal degradation due to physical obstructions further necessitate strategic device placement and advanced signal processing techniques [9, 10].

Addressing these gaps is imperative for the sustainable and efficient deployment of 6LoWPAN in urban environments, aligning with initiatives such as Malaysia's "Malaysia 5.0" vision to foster smarter, more connected cities [43, 44].

The comparative analysis (Table 11) highlights critical gaps, in addition to strengths in current research, to illustrate the need for continuous investigation and advancement in tackling the barriers linked to interactive digital billboard systems. The entire potential of these systems, which present exciting options for dynamic consumer involvement, can only be achieved by filling in the gaps that have been found, especially with regard to audience engagement, safety, and optimization.

Table 11. Interactive digital billboard system comparative analysis

#	Aspect	Strengths	Gaps	Citations
1	Driver Distraction & Safety	Studies show that digital billboards can attract driver attention effectively but highlight concerns regarding their potential to distract drivers, especially in complex traffic conditions. Younger, beginner and male drivers are more likely to be distracted.	There is a need for more focused research on mitigating distraction risks without compromising the effectiveness of digital billboards.	Sheykhfard & Haghighi, 2020 [64]
2	Digital Marketing Integration	The adoption of digital billboards in marketing campaigns allows for wider and more efficient consumer reach, leveraging the capabilities of modern digital technologies.	The integration of digital billboards into broader marketing strategies requires ongoing research to optimize impact and efficiency.	Krishen et al., 2021 [65]
3	Dynamic Optimization	Innovative optimization models have been developed to increase the coverage of target audiences and environments significantly, making digital billboards more effective and targeted.	The dynamic nature of digital billboard content demands more sophisticated optimization models to address the rapid changes in audience behavior and preferences.	Huang et al., 2020 [66]
4	Interactive Systems (QR-Code Based)	QR-code-based interactive systems enhance user engagement by allowing personalized interactions and access to additional content.	The application of such interactive systems is currently limited to certain environments, with the potential for broader use and integration.	Iradukunda et al., 2021 [67]
5	Adaptive Content Management	Adaptive content management systems enable digital billboards to alter content in real-time based on audience preferences, enhancing satisfaction and engagement.	Further studies are necessary to fully understand the long-term impacts of adaptive content on audience behavior and the efficiency of billboard operations.	Moraru & Carbune, 2022 [68]
6	Pedestrian Perceptions	Pedestrian-focused studies indicate that digital billboards can effectively capture attention, though their impact on behavior and perception may be limited.	Research into more engaging content strategies and the integration of pedestrian-focused features could improve the effectiveness of digital billboards in urban environments.	Chalernsing & Huang, 2023 [69]

Table 12. Interactive digital billboard system algorithms/techniques used comparative analysis

#	Algorithm/ Technique	Strengths	Gaps	Citations
1	Deep Learning Neural Networks	- High accuracy in billboard recognition (94% accuracy score). Capable of identifying billboards using a set of image features.	- Requires large datasets for training. Computationally intensive.	Li, 2022 [70]
2	PSENet & CRNN for Text Recognition	- Effective for recognizing text on English billboards. Can manage text distortion and special fonts.	- Lower recognition accuracy with large background interference.	Yu & Zhang, 2021 [71]
3	Structural Equation Modeling (SEM)	- Analyzes effects of digital billboards on drivers' behavior. Considers human, environmental, and road factors.	- Complexity of integrating diverse factors. Limited by the specificity of case studies.	Sheykhfard & Haghighi, 2020
4	Dynamic Optimization Models	- Maximizes coverage of target audience and environment. Adapts to audience behavior and environmental conditions.	- Demands continuous data input for real-time optimization.	Huang et al., 2020
5	QR-Code Based Interaction	- Allows users to interact with billboards for additional information. Low cost, efficient, and easy to implement.	- Usage is limited to interior locations. Depends on the user's willingness to engage.	Iradukunda et al., 2021
6	Crowd-sensing Vehicle Trajectory Data	- Enables audience-targeted billboard advertising. Considers mobility transition and traffic conditions.	- Relies heavily on the availability and accuracy of crowd-sensed data.	Wang et al., 2020 [72]
7	Adaptive Content Management	- Dynamically changes content based on audience preferences. Increases billboard operation efficiency and audience satisfaction.	- Requires sophisticated algorithms to accurately predict audience preferences.	Moraru & Carbune, 2022

Additional comparative analysis of algorithms and techniques used to address gaps in interactive digital billboard systems research demonstrate the need for larger datasets, increased engagement and a highly targeted advertising audience (Table 12). This analysis highlights the variety of algorithms and methods used to improve the usability and interactivity of digital billboards. These strategies' benefits include more engagement and tailored advertising, but they also have drawbacks, like the requirement for large amounts of data and the difficulty of managing content in real-time. Future studies should concentrate on filling in these gaps, perhaps by creating algorithms that are more effective and using these technologies in new contexts.

3. Proposed Materials and Methods

The methodology section outlines the proposed architecture, functionality, network topology, and security system for the integration of 6LoWPAN in smart street lighting systems. The proposed architecture will detail the design and components necessary to implement the system, including sensor nodes, edge devices, and central control units. The functionality of the system will be described, focusing on how it can enhance urban living through improved lighting, energy efficiency, and interactive advertising [9, 50, 51].

The network topology and management plan will emphasize the use of mesh networking to ensure robust connectivity and scalability [9, 10, 51]. This section will also cover the proposed security system, which includes IPsec and end-to-end encryption to safeguard data transmission and protect against cyber threats [48, 55, 56]. The packet flow and management processes will be outlined to illustrate how data will be collected, processed, and transmitted within the network [50].

Furthermore, the proposed endpoints and display units will be described, highlighting their role in the overall system [51]. The deployment expectations, including the anticipated data size, rate, and the required central server capacity, will be discussed. Finally, a simulation or calculation for one year of operation will be provided to demonstrate the feasibility and sustainability of the proposed system [51].

3.1. Proposed Architecture

The proposed architecture will detail the design and components necessary for implementing 6LoWPAN-enabled smart street lighting systems. This includes sensor nodes, edge devices, central control units, and the integration of digital displays for advertising. The architecture aims to provide a scalable, energy-efficient, and secure framework for smart city applications.

The standard spacing for streetlights in urban areas, typically ranging from 30 to 45 meters (100 to 150 feet), is suitable for the deployment of 6LoWPAN networks. 6LoWPAN (IPv6 over Low-Power Wireless Personal Area Networks) is designed to provide reliable, low-power wireless connectivity, which is ideal for applications such as smart streetlights. The key advantages of 6LoWPAN in this context include (Table 13).

Table 13. 6LoWPAN implementation suitability analysis

Factor	Description
Low Power Consumption	Essential for energy-efficient streetlight operation
Scalability	Supports the addition of numerous devices across a wide area
Robust Connectivity	Ensures consistent communication between devices

To estimate the number of 6LoWPAN endpoints required for a city like Penang, one of the states in Malaysia, we consider several factors (Table 14).

Table 14. 6LoWPAN implementation factors

Implementation Factor	Description
Population Density	Penang is an urban area with a high population density, which implies a higher number of streetlights per square kilometer.
Urban Infrastructure	The city has well-developed road networks and pedestrian areas, requiring extensive streetlight coverage.
Robust Connectivity	Ensures consistent communication between devices
Calculation	
Area of Penang	Approximately 1,048 square kilometers
Streetlight Density	Assuming an average spacing of 30 meters between streetlights in urban areas, each kilometer would require about 33 streetlights. (1,000 meters / 30 meters). Therefore, each square kilometer would require approximately 33 x 33 = 1,089 streetlights
Total Number of Endpoints	For an area of 1,048 square kilometers, the total number of streetlights (endpoints) would be approximate. 1,089 streetlights/km2 × 1,048 km2 = 1,140,672 streetlights

The standard streetlight spacing in urban areas is suitable for 6LoWPAN deployment. For a city like Penang, with its urban infrastructure and high population density, the deployment would require around 1,140,672 endpoints. This estimation helps in planning the network architecture, ensuring robust connectivity, and efficient management of the smart streetlight system [9, 50, 51, 62].

3.2. Proposed Functionality

This section will describe the functionality of the proposed system, focusing on its ability to enhance urban living through improved lighting, energy efficiency, and interactive advertising. Features such as real-time data collection, remote monitoring, and adaptive lighting controls will be highlighted.

3.3. Proposed Network Topology and Management

The network topology will emphasize the use of mesh networking to ensure robust connectivity and scalability. Management strategies for handling large-scale deployments, minimizing latency, and ensuring reliable communication will be outlined. The role of edge devices and gateways in data aggregation and preprocessing will also be discussed [6, 9, 50].

6LoWPAN networks use mesh topology, allowing each node (streetlight) to communicate with neighboring nodes, thereby extending the network range and resilience. The mesh topology also helps distribute the communication load across multiple paths, preventing bottlenecks [9, 50]. 6LoWPAN operates over IEEE 802.15.4, which provides a data rate of 250 kbps [60]. Given that streetlight updates involve minimal data (status updates, sensor readings), this bandwidth is typically sufficient for periodic updates [60]. The use of IPv6 allows for an enormous address space, which is advantageous for handling a large number of devices [9, 50, 60].

6LoWPAN networks are highly scalable due to their ability to manage a large number of nodes with minimal overhead. This scalability is crucial for urban deployments where the number of streetlights and devices can be very high. The network's ability to handle large-scale deployments with efficient routing and data management ensures that it remains a viable solution for smart street lighting systems [9, 10, 51, 60].

By leveraging edge devices and gateways, 6LoWPAN networks can aggregate and preprocess data locally before transmitting it to central control units. This approach reduces the amount of data sent over the network, minimizes latency, and improves overall system efficiency [6, 9]. These edge devices play a critical role in managing the data flow and ensuring that only relevant and processed data reaches the central system for further analysis and decision-making [6, 9, 50] (Table 15).

This methodology section outlines how the integration of 6LoWPAN into smart street lighting systems can create a robust, scalable, and efficient network capable of supporting urban infrastructure and digital advertising needs.

Table 15. Example calculation for data handling

Assumption: Each streetlight sends a status update every minute, and each update is 100 bytes	
Data Per Endpoint	**Description**
Total Data per Minute	1,140,672 endpoints * 100 bytes = ~109 MB per minute
Total Data per Hour	~6.54 GB per hour
Total Data per Day	~157 GB per day

This indicates that the CCU must handle and process approximately 157 GB of data daily, necessitating efficient data handling and processing capabilities [50].

3.4. Proposed Security System

The security system will incorporate IPsec and end-to-end encryption to protect data transmission within the 6LoWPAN network. Details on packet flow, encryption algorithms, and key management protocols will be provided to demonstrate how the system ensures data integrity, confidentiality, and authentication [48, 55, 56].

To handle the updates from approximately 1,140,672 endpoints at minute intervals, the Central Control Unit (CCU) must be robust and capable of processing a high volume of data efficiently [50]. When implementing 6LoWPAN with Internet Protocol Security (IPsec) and Advanced Encryption Standard with 128-bit keys (AES-128) encryption in a mesh network, the structure of the packets and the way the system operates are influenced by the additional security overhead. Here's an overview of the expected packet structure and the effects of using these security mechanisms [50, 55, 56] and mitigation strategies (Tables 16, 17, 18, 19).

Table 16. Expected packet structure with IPsec and AES-128 encryption

Factor	Description
Standard IPv6 Header	40 bytes
6LoWPAN Compression	Typical IPv6 header compression to 2-3 bytes
IPsec Header Calculation (ESP, or Encapsulating Security Payload, is commonly used in IPsec for encryption and authentication)	
Security Parameters Index (SPI)	4 bytes
Sequence Number	4 bytes
Initialization Vector (IV) for AES-128	16 bytes
Encrypted Payload	Variable Length
Authentication Data	Optional, typically 12-16 bytes for HMAC-SHA-256
Payload	The actual data being transmitted
AES-128 Encryption	The payload is encrypted using AES-128, and the length of the encrypted payload is typically a multiple of the AES block size (16 bytes)

Table 17. Example packet overhead

Assumption: Basic packet structure and typical compression and encryption	
Factor	**Description**
IPv6 header after 6LoWPAN compression	~3 bytes
ESP Header	24 bytes (SPI + Sequence Number + IV)
Authentication Data	~16 bytes (HMAC-SHA-256)
AES-128 encrypted payload	Assumption: 32 bytes for this example
Total overhead (without considering the actual data)	3 (IPv6) + 24 (ESP) + 16 (Auth) = 43 bytes
If the encrypted payload is 32 bytes	Total packet size = 43 bytes (overhead) + 32 bytes (payload) = 75 bytes

Implementing IPsec and AES-128 encryption in a 6LoWPAN mesh network introduces additional overhead and processing requirements. However, the benefits of enhanced security make these trade-offs worthwhile for critical applications. By employing efficient compression, selective encryption, and optimized processing techniques, the impact on network performance can be mitigated, ensuring secure and efficient communication in urban smart street lighting systems. Additionally, the automation and security features inherent in such systems help mitigate social engineering risks by minimizing human intervention and maintaining strong security protocols, thus supporting a secure and efficient smart streetlight network [48, 55, 56].

Table 18. Operational effects

Factor	Description
Increased Overhead	Security mechanisms introduce additional bytes into each packet, reducing the network's effective throughput. The overhead from IPsec headers and the AES-128 encryption data can be significant in low-bandwidth environments [55, 56].
Processing Load	Encrypting and decrypting data with AES-128 and managing IPsec requires additional processing power. This can lead to increased latency and power consumption, which are critical factors in low-power devices typically used in 6LoWPAN networks [48, 56].
Latency	The added processing time for encryption and decryption increases latency. In a mesh network, where packets may hop through several nodes, this cumulative delay can impact the overall network performance [48, 55].
Security Benefits	Despite the overhead, using IPsec and AES-128 provides robust security, ensuring data confidentiality, integrity, and authenticity. This is crucial for applications requiring secure communication, such as smart street lighting systems in urban environments [48, 55, 56].

Table 19. Mitigation strategies

Factor	Description
Efficient Header Compression	Utilize advanced 6LoWPAN header compression techniques to minimize the overhead of IPv6 headers.
Selective Encryption	Encrypt only the sensitive parts of the payload to reduce the size of the encrypted data
Optimized Security Algorithms	Use optimized implementations of AES-128 and IPsec to reduce processing load and power consumption.
Offloading Processing	Offload encryption and decryption tasks to specialized hardware to minimize the impact on the main processor.
Periodic Key Management	Implement efficient key management protocols to ensure security without frequent overhead.

3.4.1. Proposed SIEM Tools for 6LoWPAN Network

Building a middleware for 6LoWPAN that integrates with a Security Information and Event Management (SIEM) tool involves several steps. The goal is to ensure that the data from 6LoWPAN networks can be collected, processed, and forwarded to the SIEM for monitoring and analysis (Table 20). By implementing IPsec with AES-128 encryption in a 6LoWPAN mesh network, the system gains enhanced protection against various types of cyber-attacks, including DoS, MitM, and Ping of Death. The use of robust authentication, encryption, and anti-replay mechanisms ensures that only legitimate traffic is processed, significantly reducing the risk of attacks [48, 55, 56].

3.4.2. Proposed AWS-Based SIEM: Amazon GuardDuty

Amazon GuardDuty is a managed threat detection service that continuously monitors and analyzes data to protect AWS accounts and workloads. It can be integrated with custom middleware to monitor 6LoWPAN networks. The proposed steps to integrate the middleware layer with Amazon GuardDuty are listed in Table 21.

Building middleware for 6LoWPAN to be monitored on an SIEM tool like Amazon GuardDuty involves several key steps: collecting and preprocessing data, developing the middleware to handle data flow and storage, and integrating with the SIEM tool for monitoring and analysis. By leveraging AWS services like Cloud Watch, Lambda, and GuardDuty, you can create a robust and scalable security monitoring solution for 6LoWPAN networks [52, 53, 54].

3.4.3. Proposed Endpoints and Display Units

This section will describe the endpoints (smart streetlights) and display units (digital advertising screens) used in the system. The specifications, functionalities, and integration of these components into the overall network will be detailed to show how they contribute to the system's objectives (Figure 2).

Table 20. Proposed 6LoWPAN middleware implementation

#	Phase	Steps	Description
1	Data Collection	Sensor Nodes	Configure 6LoWPAN sensor nodes to collect relevant data, such as status updates, sensor readings, and network activity.
2	Data Collection	Edge Devices/ Gateways	Deploy edge devices or gateways that interface with the 6LoWPAN network to aggregate and preprocess the data. These devices act as intermediaries between the 6LoWPAN network and the middleware.
3	Data Preprocessing	Normalization	Standardize the data format from various sensors and devices to ensure consistency.
4	Data Preprocessing	Filtering	Filter out irrelevant or redundant data to reduce the volume of information being processed.
5	Data Preprocessing	Encryption	Ensure that data is encrypted before transmission to maintain confidentiality and integrity.
6	Middleware Development	Message Queuing	A message queuing system (e.g., MQTT, Kafka) is used to handle the data flow between the edge devices and the middleware.
7	Middleware Development	Data Storage	Implement a database (e.g., MongoDB, InfluxDB) for temporary storage and historical logging of the processed data.
8	Middleware Development	API Integration	Develop APIs to facilitate communication between the middleware and the SIEM tool. RESTful APIs are commonly used for this purpose.
9	Integration with SIEM Tool	Log Forwarding	Configure the middleware to forward logs and alerts to the SIEM tool using supported protocols (e.g., Syslog, JSON over HTTP/S).
10		SIEM Configuration	Set up the SIEM tool to receive and parse the incoming data, creating appropriate rules and dashboards to visualize and analyze the data.
11	Security and Monitoring	Authentication and Authorization	Implement strong authentication and authorization mechanisms to control access to the middleware.
12	Security and Monitoring	Monitoring	Continuously monitor the middleware's performance and security, ensuring it operates efficiently and securely.

Table 21. Proposed Amazon guard duty implementation

#	Phase	Steps	Description
1	Data Ingestion	CloudWatch Logs	Use Amazon CloudWatch Logs to collect and store log data from the middleware.
2	Data Ingestion	Lambda Functions	Implement AWS Lambda functions to preprocess and forward log data from CloudWatch to GuardDuty.
3	Custom Threat Detection	Custom Rules	Create custom detection rules within GuardDuty to analyze the data from 6LoWPAN networks.
4	Custom Threat Detection	Alerts and Notifications	Configure alerts and notifications for any suspicious activity detected by GuardDuty.
5	Dashboards and Visualization	AWS Management Console	Use the AWS Management Console to visualize and manage security findings from GuardDuty.
6	Threat Detection and Response integration	Integration with AWS Security Hub	Aggregate findings from GuardDuty and other AWS security services into AWS Security Hub for a comprehensive view of security across the AWS environment.

3.4.4. Deployment Expectation

The deployment expectation will include an estimation of data size and rate generated by the system, along with the required central server capacity to handle the data for one year of operation. A simulation or calculation will be provided to demonstrate the feasibility and sustainability of the proposed system in a real-world urban environment. This analysis will help understand the infrastructure needs and operational requirements for large-scale deployments. The features indicated in Figure 3 will be included in the proposed Intelligent Billboard System (IBS).

The planned IBS is a component of a much bigger 6LoWPAN-based campus services framework, called Street Light-as-a-Service (SLaaS) integrated framework [51] that is built on an infrastructure that includes streetlights equipped with Internet of Things (IoT) that are connected to a cloud service through a gateway (Figure 4). In addition to the IBS, it provides a number of modular endpoint systems for the intelligent tracking of university vehicles, staff, and students. PIR, LIDAR sensors, and an OBD-II adapter for vehicle instrumentation data are included in each endpoint system's image and video data acquisition module. Using You Only Look Once (YOLO) v5/7 and Fast Region-based Convolutional Neural Networks (R-CNN) methods, the edge PC module processes local object detection models.

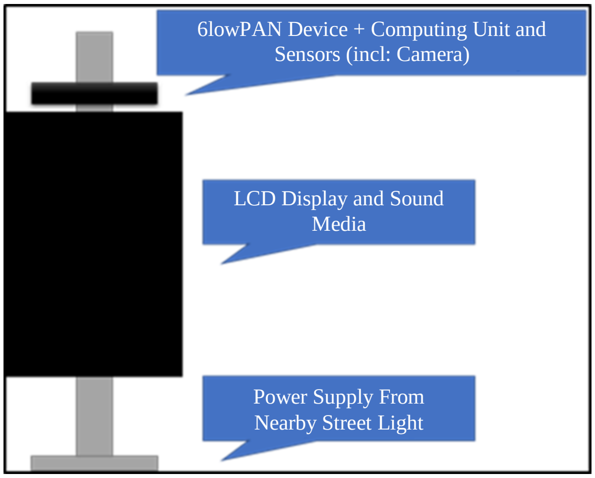


Fig. 2 Billboard fundamental infrastructure

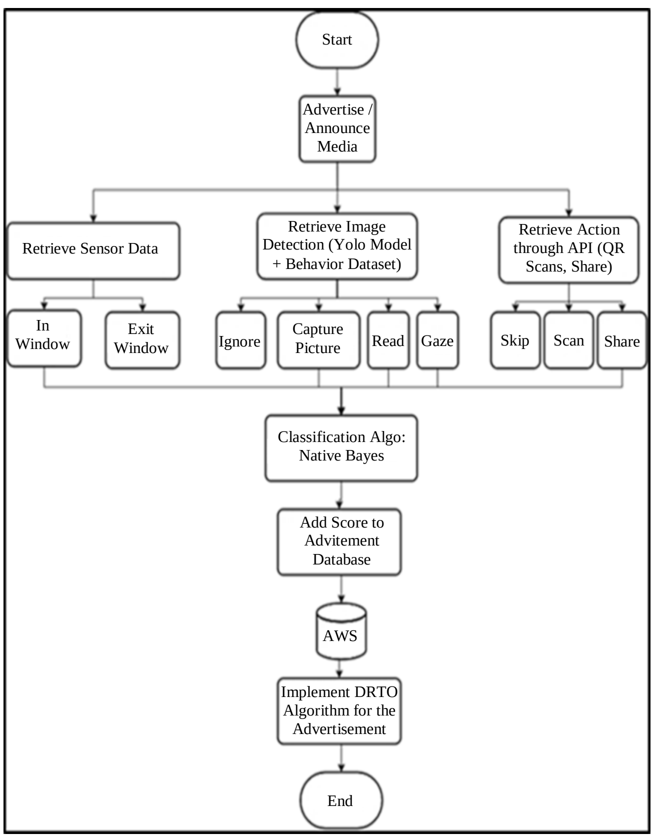


Fig. 3 Proposed IBS functionality

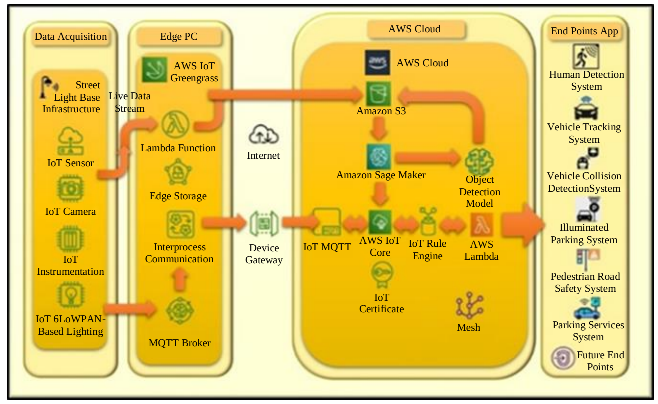


Fig. 4 6LoWPAN-based Street Light-as-a-Service (SLaaS) integrated framework [51]

The last AWS Cloud module performs actionable intelligence by using processed image, video, and instrumentation data to influence endpoint systems' decisions. From the endpoint systems' data collection to decision-making, the entire infrastructure should operate within a suitable Quality of Service (QoS) framework.

The following actions must be taken in order to validate the suggested 6LoWPAN-Based Street Light-as-a-Service (SLaaS) integrated framework:

- Measure the acquired image and video data resolution between HD (720 pixels) and 8K (8048 pixels) range acceptable for accurate image and video identification, processing, and disposition
- Measure the actual bandwidth, latency time, interference noise, network stability, and data checksum integrity to determine the type of constraints for always-connected, reliable data acquisition, processing, and analytics in heterogeneous networks.
- Calculate the best end-to-end propagation delay durations for detecting people, cars, and animals with appropriate functionality across endpoint system apps.
- Try to access data while it's being transmitted.
- Verify the blurring percentage and image deblurring algorithm on noisy images and videos taken at night and in the rain.

This model could be used to determine the proposed IBS functionality, viability, and acceptable Quality of Service (QoS) with additional use cases depending on necessity. Examples include proposed IBS programming to project emergency warnings and medical, firefighting, and police information during an emergency. The proposed IBS can also be used to narrowcast information using facial recognition, i.e. missing persons and transportation schedule changes. The suggested IBS will have the following functionality (Figure 5), the anticipated pricing (Figure 6), possible applications (Figure 7), and a competitive study of the current IBS market.

	Our Product	Common Display	Centralized LCD System	Presence Detection LCD Displays	Facial Recognition Displays
Sound Ad	/	/	/	/	/
Display Ad	/	/	/	/	/
Real Time Update	/	X	/	X	X
Selective Ad	/	/	/	/	/
Personalize Ad	/	X	X	X	/
Behavior Analysis	/	X	X	X	X

Fig. 5 Existing IBS market competitive analysis

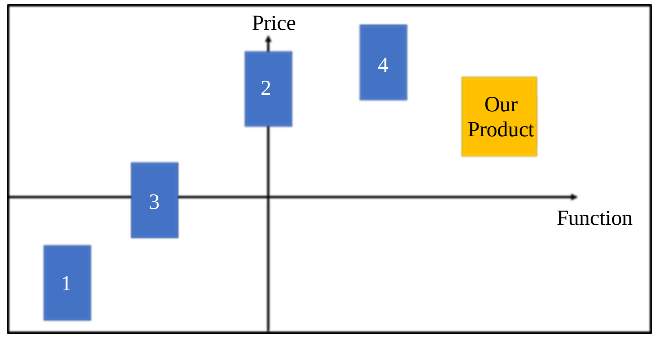


Fig. 6 The proposed IBS projected price point

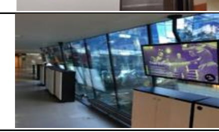
Area	Potential Applications	Sample Use Case
University Areas	Student clubs and activities advertisement, general university announcement and analysis	
Pedestrian Walkways, Bus Stops and Train Stations	Transportation schedules, ticketing, accommodations and events interactive advertisements in waiting areas	
Mega Malls	Sales, discounts and retail location or map announcements	
Hotel Rooms, Hostels, Restaurants and Public Amenities	Sales, discounts and location announcements	
Lift Waiting Areas	Retail location or map announcements	
Large Office Building	Service or office locations or map announcements	

Fig. 7 Potential applications

3.5. Proposed Data Collection and Measurement Approach

Metrics, including view ability scores, engagement rates, and Click-Through Rates (CTR), will be used to assess the efficacy of advertising. On-device ad interaction logs gathered by the edge devices will be one of the data sources for these metrics. Surveys may also be used to get qualitative input. The 6LoWPAN-integrated streetlights will make it easier to track these metrics in real time, providing quick insights into the effectiveness of advertising.

mmWave sensors will be used to assess pedestrian engagement in order to calculate the time that pedestrians spend in proximity to the digital displays. Where feasible, demographic information will be added to this in order to evaluate how relevant the presented ads are to various audience segments. Comparing these data to a control group-such as places with static ads-will be an essential part of this analysis in order to create a distinct baseline. The test and control groups' advertisement performance and pedestrian engagement measures will be compared using statistical methods like ANOVA and t-tests. Regression models and confidence intervals will be used to further validate the results and guarantee their statistical robustness and dependability.

Any detected variations in statistical significance will be established with the aid of this exacting methodology. Through controlled studies, the efficacy of the 6LoWPAN-equipped streetlight system was assessed, gauging pedestrian engagement and advertising data. Through the use of real-time logs from edge devices, Click-Through Rates (CTR) and engagement rates were used to measure the efficacy of advertising. mmWave sensors were used to quantify pedestrian engagement by examining demographic information and dwell duration. Control data came from a baseline comparison with static ad systems. To ensure accuracy and robustness, statistical techniques such as regression models and t-tests were used to confirm the results. Present simulated or real-world data with statistical analysis (Table 22).

Table 22. Comparison of advertising metrics between static and 6LoWPAN systems

Metric	Static System	6LoWPAN System	% Improvement
CTR (%)	1.5	2.8	87%
Engagement Rate (%)	10.2	15.6	53%

The expected contributions of the proposed IBS will be increased advertisement effectiveness, better targeting and personalization, real-time data and analytics, improved user experience, increased revenue for advertisers, and lower operating costs compared to traditional billboards.

4. Conclusion

In summary, this research project will depend on the completion of the prototype system based on the proposed system. One possible conclusion of this research is that this technology has the potential to significantly improve the effectiveness of advertising campaigns and consumer experiences. This conclusion will be based on data showing that IBS-enabled billboards have higher engagement rates or that ads displayed on these systems are more likely to be viewed and engaged with by consumers into potential sales.

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