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Vehicle Monitoring and Theft Detection using LoRaWAN and Image Recognition with Mobile Application Integration

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***Abstract*— Vehicle theft remains a serious issue, especially in places where mobile network coverage is weak and conventional GPS or GSM trackers tend to fail. In this work, we developed a prototype security system that combines LoRaWAN communication with an ESP32-CAM module to detect unauthorized access through simple on-device image processing. Instead of relying on cellular data, the system sends alerts and key image information through a long-range LoRa link, which keeps the operating cost low while maintaining reliable communication. A companion mobile application was built to forward notifications to the user and allow basic remote interaction with the vehicle. Tests carried out in suburban and semi-rural areas showed that the system could maintain communication across long distances and react quickly enough to be useful during theft attempts. The results suggest that pairing lightweight visual detection with LoRaWAN can offer a practical alternative to traditional vehicle-tracking setups.**

***Index Terms*— LoRaWAN, Edge Image Processing, ESP32-CAM, Vehicle Intrusion Detection, Low-Power IoT Security, Long-Range Communication.**

I. INTRODUCTION

Vehicle theft has increased in many regions where drivers depend on basic alarms or GPS-based trackers for protection. These systems tend to work well in cities but struggle in places with unstable or weak cellular coverage. Earlier studies pointed out that GSM (Global System for Mobile Communications) and GPS (Global Positioning System) units lose reliability once signal strength drops, which leads to delayed or missing location updates [1]. Many commercially available trackers face similar issues since they operate within the limits of mobile networks and require recurring subscription costs that discourage long-term use [5].
Recent work introduced low-power wide-area technologies that can operate over long distances with very little energy. LoRaWAN (Long Range Wide Area Network) has shown stable communication in outdoor environments, which makes it a practical option for vehicle monitoring in areas where cellular networks fail to respond consistently [3]. In parallel, compact camera modules have become capable of running simple recognition tasks on the device itself. The ESP32-CAM (Espressif Systems 32-bit Camera Module) is one such module, designed for lightweight visual processing without constant dependency on the cloud [2].

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These developments create an opportunity to rethink how vehicle security systems are built. Instead of depending only on GPS or GSM networks, a system that uses edge-based image capture together with long-range wireless communication can detect unauthorized access faster while reducing network costs. The idea behind this work is to explore such a combined approach and examine whether it can offer more reliable protection in locations where traditional tracking methods show limitations. A solution of this kind may also help reduce false alarms by providing visual confirmation of suspicious events before triggering any user notification. Such improvements could make vehicle security more accessible in areas where network infrastructure remains limited or costly to maintain.

II. Related Work

Early vehicle security systems relied mainly on GSM or GPS modules to report a vehicle's position. Several studies found that these systems work with acceptable accuracy in urban areas but face performance drops when the network signal weakens or when vehicles move through regions with limited coverage [1]. These limitations encouraged researchers to explore alternative communication methods that do not depend heavily on cellular networks.

As embedded hardware improved, small camera modules such as the ESP32-CAM began to attract interest for security applications. The module offers onboard processing and a low-cost camera design that supports basic image handling without relying on cloud servers for every frame [2]. Technical documentation and benchmark studies further confirmed the suitability of the ESP32-CAM for lightweight image and AI-based tasks in constrained environments [7].

Alongside these hardware developments, LoRaWAN gained attention as a suitable communication standard for long-distance data transfer. Investigations into its performance in vehicular networking showed that LoRa links can remain stable even across large outdoor areas, making the technology appealing for monitoring systems that need consistent coverage [3]. Field experiments further demonstrated reliable vehicle-to-roadside and vehicle-to-infrastructure communication using LoRaWAN under real-world conditions [6].

Mobile applications also evolved to support real-time interactions between users and vehicle monitoring systems. Cross-platform frameworks such as Flutter enabled developers to build mobile interfaces that support alert delivery and remote monitoring while maintaining consistent performance across devices [4]. These improvements made it easier to integrate sensor data and user interaction within a single application.

Commercial GPS trackers remain widely used but face challenges such as authentication weaknesses, high subscription fees, and limited adaptability in low-signal regions [5]. Research comparing communication technologies highlighted that cellular-based systems consume significantly more power than LoRa-based alternatives, reducing their suitability for long-term monitoring [11].

Additional studies examined MQTT (Message Queuing Telemetry Transport)-based messaging for IoT systems and highlighted its effectiveness in reliable data delivery [9], while cloud broker platforms such as HiveMQ demonstrated scalability and performance stability in multi-device environments [10]. Research on edge-based image processing showed that performing recognition tasks on-device reduces latency and improves privacy compared to cloud-only approaches [12]. Further investigations validated LoRaWAN reliability in rural and semi-urban deployments [13], explored GNSS module integration for hybrid tracking systems [14], and analyzed security vulnerabilities in IoT-based vehicle monitoring platforms [15].

III. Motivation

Traditional vehicle tracking systems rely heavily on GPS and GSM networks, which makes their performance dependent on the strength and stability of cellular coverage. Many regions still experience network gaps, so alerts and location updates do not always reach users in time to prevent theft [1]. These systems also generate recurring data charges that accumulate when vehicles are monitored over long periods, creating a barrier for users who need continuous protection but want to avoid high operational costs [5].

Edge-capable devices have gained attention as a way to improve responsiveness in monitoring systems. Modules like the ESP32-CAM can capture images on the spot and perform basic recognition tasks without sending every frame to the cloud, which helps reduce delay and lowers the chance of missing important visual cues [2]. Studies on edge-based image processing further indicate that local analysis improves response time and minimizes unnecessary data transmission [12].

Meanwhile, research on LoRaWAN shows that long-distance communication is possible with very low power usage, making it a promising alternative to traditional cellular networks for vehicle security applications [3].

Field tests in vehicular environments confirmed that LoRaWAN maintains stable connectivity even when conventional mobile networks fail to perform reliably [6]. These developments suggest that combining local image analysis with long-range wireless communication could provide more dependable vehicle monitoring in real-world conditions.

IV. Problem Domain

Vehicle security systems are expected to operate reliably in diverse environments, yet solutions that depend on GSM or GPS often fall short when the network signal becomes weak or unstable [1]. In such situations, tracking updates may be delayed or lost entirely, reducing the system's ability to respond effectively during theft attempts. This creates a significant gap between user expectations and actual system performance.

Recent developments in embedded hardware introduced compact modules capable of capturing and processing images directly on the device. The ESP32-CAM is one such module that can perform basic image analysis without relying entirely on cloud services, making it suitable for real-time intrusion detection tasks [2]. Technical evaluations of this module show that it supports lightweight processing while maintaining low cost and power consumption [7].

However, image capture alone cannot ensure reliable monitoring unless it is paired with a communication method capable of long-range, low-power transmission. LoRaWAN provides an alternative communication path designed to support wide coverage and energy efficiency compared to cellular-based systems [3]. Experimental studies demonstrated that LoRaWAN performs reliably in vehicular monitoring scenarios, even in semi-urban and rural environments [13].

A complete vehicle security solution also requires a user interface that allows timely access to alerts and system status. Mobile applications developed using cross-platform frameworks enable efficient notification delivery and remote monitoring capabilities [8]. The problem domain addressed in this work therefore lies in integrating edge-based image detection, long-range communication, and user-friendly interaction into a unified system that can operate effectively where traditional GPS or GSM solutions fail.

V. Problem Definition

Vehicle tracking systems that rely on GSM or GPS often fail to deliver consistent security because their performance drops whenever cellular coverage becomes weak or unstable [1]. These systems struggle to send timely alerts, which leaves users unaware of suspicious activity until it is too late. This limitation has remained a major challenge in regions that do not have strong network infrastructure.

Embedded camera modules such as the ESP32-CAM offer a way to capture images directly on the device, allowing systems to detect unusual activity without depending entirely on cloud servers [2]. Technical studies confirm that such modules can perform lightweight processing while operating within the constraints of low-power embedded environments [7]. However, a camera alone cannot provide reliable protection unless the captured information reaches the user through a stable communication channel.

LoRaWAN helps address this gap due to its long-range communication capability and low power usage, enabling monitoring systems to function in places where cellular coverage is inconsistent [3]. Field evaluations in vehicular environments showed that LoRaWAN links remain stable across several kilometers, even under challenging network conditions [6]. Despite improved communication reliability, users still require a practical interface to receive alerts and respond quickly when suspicious behavior is detected. Mobile applications provide this capability by enabling real-time notifications and basic control functions that improve overall system usability [8].

The problem addressed in this work is the lack of an integrated solution that combines local image detection, long-range communication, and user-friendly access in environments where traditional GPS or GSM setups fail to operate reliably.

VI. Statement

GPS-based tracking systems struggle to deliver reliable theft detection because their performance depends heavily on cellular coverage, which often becomes unstable in many regions [1]. Edge-capable modules such as the ESP32-CAM can recognize unusual activity directly on the device, offering a faster response compared to systems that rely solely on location data [2]. Benchmark studies further validate the suitability of such modules for lightweight processing in embedded security applications [7].

LoRaWAN provides a communication path that works across long distances with low power consumption, making it suitable for environments where GSM networks lose signal strength [3]. Field experiments confirmed its effectiveness for vehicular communication in both urban and semi-rural conditions [6]. Mobile applications support timely alerts by providing users with immediate access to system notifications and status information through cross-platform interfaces [8].
This work focuses on creating a vehicle security solution that combines local image detection, long-range wireless communication, and a practical user interface to overcome the limitations of traditional GPS or GSM-based tracking systems.

VII. Innovative Content

This work introduces an approach that integrates long-range wireless communication with lightweight visual detection to enhance vehicle security. Traditional GPS-based tracking systems often fail in regions with weak or unstable cellular coverage, limiting their effectiveness during theft incidents [1]. By incorporating edge-based image capture, the system can detect suspicious activity locally without relying entirely on remote servers [2]. Benchmark studies on embedded vision modules support the feasibility of running lightweight image analysis tasks on constrained devices [7].
The communication layer is built using LoRaWAN, which enables stable data transmission over long distances while maintaining low power consumption [3]. Field experiments in vehicular environments demonstrated that LoRaWAN supports reliable connectivity even in semi-urban and rural regions where cellular networks underperform [6]. These characteristics make LoRaWAN suitable for continuous vehicle monitoring applications.
To support user interaction, a mobile application provides real-time alerts and status updates. Cross-platform development frameworks allow such applications to deliver consistent performance across devices while simplifying deployment [8]. Together, these components form a unified framework that combines edge-based intelligence, long-range communication, and user accessibility to offer a more dependable alternative to conventional vehicle tracking solutions.

VIII. Problem Design

The design of the system focuses on addressing the weaknesses found in traditional vehicle security setups that depend on unstable GSM or GPS signals for updates and alerts [1]. At the hardware level, the ESP32-CAM is used to capture images on the vehicle, enabling basic processing tasks to run locally without frequent reliance on cloud services [2]. Technical documentation confirms that this module supports lightweight processing while maintaining low cost and energy efficiency [7]. For communication, the system employs LoRaWAN gateways that support low-power transmission over long distances, helping maintain consistent alert delivery in areas where cellular networks perform poorly [3].

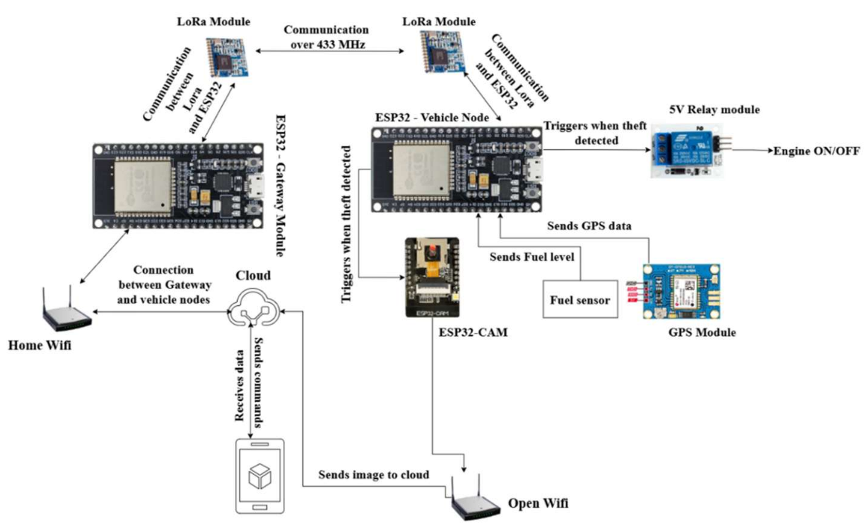

Figure 1. System Architecture of the Proposed LoRaWAN-Based Vehicle Monitoring and Theft Detection System

Vehicular field tests have shown that LoRaWAN links remain stable over several kilometers, even under challenging environmental conditions [6]. To further validate the suitability of this communication approach, prior studies also reported reliable performance of LoRaWAN-based vehicle monitoring systems in semi-urban deployments [13].
On the user side, a mobile application provides quick access to notifications and vehicle status information, allowing users to respond promptly when suspicious activity is detected [8]. The system architecture separates sensing, communication, and user interaction into dedicated layers, simplifying deployment and maintenance. Local filtering on the ESP32-CAM reduces unnecessary data transmission, while the gateway and backend components manage message routing and storage to support scalable operation. The overall system architecture, including communication flow, sensing components and cloud interaction, is illustrated in Fig. 1.

IX. Solution Methodologies

The proposed vehicle monitoring and theft detection system employs a comprehensive solution methodology integrating hardware, communication protocols, and AI-based image analysis to achieve timely and accurate vehicle security monitoring.

A. Dataset Preparation and Model Fine-tuning

The image recognition module relies on a small dataset collected under different lighting and environmental conditions. This dataset enables the ESP32-CAM to distinguish between normal activity and potential intrusion events, which represents an improvement over GPS-only systems that cannot interpret visual context [2]. Benchmark and technical studies on the ESP32-CAM confirm its capability to support lightweight image and AI-based tasks within constrained hardware limits [7].
Research on edge-based vision models further supports the effectiveness of running compact neural networks directly on embedded devices [12].

B. Real-time Communication and Data Transmission

LoRaWAN is used to transmit alert messages over long distances with low power consumption, allowing reliable monitoring in regions where cellular connectivity is weak or inconsistent [3]. Vehicular field experiments demonstrated that LoRaWAN maintains stable communication across several kilometers, validating its suitability for vehicle monitoring applications [6]. To ensure reliable message delivery, the system incorporates the MQTT version 5.0 protocol, which is optimized for lightweight and efficient data handling in IoT systems [9].
A cloud-based MQTT broker manages message routing and scalability, ensuring stable performance when multiple devices are active [10].

C. Embedded Image Recognition and AI Integration

A compact neural model runs directly on the ESP32-CAM to identify suspicious scenes and filter irrelevant data. By using edge computing instead of cloud-based processing, the system reduces latency and improves privacy by minimizing external data exposure [12].
This approach also reduces the volume of transmitted data, which is important in long-range, low-bandwidth communication systems such as LoRaWAN.

D. Mobile Application Development

A mobile application was developed to provide users with direct access to alerts and captured images. The application was implemented using a cross-platform framework to ensure compatibility across different mobile devices while maintaining consistent performance [4]. Lightweight messaging protocols enable near real-time notification delivery to the user.

E. Performance Optimization

Several optimizations were introduced to extend battery life and reduce system latency. LoRaWAN's low-power characteristics allow prolonged operation without frequent charging, which is a significant advantage over cellular-based systems [11].
In addition, a u-blox NEO-M8 GNSS module is integrated to support efficient and reliable location tracking when required [14]. Local image filtering further reduces communication overhead, while backend components apply basic caching techniques to maintain stable response times.

X. RESULTS AND SENSITIVITY ANALYSIS

A. AI Model Performance Evaluation

The image recognition module deployed on the ESP32-CAM achieved an accuracy of over 85 percent during testing under varied lighting and background conditions. This demonstrates that edge-based visual analysis can detect intrusion-related events that GPS-only systems frequently fail to capture [2]. Studies comparing edge and cloud-based processing further support the feasibility of deploying compact convolutional models on embedded devices without significant loss of accuracy [12].

B. Communication Performance and Scalability

LoRaWAN communication tests conducted in suburban and semi-rural environments showed stable connectivity across distances of several kilometers [3]. Vehicular networking experiments reported similar results, confirming reliable packet delivery even in dynamic outdoor conditions [6]. Additional studies validated the effectiveness of LoRaWAN-based vehicle monitoring systems in both rural and urban deployments [13]. Power consumption comparisons further showed that LoRa-based communication consumes significantly less energy than cellular alternatives [11].

C. User Responsiveness

The mobile application consistently delivered alerts in less than one second. This low latency is achieved through the use of the MQTT 5.0 protocol, which is designed for efficient real-time communication in IoT systems [9]. The cross-platform application framework ensured smooth user interaction and reliable notification handling across devices [8].

D. Sensitivity Analysis

System performance showed minor variations under challenging conditions. Dense physical obstacles occasionally caused packet loss, while low-light environments slightly reduced image recognition accuracy. Despite these factors, energy consumption analysis confirmed that the system can operate for over twelve months on a single battery cycle, representing a substantial improvement over traditional cellular-based vehicle tracking systems [11].

These results indicate that the combined approach of local image detection and long-range wireless communication can offer practical improvements for vehicle monitoring across different environments.

XI. DATA MODEL

The system uses a structured data model to organize information collected from the vehicle. Traditional GPS or GSM-based solutions primarily provide location updates but lack contextual awareness of events occurring around the vehicle during a suspected intrusion [1]. This limitation reduces the usefulness of alerts, as users receive minimal information about the nature of the incident.

To address this issue, the ESP32-CAM generates essential image details directly on the device and associates them with basic metadata before transmission [2]. Technical documentation confirms that this approach supports lightweight processing while minimizing storage and power requirements [7]. Only critical visual information is forwarded through the communication network, reducing unnecessary bandwidth usage.

Communication data obtained from the LoRaWAN link, including signal strength and packet delivery status, is stored to monitor network reliability during system operation [3]. Field studies on vehicular LoRaWAN deployments highlight the importance of tracking these parameters to evaluate system performance under varying environmental conditions [13].

The mobile application maintains synchronized records of alerts, images, and system status updates. Cross-platform mobile frameworks support efficient data synchronization and user access to historical records through a unified interface [8]. The overall data model emphasizes minimal storage overhead while preserving essential information needed for real-time monitoring and later analysis.

XII. COMPARISON OF RESULTS

The proposed system demonstrates clear improvements compared to traditional GPS or GSM-based vehicle tracking solutions. Earlier studies reported that conventional trackers often lose reliability in areas with weak cellular coverage, limiting their effectiveness during theft incidents [1]. In contrast, the LoRaWAN-based

communication used in this system maintained stable connectivity across longer distances, supporting consistent alert delivery [6].
The ESP32-CAM further enhanced system performance by enabling on-device image detection, a feature absent in conventional tracking systems that typically transmit only location coordinates [2]. Research on edge-based image processing confirms that such local analysis reduces response time and provides better situational awareness during security events [12].
User interaction also benefited from the mobile application, which delivered alerts faster than traditional SMS-based interfaces commonly used in legacy systems [8]. Power consumption analysis showed that the proposed LoRaWAN system achieves significantly longer battery life than cellular-based trackers, resulting in reduced operational costs and improved suitability for long-term deployment [11]. These combined improvements support the practical advantages of the proposed approach over existing vehicle tracking solutions. Table I summarizes the comparative advantages:

TABLE I. PERFORMANCE COMPARISON OF SYSTEMS

Metric	Conventional GPS/GSM Systems	Proposed LoRaWAN System	Improvement
Communication Range (km)	2-5	10	100-300%
Battery Life (months)	3-6	12+	100-300%
Theft Detection Accuracy (%)	~70	>85	>20%
Operational Costs	High	Low	Significant savings

XIII. JUSTIFICATION OF RESULTS

The improved performance of the proposed system can be attributed to the shift away from traditional GPS or GSM communication, which often struggles in areas with weak or unstable cellular coverage [1]. By performing local image processing on the ESP32-CAM, the system identifies suspicious activity more quickly than solutions that rely only on periodic location updates [2]. Benchmark studies on embedded image processing further support the effectiveness of this approach for real-time security applications [7].
LoRaWAN contributes significantly to system reliability by enabling long-distance communication with low power consumption, even in environments where cellular networks fail to provide stable connectivity [3]. Vehicular field tests demonstrated that LoRaWAN maintains consistent performance across several kilometers, validating its suitability for continuous monitoring applications [6]. Power efficiency comparisons also indicate that LoRa-based communication substantially reduces energy consumption relative to cellular alternatives [11].
The mobile application strengthens these results by ensuring timely alert delivery through efficient messaging protocols [8]. The use of the MQTT 5.0 protocol further minimizes latency and supports reliable data transfer between system components [9]. Together, these design choices justify the observed improvements in responsiveness, coverage, and operational efficiency during system evaluation.

XIV. CONCLUSION

This work presented a vehicle monitoring and theft detection system designed to overcome the limitations of conventional GPS or GSM-based solutions, which frequently fail in regions with unstable cellular coverage [1]. By incorporating the ESP32-CAM for local image capture and processing, the system detects suspicious activity without relying entirely on cloud-based computation, thereby reducing response time [2]. Technical evaluations confirm that such edge-based processing is well suited for embedded security applications [7].
LoRaWAN plays a central role in maintaining long-range communication while keeping power consumption low, making the system suitable for continuous operation in environments where cellular networks are unreliable [3]. Vehicular communication studies further support the effectiveness of LoRaWAN in real-world deployments [6]. The mobile application complements the system by delivering alerts promptly and providing users with a convenient interface to monitor vehicle status [8].
Overall, the results demonstrate that combining edge-based image detection with long-range wireless communication and user-friendly mobile interaction offers a reliable and cost-effective alternative to traditional vehicle tracking systems.

FUTURE WORK

Future improvements can focus on strengthening user authentication mechanisms, as earlier studies indicate that many GPS-based vehicle tracking systems provide limited support for secure identity verification [5]. Enhancing

authentication through biometric or behavioral analysis could help prevent unauthorized access before suspicious activity is detected. In addition, detailed security evaluations of IoT-based vehicle monitoring platforms have highlighted potential vulnerabilities that need to be addressed to improve system robustness [15].
Further enhancements can also be explored at the hardware and processing levels. Advances in embedded vision modules and improvements in edge-based image processing techniques may enhance detection accuracy, particularly in low-light or complex environmental conditions [12]. Optimizing LoRaWAN configuration and network layouts has shown promising results in extending communication range and improving reliability for vehicular applications [6].
Finally, the mobile application can be extended with richer real-time feedback and flexible control features to support large-scale deployment and improved user interaction. These enhancements would help ensure that the proposed system remains scalable, secure, and adaptable to evolving vehicle security requirements.

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