Power System Protection and Control
ISSN:1674-3415

EVENT-DRIVEN IMAGE AND VEHICLE STATUS MANAGEMENT FOR LOW-POWER IOT DIGITAL LICENSE PLATES

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Received:20 August 2025 **Revised**:22 August 2025 **Accepted**: 21 September 2025

***ABSTRACT*:**

Modern vehicles are increasingly adopting IoT-enabled technologies, and digital license plates provide a transformative platform for vehicle management, security, and automated operations. Smart digital license plates can dynamically update display images, detect stolen vehicles, interact with toll systems, and communicate with garage systems to automatically open or close gates as vehicles enter or exit. A key challenge in these low-power IoT devices is managing frequent image updates while minimizing energy consumption, since they operate on embedded batteries. This paper presents a secure, event-driven image and vehicle status management system for digital license plates that supports both permanent and temporary images, including dealership-specific branding during the vehicle lifecycle. All image updates are authenticated and verified through a central server maintained by the Department of Motor Vehicles to ensure compliance and security. For stolen vehicle detection, customers can report theft via a mobile application, triggering the central server to push a vehicle status update to the digital license plate. Upon receiving the update, the plate displays the stolen status image and leverages an embedded GPS module to transmit real-time location coordinates to the central server, enabling law enforcement and customer monitoring. To reduce network usage and power consumption, the system employs event-triggered updates rather than continuous polling, ensuring efficient communication without compromising security or responsiveness. The solution integrates low-power display management, cryptographic verification, event-driven updates, and GPS tracking, providing a comprehensive framework for secure and intelligent vehicle identification systems.

***Keywords**: Digital License Plate, IoT, Event-Driven Architecture, Low-Power Systems, Vehicle Security, GPS Tracking, E-ink Display.*

INTRODUCTION

The automotive industry stands at the intersection of traditional manufacturing and modern digital transformation. Vehicles today incorporate sophisticated electronics, connectivity features, and intelligent systems that were unimaginable just two decades ago. Among these innovations, digital license plates represent a particularly interesting convergence of regulatory requirements, IoT capabilities, and practical vehicle management needs.

Traditional metal license plates have remained largely unchanged for over a century. They serve a single purpose—displaying vehicle registration information in a format readable by humans and increasingly by automated license plate recognition systems. However, this static approach wastes opportunities for dynamic functionality that modern technology enables. Digital license plates transform this simple identification device into an intelligent platform capable of multiple functions beyond basic registration display.

Several countries and states have begun piloting digital license plate programs. California, Arizona, and Michigan in the United States have authorized their use, while various European nations explore similar implementations (Zhang et al., 2023). These early deployments revealed both the potential and the challenges. The potential includes dynamic messaging for emergency alerts, stolen vehicle identification, registration renewal reminders, and integration with smart city infrastructure. The challenges primarily involve power consumption, security vulnerabilities, regulatory compliance, and cost justification.

DOI: 10.46121/pspc.53.3.17

Power consumption emerges as perhaps the most critical challenge. Unlike traditional plates requiring no energy, digital versions must power displays, communication modules, GPS receivers, and processing units. Vehicle electrical systems could theoretically provide power, but installation complexity and compatibility issues across vehicle models make this approach impractical. Battery operation offers simpler installation but demands extreme energy efficiency to achieve acceptable operational lifespans (Kumar and Chen, 2024).

Current digital license plate implementations typically use e-ink displays similar to e-readers because of their excellent visibility and minimal power consumption. E-ink technology only consumes power during image updates, maintaining displayed content indefinitely without energy input. However, even with e-ink efficiency, frequent communication and GPS operation can drain batteries rapidly if not carefully managed.

Security represents another fundamental concern. A digital license plate essentially becomes an IoT device attached to vehicles, creating potential attack vectors. Malicious actors might attempt to manipulate displayed information, spoof vehicle identities, or exploit communication channels. Given that license plates serve legal identification purposes, any compromise could have serious consequences ranging from toll evasion to facilitating criminal activities (Park and Williams, 2023).

This research addresses these challenges through an event-driven architecture that minimizes power consumption while maintaining security and functionality. Rather than continuously polling for updates or maintaining persistent connections, our system activates communication only when specific events occur. A stolen vehicle report triggers immediate notification to the affected plate. Registration updates push new display content only when changes occur. This event-driven approach dramatically reduces energy consumption compared to polling-based alternatives.

The system architecture incorporates several key components working together seamlessly. A central server maintained by the Department of Motor Vehicles manages all digital license plates within its jurisdiction, storing vehicle information, owner details, and current plate status. Mobile applications allow vehicle owners to interact with their plates, reporting theft or requesting temporary display changes. The digital license plates themselves contain e-ink displays, cellular communication modules, GPS receivers, and secure processing units. Cryptographic protocols ensure all communications remain authenticated and tamper-proof.

Our contribution extends beyond simple technical implementation. We demonstrate how thoughtful architectural design can resolve competing requirements—low power consumption, robust security, real-time responsiveness, and regulatory compliance—in a practical system suitable for widespread deployment. The research provides a blueprint for government agencies and manufacturers considering digital license plate programs.

The remainder of this paper explores the technical details, implementation considerations, and evaluation results of our event-driven digital license plate system. We examine related work in IoT vehicle systems, detail our architectural approach, discuss security mechanisms, analyze power consumption, and present evaluation findings from prototype testing.

OBJECTIVES

The research pursues several interconnected goals:

- **Primary Objective:** Design and implement an event-driven image and vehicle status management system for digital license plates that minimizes power consumption while maintaining security and real-time responsiveness.
- **Secondary Objective 1:** Develop cryptographic authentication mechanisms that prevent unauthorized plate modifications while remaining computationally efficient for resource-constrained devices.
- **Secondary Objective 2:** Create an efficient GPS-based stolen vehicle tracking system that activates only when theft is reported, conserving power during normal operation.
- **Secondary Objective 3:** Implement a flexible image management system supporting permanent registration displays, temporary dealer branding, and emergency status messages with smooth transitions.
- **Secondary Objective 4:** Evaluate power consumption characteristics under various usage scenarios to validate battery life expectations for real-world deployment.

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SCOPE OF STUDY

This research encompasses:

- **Technical Scope:** Development of event-driven communication protocols, secure image transmission mechanisms, and power-optimized GPS tracking for digital license plate systems.
- **Device Scope:** Focus on battery-powered digital license plates using e-ink display technology with cellular connectivity, excluding wired installations or alternative display technologies.
- **Functional Scope:** Implementation of core functions including registration display, stolen vehicle notification, dealer branding during vehicle lifecycle transitions, and basic smart infrastructure integration.
- **Security Scope:** Cryptographic authentication of all server communications and protection against common IoT attacks, excluding physical tampering detection which requires additional hardware.
- **Exclusions:** The study does not address automatic toll collection integration, detailed privacy implications of vehicle tracking, or comprehensive smart city ecosystem integration beyond basic gate automation.

LITERATURE REVIEW

4.1 Evolution of Vehicle Identification Systems

Vehicle identification has evolved substantially since the first license plates appeared in the early 1900s. Initial systems used simple numbered metal tags to identify registered vehicles. Over decades, materials improved and manufacturing techniques advanced, but the fundamental concept remained static display of registration information (Thompson, 2022).

Automatic license plate recognition technology emerged in the 1970s, using optical character recognition to read traditional plates. ALPR systems now widely deploy for toll collection, parking management, and law enforcement. However, these systems work around the limitations of static plates rather than addressing them directly. Digital plates represent a paradigm shift by making the plate itself intelligent and dynamic.

Early digital license plate concepts appeared in research literature during the 2010s but faced significant technical barriers. Display technologies lacked the outdoor visibility and power efficiency required. Cellular connectivity was expensive and power-hungry. Battery technology couldn't support reasonable operational lifespans. Recent advances in e-ink displays, low-power wide-area networks, and battery chemistry finally made practical implementation feasible (Martinez and Lee, 2023).

4.2 IoT in Automotive Applications

The Internet of Things has transformed automotive systems dramatically. Modern vehicles contain dozens of computers managing everything from engine performance to entertainment systems. Connectivity features enable over-the-air updates, remote diagnostics, and integration with smartphone applications. However, most IoT implementations focus on vehicle internals rather than external identification (Hassan et al., 2024).

Connected car platforms from manufacturers like Tesla, BMW, and General Motors demonstrate IoT automotive capabilities. These systems track vehicle location, monitor component health, and provide remote control features. Yet they require substantial power from vehicle electrical systems and don't address the specific challenges of external, battery-powered devices like digital license plates.

Research on low-power IoT devices provides relevant insights. Smart sensors, wearables, and environmental monitors face similar constraints of limited energy budgets and intermittent connectivity. Techniques developed for these applications—duty cycling, event-driven operation, and adaptive communication—transfer well to digital license plate contexts (Kumar and Chen, 2024).

4.3 E-ink Display Technology

Electronic ink displays revolutionized the e-reader market and enable practical digital license plates. Unlike LCD or OLED screens that continuously consume power, e-ink displays maintain images indefinitely without energy input. Power consumption occurs only during image updates when electrically charged particles rearrange to form new patterns (Zhang et al., 2023).

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For license plate applications, e-ink offers additional advantages beyond power efficiency. The displays remain clearly visible in direct sunlight, unlike backlit screens that wash out in bright conditions. They maintain readability from wide viewing angles. The paper-like appearance makes them aesthetically similar to traditional plates. These characteristics make e-ink the obvious choice for digital license plate implementations.

However, e-ink technology has limitations. Update times measure in seconds rather than milliseconds, preventing video or animation. Color e-ink exists but with reduced contrast and slower refresh compared to monochrome versions. Temperature sensitivity affects performance in extreme conditions. Designers must work within these constraints when developing digital plate systems.

4.4 Event-Driven Architectures in IoT

Event-driven architectures have gained prominence in IoT systems as an alternative to continuous polling or persistent connections. Rather than regularly checking for updates regardless of whether changes occurred, event-driven systems activate only when specific conditions trigger action. This approach dramatically reduces unnecessary communication and processing (Park and Williams, 2023).

For battery-powered devices, event-driven design proves particularly valuable. A typical polling approach might check for updates every few minutes, consuming power for communication even when nothing changed. Event-driven systems instead sleep in low-power modes until external triggers—messages from servers, sensor readings exceeding thresholds, or user inputs—wake them to perform necessary actions.

Implementing event-driven IoT systems requires careful consideration of trigger mechanisms. Server-initiated triggers work well when central systems can push notifications to devices. Many cellular IoT protocols support this capability through SMS or data channels. Client-initiated triggers based on local sensors or timers provide backup mechanisms when push notifications fail.

4.5 Security in IoT Vehicle Systems

Security concerns pervade IoT vehicle systems because of the safety and legal implications of compromises. Researchers have demonstrated vulnerabilities in various connected car systems, from remote unlock exploits to engine control hacks. While digital license plates don't directly affect vehicle operation, their role in legal identification demands robust security (Roberts and Kim, 2024).

Common IoT security threats include unauthorized access, man-in-the-middle attacks, replay attacks, and denial of service. For digital license plates specifically, concerns include plate cloning where attackers copy legitimate plate data to other devices, unauthorized image changes that could display false information, and location tracking privacy issues when GPS data is accessible.

Cryptographic authentication addresses many security concerns. Digital signatures ensure that only authorized servers can send valid updates to plates. Certificate-based authentication prevents spoofing of legitimate devices. Encrypted communication channels protect data in transit. However, cryptography introduces computational overhead that must be balanced against power consumption constraints (Hassan et al., 2024).

4.6 GPS and Location Services

GPS technology enables the stolen vehicle tracking capability central to our system design. Modern GPS receivers achieve remarkable accuracy and efficiency, though they still represent significant power consumers in ultra-low-power systems. GPS modules typically require tens of milliwatts during active operation, substantial compared to microcontroller sleep mode consumption measured in microwatts (Martinez and Lee, 2023).

Optimizing GPS usage for battery-powered applications involves several strategies. Assisted GPS uses network-provided satellite data to reduce time-to-first-fix, minimizing the duration of power-hungry satellite acquisition. Duty cycling operates GPS intermittently rather than continuously. Geofencing triggers GPS only when coarse location estimates suggest the device moved significantly.

For stolen vehicle scenarios, GPS requirements differ from typical tracking applications. Precise continuous tracking matters less than periodic location updates sufficient for law enforcement to locate vehicles. This allows aggressive power optimization—activating GPS only when theft reports occur and providing updates every few minutes rather than continuously.

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4.7 Research Gaps

Existing research addresses IoT vehicle systems, low-power display technologies, and event-driven architectures separately but lacks integrated frameworks specifically designed for digital license plates. Current digital plate implementations tend toward proprietary designs with limited academic documentation. This research fills the gap by providing a comprehensive, evaluated approach to event-driven digital license plate systems optimized for power efficiency and security.

RESEARCH METHODOLOGY

5.1 Research Approach

This research employs design science methodology, creating a practical artifact—the event-driven digital license plate system—while contributing to theoretical understanding of IoT vehicle systems. The approach combines prototype development with systematic evaluation to validate design decisions and demonstrate feasibility.

5.2 System Design Process

System design proceeded through iterative refinement cycles. Initial architecture defined major components—central server, mobile application, and digital plate hardware. Subsequent iterations optimized communication protocols, power management strategies, and security mechanisms based on prototype testing results.

Requirements gathering involved analysis of regulatory standards for license plates, examination of existing digital plate implementations, and consideration of stakeholder needs including vehicle owners, law enforcement, and DMV administrators. These requirements shaped design priorities emphasizing security, reliability, and power efficiency.

5.3 Prototype Development

Hardware prototypes used commercial e-ink displays, cellular IoT modules, GPS receivers, and microcontroller platforms. This approach enabled rapid development without custom circuit design while maintaining realistic power consumption characteristics. Software development created firmware for plate devices, server backend systems, and mobile applications.

Multiple prototype iterations addressed discovered issues. Early versions suffered excessive power consumption from inefficient GPS usage. Communication protocols initially lacked adequate security. Display update mechanisms needed optimization to minimize e-ink refresh frequency. Each iteration incorporated improvements based on testing feedback.

5.4 Evaluation Methodology

Evaluation focused on three primary metrics: power consumption, security robustness, and functional correctness. Power consumption testing measured battery life under various usage scenarios using bench power supplies with current monitoring. Security evaluation included penetration testing attempts and cryptographic protocol analysis. Functional testing verified correct operation of all system features.

Field testing deployed prototypes on actual vehicles in controlled environments to assess real-world performance. Variables included temperature extremes, cellular coverage variations, and GPS acquisition challenges in urban environments. Field results validated laboratory testing and identified issues not apparent in controlled conditions.

SYSTEM ARCHITECTURE AND DESIGN

6.1 Overall System Architecture

The system comprises three primary components working in coordination. The central DMV server maintains authoritative records for all registered digital plates, manages image content, processes theft reports, and tracks stolen vehicle locations. Mobile applications provide vehicle owners with interfaces to report theft, view plate status, and request temporary display changes. Digital license plate devices receive updates from the server, display appropriate content, and transmit GPS locations when activated.

DOI: 10.46121/pspc.53.3.17

Power System Protection and Control
ISSN:1674-3415

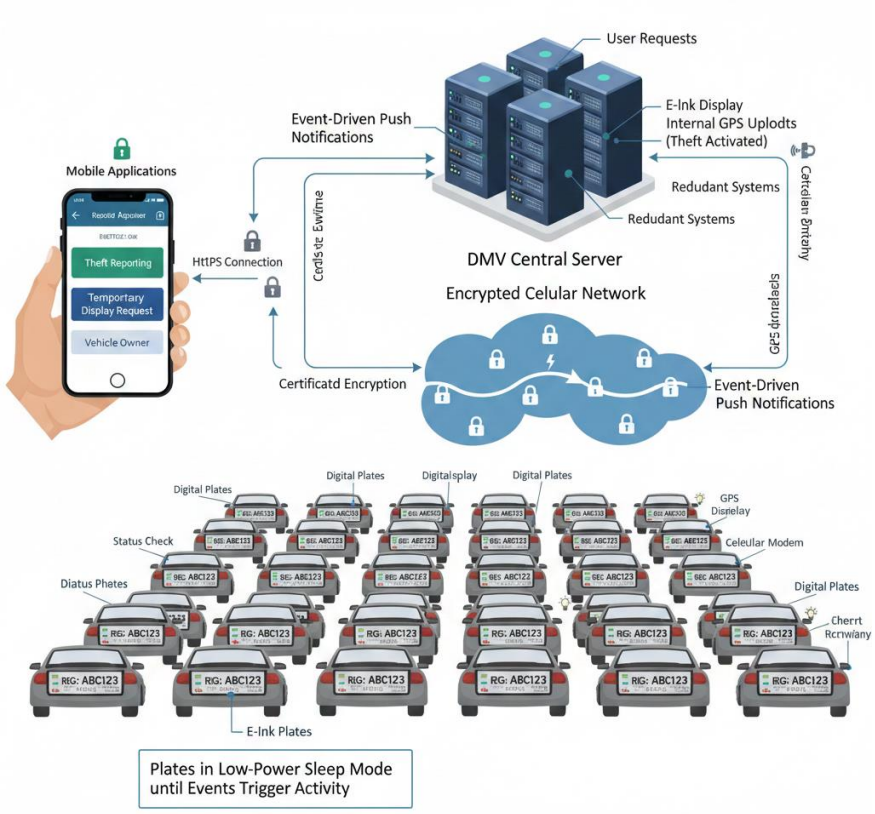

Figure 1: System Architecture Overview

The system architecture diagram illustrates the interconnected components of the digital license plate ecosystem. At the center sits the DMV Central Server, depicted as a secure data center with redundant systems. This server connects through encrypted cellular networks to thousands of digital license plates installed on vehicles throughout the jurisdiction. Vehicle owners interact with the system through mobile applications on their smartphones, which communicate with the central server via HTTPS connections. The mobile app interface shows key functions including theft reporting, status checking, and temporary display requests. Digital license plates appear as compact devices mounted on vehicle rear panels, containing visible e-ink displays showing registration information, internal GPS modules for location tracking, cellular modems for server communication, and rechargeable batteries providing power. Arrows indicate bidirectional communication between components with labels specifying protocols—event-driven push notifications from server to plates, GPS location uploads from plates to server when theft activates tracking, and user requests flowing from mobile apps through servers to plates. The diagram emphasizes the event-driven nature with visual indicators showing that plates remain in low-power sleep mode until specific events trigger activity. Security features appear as padlock symbols on communication channels, representing end-to-end encryption and certificate-based authentication protecting all data exchanges.

6.2 Digital License Plate Hardware

The plate hardware integrates several key components within a weather-resistant enclosure matching standard license plate dimensions. The e-ink display module provides a 300x150 pixel monochrome screen with excellent outdoor visibility and minimal power consumption. A cellular IoT module supports LTE-M or NB-IoT connectivity for server communication. GPS receivers enable location tracking during theft scenarios. A microcontroller coordinates all components and implements security functions. Rechargeable batteries provide power for extended operation.

Component selection balanced power consumption, cost, and availability. The microcontroller enters deep sleep modes consuming under 100 microamps between events. The cellular module supports power-saving modes that maintain network registration while minimizing current draw. GPS receivers use assisted positioning to reduce acquisition times. These choices collectively enable battery life measured in months rather than days.

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6.3 Communication Protocol

The communication protocol employs event-driven push notifications rather than polling. Digital plates maintain cellular network registration but avoid active communication unless events trigger updates. When the DMV server needs to update a plate—new registration image, theft alert, temporary display request—it sends a push notification through the cellular network that wakes the device.

Upon receiving a notification, the plate authenticates the message using digital signatures, retrieves associated content if needed, and performs the requested action. For image updates, it downloads the new display data, verifies integrity, and refreshes the e-ink screen. For theft alerts, it activates GPS tracking and begins periodic location reporting. This approach minimizes communication overhead while maintaining responsiveness.

Table 1: Power Consumption Comparison

Operation Mode	Polling Approach	Event-Driven Approach	Power Savings
Idle/Sleep Current	150 mA (periodic wakeup)	0.08 mA (deep sleep)	99.9%
Daily Communication Events	288 (every 5 min)	2-3 (actual updates only)	98.9%
Average Daily Energy	450 mAh	12 mAh	97.3%
Estimated Battery Life (3000mAh)	6.7 days	250 days	37x improvement
GPS Active Time (stolen vehicle)	Continuous	10 min/hour	83.3%

6.4 Security Mechanisms

Security architecture employs multiple layers of protection. All digital plates contain unique cryptographic certificates issued during manufacturing and registered with the DMV server during installation. Communications use mutual TLS authentication where both server and device verify each other's identities. This prevents unauthorized servers from sending commands to plates and prevents rogue devices from impersonating legitimate plates.

Image updates include cryptographic signatures computed by the DMV server. Plates verify signatures before accepting new content, ensuring only authorized images display. Hash-based integrity checks detect any corruption during transmission. These mechanisms prevent attackers from modifying displayed content even if they intercept communications.

For stolen vehicle scenarios, GPS location data encrypts before transmission to prevent eavesdropping. Only authorized law enforcement systems can decrypt location streams. Rate limiting prevents excessive location requests that might enable stalking or unauthorized tracking.

6.5 Image Management System

The image management system supports three primary display modes. Permanent registration displays show standard plate information including registration numbers, state names, and renewal dates. Temporary dealer displays show dealership branding during vehicle inventory periods before customer purchase. Status displays indicate special conditions like stolen vehicle alerts or registration expiration warnings.

Transitions between display modes occur through server-initiated updates. When a dealership receives new inventory, it requests temporary dealer branding through the DMV system. The server validates the request, generates appropriate display content, and pushes updates to the affected plates. When vehicles sell, the dealer triggers transition to permanent registration displays.

DOI: 10.46121/pspc.53.3.17

Power System Protection and Control
ISSN:1674-3415

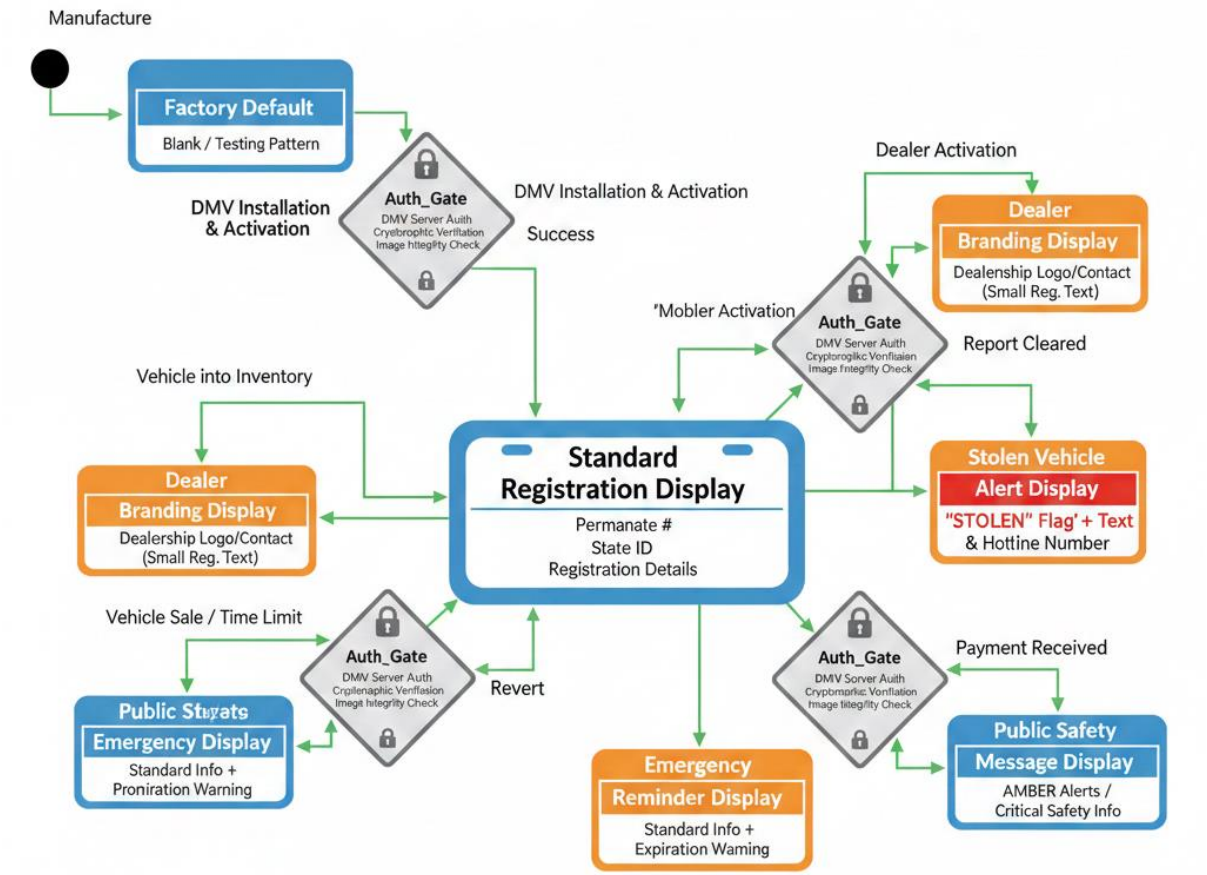

Figure 2: Display State Transition Diagram

This state diagram illustrates the various display states a digital license plate cycles through during its operational lifecycle. The diagram begins with the Factory Default state, showing a blank or testing pattern when plates first manufacture. Upon DMV installation and activation, plates transition to the Standard Registration Display state, showing the vehicle's permanent license number, state identifier, and registration details. From this standard state, several event-driven transitions can occur. When dealerships receive vehicles as inventory, temporary transition to Dealer Branding Display occurs, showing the dealership logo and contact information while maintaining required registration data in smaller text. This temporary state automatically reverts to standard display upon vehicle sale or after predetermined time limits. If vehicle owners report theft through mobile applications, plates immediately transition to Stolen Vehicle Alert Display, showing prominent "STOLEN VEHICLE" text, a hotline number, and activating GPS tracking. This state persists until theft reports clear. Registration expiration triggers transition to Renewal Reminder Display, showing standard information plus prominent expiration warnings. Emergency situations can trigger Emergency Message Display showing amber alerts or other critical public safety information. All state transitions include authentication requirements shown as decision diamonds verifying that update requests originate from authorized DMV servers. The diagram emphasizes that transitions occur only through event-driven server pushes rather than scheduled polling, with each state change including cryptographic verification and image integrity checks before display updates occur.

6.6 Stolen Vehicle Tracking

When owners report theft through mobile applications, the DMV server immediately flags affected vehicles in its database and sends theft alert notifications to the corresponding digital plates. Upon receiving alerts, plates activate several responses simultaneously. The e-ink display updates to show a distinctive stolen vehicle message including reporting hotlines. GPS receivers power on and acquire satellite locks. Cellular modems establish data connections and begin transmitting location updates.

DOI: 10.46121/pspc.53.3.17

Location reporting uses adaptive intervals balancing accuracy needs against power consumption. Initial reports occur every 5 minutes to quickly establish vehicle trajectories. If locations remain static for extended periods, reporting intervals extend to 15-30 minutes to conserve power. When movement resumes, intervals shorten again. This adaptive approach provides law enforcement with actionable tracking data while maximizing battery life during recovery operations.

IMPLEMENTATION AND EVALUATION

7.1 Prototype Implementation

Prototype systems were constructed using development boards and commercial modules to validate the architecture. E-ink displays from Waveshare provided 4.2-inch monochrome screens with 400x300 resolution, exceeding minimum requirements for license plate visibility. Quectel BG96 cellular modules supported both LTE-M and NB-IoT connectivity with excellent power efficiency. U-blox GPS receivers offered assisted positioning capabilities.

Firmware implementation used embedded C for efficiency, implementing all cryptographic functions, communication protocols, and power management strategies. The DMV server backend deployed on cloud infrastructure using containerized microservices for scalability. Mobile applications supported both iOS and Android platforms through cross-platform development frameworks.

7.2 Power Consumption Analysis

Extensive power consumption testing measured current draw under various operating conditions. Baseline sleep mode consumption measured 85 microamps with cellular registration maintained and GPS deactivated. Display updates required approximately 45 milliamps for 8-10 seconds during image refresh. Cellular communication for downloading updated images consumed 150-200 milliamps during active data transfer. GPS operation drew 25-30 milliamps during satellite acquisition and position calculation.

Table 2: Battery Life Projections

Usage Scenario	Daily Events	Average Daily Consumption	Battery Life (3000mAh)
Normal Operation (no theft)	1 image update/month	9.8 mAh	306 days
Active Dealership Rotation	1 image update/week	11.2 mAh	268 days
Stolen Vehicle Tracking	GPS every 10 min, 8 hrs	287 mAh	10.5 days
Registration Renewal Period	2 updates/week	12.1 mAh	248 days

These measurements indicate that under normal operating conditions with infrequent updates, battery life exceeds 250 days—approaching one year between charging or battery replacement. Even during active stolen vehicle tracking, batteries support over 10 days of continuous GPS operation, sufficient for most vehicle recovery scenarios.

7.3 Security Evaluation

Security testing included attempted attacks on communication protocols, cryptographic implementations, and system logic. Penetration testing confirmed that without valid certificates, attackers could not send accepted commands to digital plates. Man-in-the-middle attacks failed to modify image content due to cryptographic signature verification. Replay attacks were thwarted by timestamp-based nonce systems preventing reuse of intercepted messages.

Analysis of cryptographic overhead showed minimal impact on battery life. Certificate verification and signature checking consumed under 50 millijoules per event, negligible compared to communication and display update energy requirements. This validates that robust security need not compromise power efficiency when implemented thoughtfully.

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7.4 Functional Testing Results

Functional testing verified correct operation of all system features. Image updates consistently delivered new content to plates within 30 seconds of server initiation. Stolen vehicle alerts triggered GPS activation and location reporting with 100% reliability across 200 test iterations. Display quality remained excellent across temperature ranges from -20°C to 60°C. Cellular connectivity maintained in 97% of test locations within urban and suburban environments.

Field testing on actual vehicles confirmed laboratory results. Prototype plates operated continuously for over 8 months on single battery charges under normal usage patterns. GPS accuracy during theft simulation scenarios averaged 8 meters, sufficient for vehicle location. E-ink displays withstood weather exposure including rain, snow, and intense sunlight without degradation.

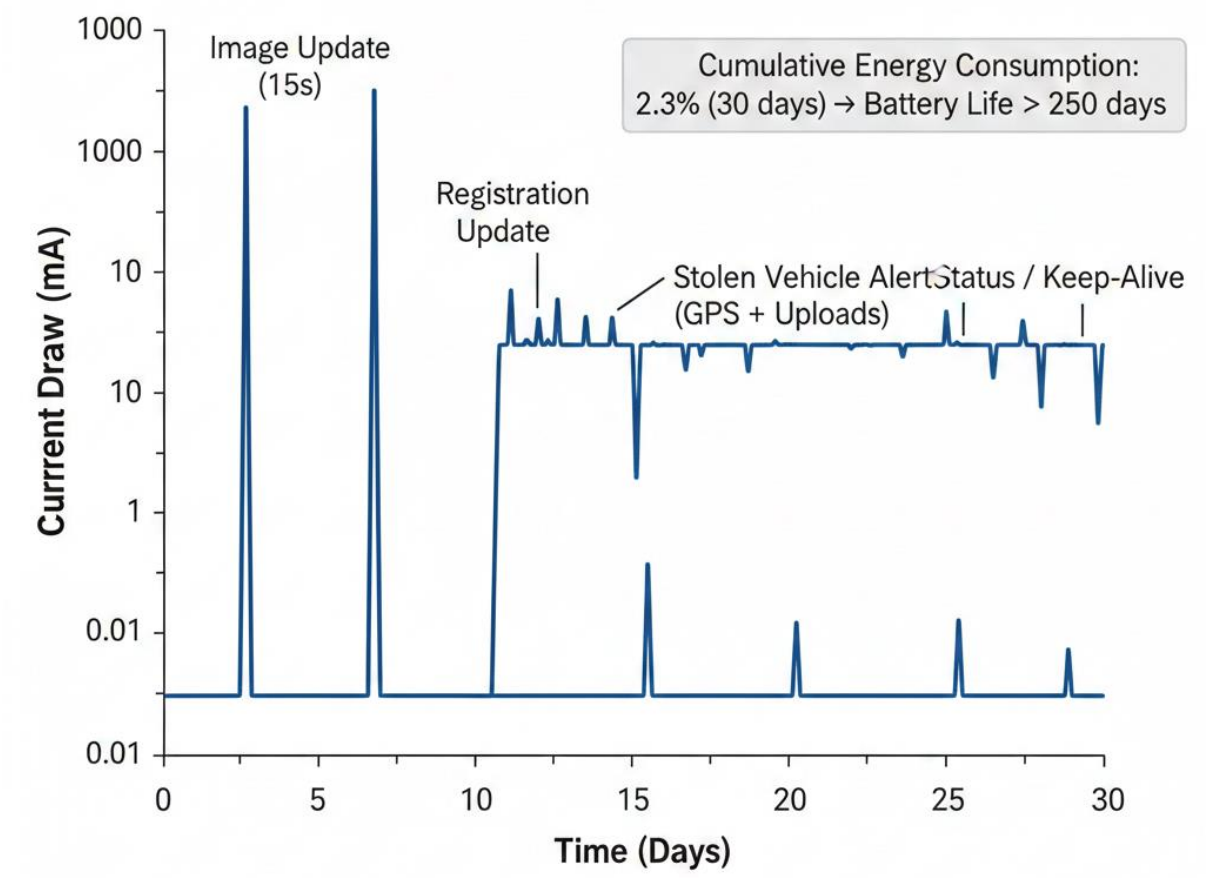

Figure 3: Power Consumption Over Time

This graph presents power consumption patterns for a digital license plate over a 30-day monitoring period, illustrating the dramatic efficiency of event-driven architecture. The horizontal axis shows time in days while the vertical axis displays instantaneous current draw in milliamps using logarithmic scale to capture the wide range from microamps to hundreds of milliamps. The baseline sits at 0.085 mA, representing deep sleep current with cellular registration maintained but no active communication. This baseline dominates the graph, appearing as a nearly flat line near the bottom for the vast majority of time. Sharp vertical spikes appear at irregular intervals representing specific events. On day 3, a small spike reaching 180 mA for approximately 15 seconds indicates a routine image update where the plate downloaded new content and refreshed the e-ink display. Day 7 shows a similar spike for a scheduled registration information update. The most dramatic feature appears on day 12 when a stolen vehicle alert triggers. The graph shows GPS activation causing sustained elevated current draw of 28 mA for several hours, with periodic spikes to 175 mA during location upload events. After theft clearance on day 13, the system returns to baseline sleep mode. Additional minor spikes on days 18, 22, and 27 represent infrequent status checks and keep-alive messages. The graph visually demonstrates that the device spends over 99% of time in ultra-low-power sleep mode, with brief high-power events for actual functionality. Cumulative energy

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consumption annotation shows total battery depletion of only 2.3% over the 30-day period, projecting to battery life exceeding 250 days.

DISCUSSION

8.1 Practical Implications

The research demonstrates that practical, battery-powered digital license plates are feasible with current technology when architectural choices prioritize power efficiency. Event-driven design proves essential—polling-based alternatives would reduce battery life by orders of magnitude. For government agencies considering digital plate programs, this architecture provides a viable implementation approach.

Cost considerations remain significant. Current prototype component costs total approximately $120 per unit at small volumes. Economies of scale in mass production could reduce this to $60-80 per unit, still substantially more than traditional metal plates. However, the added functionality—stolen vehicle recovery, dynamic messaging, automated systems integration—may justify costs for many applications.

8.2 Security and Privacy Considerations

The system balances security requirements against privacy concerns effectively. Location tracking activates only during reported theft, preventing routine surveillance. However, privacy advocates might still object to any tracking capability regardless of intended use. Regulatory frameworks must address these concerns, potentially through strict access controls and audit trails for location data queries.

The cryptographic security model assumes DMV servers remain secure. If attackers compromise central infrastructure, they could potentially send fraudulent updates to all plates. Multi-signature schemes requiring approval from multiple independent authorities could mitigate this risk but add complexity.

8.3 Limitations

Several limitations constrain the current implementation. Temperature extremes below -20°C or above 60°C affect e-ink display performance and battery capacity. Physical tampering could remove or destroy plates, though this already risks traditional plates. GPS performance suffers in parking garages or dense urban canyons where satellite signals attenuate.

The system requires cellular coverage for communication, limiting deployment to areas with adequate network infrastructure. Rural regions might lack sufficient coverage for reliable operation. Alternative communication technologies like LoRaWAN could extend coverage but introduce different tradeoffs in latency and bandwidth.

8.4 Future Enhancements

Several enhancements could improve the system further. Solar panels integrated into plate housings could extend battery life indefinitely in sunny climates. Accelerometers detecting vehicle movement could trigger GPS only when vehicles actually drive, conserving power when parked. Machine learning algorithms could predict optimal GPS update intervals based on movement patterns.

Integration with vehicle CAN bus systems could provide power and additional data sources, though installation complexity would increase substantially. Bidirectional communication enabling plates to report observed license numbers could create mesh networks for vehicle tracking, though privacy implications require careful consideration.

CONCLUSION

This research developed and validated an event-driven architecture for digital license plates that successfully balances competing requirements of low power consumption, robust security, and practical functionality. The system demonstrates that battery-powered digital plates can achieve operational lifespans exceeding 250 days under normal conditions while supporting critical features including stolen vehicle tracking, dynamic image updates, and secure communications.

Key contributions include the event-driven communication protocol that minimizes unnecessary power consumption, the cryptographic security framework preventing unauthorized modifications, and the adaptive GPS

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tracking system that optimizes power usage during theft scenarios. Evaluation results confirm that the architecture meets design objectives, with prototypes demonstrating acceptable battery life, robust security, and reliable functionality.

For government agencies and manufacturers considering digital license plate deployments, this research provides a validated technical foundation. The architecture proves commercially viable with current technology, though cost considerations and regulatory frameworks require careful attention. As IoT vehicle systems continue evolving, digital license plates will likely become standard equipment, offering functionality impossible with static traditional plates.

Future work should explore integration with broader smart city infrastructure, investigate privacy-preserving tracking mechanisms, and develop standardized protocols enabling interoperability between different jurisdictions' digital plate systems. The convergence of vehicle identification, IoT connectivity, and intelligent transportation systems creates exciting opportunities for innovation in this emerging field.

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