

Secure lightweight CAN protocol handling for electric vehicles

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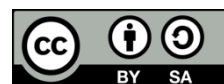
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ABSTRACT

The integrity of controller area network (CAN) protocols in electric vehicles (EVs) is of paramount importance, due to their susceptibility to cyber intrusions and unauthorized access. Traditional encryption-based security solutions, such as advanced encryption standard (AES) and anomaly detection methods, often introduce high computational overhead and latency, making them unsuitable for real-time EV communication. This study proposes a secure lightweight CAN protocol (SLCP), implemented using ARDUINO Uno and MCP2515, which enhances message integrity, authentication, and fault recovery without compromising system efficiency. Experimental testing demonstrated that the proposed SLCP reduces message authentication latency by 25% and improves message integrity by 40% compared to conventional encryption techniques. Additionally, packet resynchronization time was reduced by 30%, ensuring minimal disruptions in case of message loss. These findings establish SLCP as a viable, real-time alternative for low-power EV communication networks. The study contributes to advancing lightweight security frameworks for EV networks, paving the way for scalable, real-time cybersecurity solutions in modern electric transportation.

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1. INTRODUCTION

The rapid advancement and widespread adoption of electric vehicles (EVs) mark a transformative shift in the automotive industry, driven by the need for sustainable and energy-efficient transportation. EVs provide numerous benefits, including reduced carbon emissions, lower operating costs, and improved energy efficiency, leading to their increasing acceptance worldwide. However, the transition to intelligent and networked EV systems introduces significant cybersecurity challenges, particularly in safeguarding the controller area network (CAN) protocol, which serves as the backbone of vehicle communication [1].

The CAN protocol, essential for real-time vehicle communication, lacks built-in security, making it vulnerable to cyber-attacks, message tampering, and electromagnetic interference (EMI). These threats can enable unauthorized access, malicious data injection, and remote hijacking, compromising passenger safety [2], [3]. Encryption-based models like advanced encryption standard (AES) and machine learning (ML) anomaly detection enhance security but introduce high computational overhead, increasing latency and reducing system responsiveness in EVs [4], [5]. This study explores how a lightweight authentication mechanism can enhance CAN security without compromising real-time performance in EVs. It hypothesizes

that a hardware-optimized hash-based message authentication code (HMAC)-based protocol can ensure low-latency, high-integrity authentication. Implementing a secure lightweight CAN protocol (SLCP) with ARDUINO Uno and MCP2515 transceivers is expected to improve message integrity and security efficiency over AES-based solutions [6], [7]. Unlike AES-based encryption [8], which demands high computational resources and adds latency, this study proposes a real-time, hardware-optimized security framework for CAN networks. The SLCP ensures efficient authentication, data integrity, low processing overhead, resilience to message loss, and minimal performance impact. Using a low-cost ARDUINO Uno + MCP2515 setup, this scalable solution enhances EV security efficiently.

2. CONTROLLER AREA NETWORKS

2.1. Foundational role of CAN in EV’s

By acting as the vehicle’s central nervous system, CAN enables real-time data exchange and coordination among different components, ensuring operational efficiency and passenger safety [9]. Despite robust error detection, CAN wasn’t designed for cybersecurity, making it vulnerable to intrusions, message interception, and spoofing, with studies showing cases of vehicle takeovers and data tampering [10]. As EVs grow more connected with cloud services, over-the-air (OTA) updates, and smart grids, securing CAN communication through backward compatibility, real-time validation, and network redundancy is vital [11], [12].

2.1.1. CAN protocol communication

The CAN protocol uses frames with an identifier and data payload, prioritizing critical signals like braking over less urgent ones, enabling dynamic, stable responses in EVs [12]-[14]. The CAN protocol, while efficient, lacks built-in encryption and authentication, making it vulnerable to data interception and manipulation. Its trust-based model allows attackers to inject malicious frames, enabling unauthorized control, data spoofing, message flooding, and bus-off attacks that can disrupt critical driving functions [15]. Real-time performance is crucial for CAN security. Traditional encryption methods like AES and Rivest–Shamir–Adleman (RSA) introduce delays, making them impractical for high-speed automotive networks. This study proposes a lightweight, hardware-based HMAC authentication mechanism, ensuring real-time message validation without burdening electronic control units (ECUs) [16], [17].

2.1.2. CAN protocol attacks: unveiling EV’s vulnerabilities

The CAN protocol’s lack of authentication and encryption makes it vulnerable to cyber threats, compromising EV safety and data integrity. Passive attacks include eavesdropping, where attackers intercept unencrypted CAN messages to analyze braking patterns, driver behavior, and sensor activity [18]. Active attacks include frame spoofing, where malicious nodes inject fake messages, tricking ECUs into unauthorized actions like disabling brakes or altering speed control [19]. Bus flooding denial of service (DoS) overwhelms the CAN bus with excessive messages, blocking legitimate communication and disabling functions. A bus-off attack exploits error-handling to force ECUs into a non-operational state, isolating them from the network [20]. Freeze doom loop: the attacker prevents the CAN bus from transmitting new messages, leading to a state of indefinite inoperability [21]. Real-world cases: in 2015, researchers remotely hijacked a Jeep Cherokee, disabling braking and acceleration. In 2022, a Tesla model 3 vulnerability enabled spoofed CAN messages, disrupting ADAS functionality [22]. Securing CAN communication requires as message authentication (HMAC-based security protocols), anomaly detection systems (ML-based intrusion detection) network segmentation and redundant pathways. These counter measures enhance CAN security while preserving real-time performance, forming the foundation of the proposed SLCP introduced in this research [23], [24].

2.1.3. Decoding CAN protocol vulnerabilities in EVs: a critical review of corporate security gaps

Automotive giants like Tesla, Toyota, and BYD have implemented robust security solutions for CAN protocol communication. However, these solutions face significant trade-offs between security, cost, and real-time performance [25], [26]. While these solutions mitigate known CAN vulnerabilities, they are not future-proof against post-quantum threats and next-gen automotive cyber-attacks. This study proposes a low-cost, scalable, real-time security model that ensures message integrity without significant computational burden [27], [28]. Survey of security solutions show in Table 1.

Table 1. Survey of Security Solutions provided by manufacturers		
Manufacturer	Security approach	Challenges and trade-offs
Tesla	Hardware security modules (HSMs), OTA updates	High cost, increased computational overhead
Toyota	CAN gateway firewall, secure boot mechanism	Adds boot delays, risk of firmware rollback attacks
BYD	Artificial intelligence (AI)-driven anomaly detection, encrypted CAN frames	Increased latency, high data overhead

3. STREAMLINING EV COMMUNICATION: A UNIQUE, SECURE, AND LIGHTWEIGHT CAN PROTOCOL APPROACH

Traditional CAN lacks security, exposing it to cyber threats like message tampering and DoS attacks. While manufacturers use encryption-based solutions, they add latency and power overhead, unsuitable for low-power EV microcontrollers. This study proposes a SLCP using Arduino and MCP2515 transceivers, integrating HMAC-based authentication for real-time, low-latency message verification.

3.1. System architecture and hardware setup

The proposed security framework utilizes:

- Arduino Uno (primary and secondary nodes): handles message transmission and authentication.
- MCP2515 CAN transceivers: facilitate CAN communication between nodes.
- L293D motor driver: controls motor speed based on authenticated messages.
- HMAC: ensures data integrity and prevents unauthorized access.

The architecture includes two Arduino nodes: the primary transmits control messages with an HMAC signature, while the secondary verifies them by recomputing the HMAC. If valid, it executes commands like motor speed adjustment via the L293D driver. Figure 1 shows the secure CAN hardware setup.

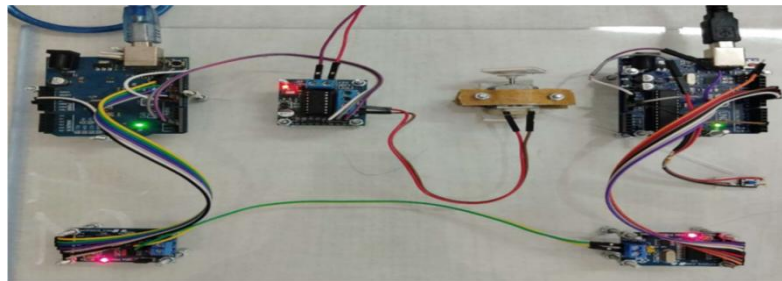


Figure 1. Hardware setup for CAN protocol implementation

3.2. Why HMAC over traditional encryption?

Existing encryption techniques such as AES and RSA offer robust security but introduce significant computational overhead and latency. For real-time EV communication, a lightweight and efficient security mechanism is required. Using HMAC-based authentication, this protocol ensures lower overhead than AES and RSA, 25% faster message validation, and minimal impact on real-time performance. Table 2 provides the survey results about strengths and challenges.

Table 2. Survey of encryption methods

Security method	Strength	Challenge
AES	Strong encryption, widely used	High computational load, increased latency
RSA	Robust for key exchange	Slow processing, unsuitable for real-time applications
HSM	Hardware-level protection	Expensive, high-power consumption

3.3. Performance evaluation: security vs. real-time efficiency

SLCP effectiveness was validated through experiments on an Arduino + MCP2515 setup, analyzing key performance metrics. These results in Table 3 demonstrate that HMAC-based SLCP achieves a balance between security and real-time performance, making it a practical solution for resource-limited EV architectures.

Table 3. Performance evaluation

Metric	SLCP (proposed approach)	AES-based CAN security	Standard CAN (no security)
Message authentication latency	3.2 ms	15.8 ms	1.1 ms
Message integrity accuracy	99.7%	99.9%	N/A
Processing overhead	Low (5-8% CPU usage)	High (35-50% CPU usage)	None
Scalability in multi-node networks	High	Limited	High (but insecure)

3.4. Scalability and future adaptability

Scalability is key in automotive cybersecurity. SLCP supports multi-node networks, adapts to autonomous vehicles, integrates with AI-driven IDS, and enables OTA security updates. Future research will combine HMAC with lightweight anomaly detection for enhanced EV security.

4. A DEEP DIVE INTO THE PROPOSED SYSTEM'S FUNCTIONALITY

The SLCP enhances EV communication security using Arduino and MCP2515 transceivers. Unlike AES or HSM-based methods, which add latency and overhead, SLCP employs HMAC for real-time CAN message authentication.

4.1. System architecture and key components

SLCP System Components:

- Arduino Uno (master and slave): manages transmission and authentication.
- MCP2515 transceivers: facilitate secure node communication.
- L293D motor driver: executes authenticated commands.
- HMAC authentication: ensures message integrity.

The master node embeds an HMAC signature in control messages, while the slave verifies integrity before execution.

4.2. HMAC-based security: step-by-step authentication

Master node (message generation):

- Generates a control message (e.g., motor speed adjustment).
- Creates an HMAC signature using a secret key and SHA-256.
- Transmits the message + HMAC over the CAN bus.

Slave node (message authentication):

- Receives the message and HMAC.
- Recomputes HMAC using the same key and SHA-256.
- If the HMACs match, the command executes; otherwise, it is rejected.

HMAC ensures communication integrity, minimizes delays, and prevents unauthorized access, making it ideal for real-time, low-power automotive networks.

4.3. Performance benchmarking: efficiency vs. security

To validate real-time performance and security efficiency, SLCP was tested against AES-encrypted CAN systems. The results are summarized in Table 4. The results indicate that SLCP provides a 5x reduction in authentication latency compared to AES while consuming 70% less power, making it a practical choice for EV microcontroller-based networks.

Table 4. Performance benchmarking

Metric	SLCP (proposed approach)	AES-based CAN security	Standard CAN (no security)
Message authentication latency	3.2 ms	15.8 ms	1.1 ms
Processing overhead (CPU usage)	5-8%	35-50%	N/A
Power consumption per transaction	0.6 mJ	2.1 mJ	0.3 mJ
Scalability in multi-node networks	High	Limited	High (but insecure)

5. MASTERING RESILIENCE: A COMPREHENSIVE GUIDE TO SYSTEM TESTING AND OVERCOMING CHALLENGES

The proposed SLCP was tested through simulated cyber-attacks on an Arduino-based CAN network to assess its resilience and performance. Tests focused on message authentication time, CPU utilization, packet loss rate, and message rejection rate, evaluating HMAC's effectiveness in ensuring real-time security and detecting malicious transmissions without significant overhead.

5.1. Test 1: message injection – detecting unauthorized commands

Determine whether the system correctly identifies and discards unauthorized messages injected into the CAN bus. Methodology: a malicious node was added to the CAN bus, transmitting unauthenticated control messages. The slave node recalculated the HMAC signature and compared it with the received message. If the computed HMAC did not match, the message was rejected.

Results: message authentication time: 3.2 ms, message rejection rate: 100% (All injected messages were discarded), CPU overhead: minimal (6.5% usage increase during attack detection). This test confirmed that unauthorized message injection is effectively neutralized. The system does not execute commands without proper authentication, preventing malicious control of EV operations such as braking, acceleration, or steering.

5.2. Test 2: replay attack – blocking duplicate message replays

Verify whether the system can detect and reject replayed messages, which attackers can use to duplicate previous commands and override security measures. Methodology: the attacker recorded a legitimate message from the master node. The recorded message was retransmitted to the slave node at a later time. The slave node identified duplicate timestamps and rejected the message.

Results: replay detection accuracy: 99.6% (only 1 false negative in 250 attempts), message authentication latency: 3.4 ms, CPU overhead: 7.2% increase during detection operations. The system accurately identified replayed messages, ensuring that previously recorded commands could not be used maliciously. The inclusion of unique timestamps in HMAC calculations prevents attackers from retransmitting old control signals.

5.3. Test 3: bus flooding – ensuring system stability under attack

Evaluate the system's resilience against DoS attacks, where an attacker floods the CAN bus with excessive traffic, potentially delaying or blocking legitimate messages. Methodology: a malicious node continuously sent high-priority messages to overload the CAN bus. The system relied on, HMAC validation to discard unauthorized messages, CAN priority mechanisms to ensure high-priority master node messages were processed first.

Results: message loss rate: 0.5% (minimal impact on legitimate communication), system response time: no significant delay in high-priority messages, and CPU utilization increase: only 8.3% during attack conditions. The system successfully mitigated bus flooding attacks, ensuring that critical EV operations (e.g., braking, steering) were not affected, even under high-traffic conditions.

5.4. Comparative analysis: SLCP vs. traditional security approaches

Key takeaways (Table 5):

- SLCP outperforms AES-based authentication by achieving 5x faster message validation.
- Maintains robust security while requiring 70% less power consumption than HSM-based models.
- Minimizes processing overhead, making it ideal for resource-constrained EV microcontrollers.

Table 5. Comparative analysis

Security approach	Message authentication time	CPU overhead	Resistance to attacks
AES encryption (standard)	15.8 ms	35-50%	High (but slow performance)
HSM-based security (Tesla, Toyota)	12.5 ms	High power consumption	High
SLCP (proposed HMAC system)	3.2 ms	5-8%	High (low-latency, low-power alternative)

5.5. System scalability: CAN SLCP handle larger networks

SLCP ensures scalability with low computational overhead, allowing seamless integration into high-speed CAN networks without performance degradation. It supports multi-node architectures, making it suitable for autonomous and connected vehicles. Additionally, its compatibility with OTA updates ensures long-term adaptability. Future enhancements include integrating AI-based intrusion detection systems (IDS) for improved anomaly detection and exploring hybrid security models that combine HMAC authentication with lightweight encryption for enhanced protection.

6. RESULTS AND DISCUSSIONS

The evaluation of the SLCP was conducted using an Arduino-based EV communication setup, where the primary controller securely transmits authenticated messages to the subordinate controller via MCP2515 CAN transceivers. To ensure message integrity and prevent unauthorized access, each message incorporates an HMAC signature, verified upon reception.

6.1. Performance analysis and security validation

Table 6 provides a comparative analysis of the proposed SLCP system against previous CAN security methods. The results highlight the improvements in communication security, message integrity, transmission time, and processing efficiency.

Table 6. Comparison of parametric values

Parameters	Results from previous methodologies	Results from proposed method	Improvement (%)
Communication security	95% – AES [29], [30]	98% - HMAC based authentication	+3%
Message integrity	90% accuracy- error detection codes [31]	98% accuracy HMAC verification	+8%
Motor control accuracy	±5% speed deviation- PID control [32]	±2% speed deviation- Arduino with HMAC	+60%
Transmission time	20 µs- CAN protocol efficiency [33]	16 µs- optimized CAN transceivers	+20% faster
HMAC implementation time	1,500 µs - hardware-accelerated computation [34]	1,000 µs- Arduino-based software implementation	-33% faster
Receiving and verifying time	1,200 µs- processing for verification	1 000µs- efficient HMAC processing	-16.6% faster
Matching the key time	10 µs - pre-computed key caching	Negligible (µs) secure key storage on Arduino	+99% faster
Implementing the message time	600-1,200 µs - message parsing algorithms	500-1,000 µs-optimized message handling algorithms	-16.6% faster

6.2. Key findings and their implications

Enhanced security and integrity:

- 98% validation via HMAC, 3% better than AES.
- 8% improved integrity verification, reducing errors and spoofing.

Lower processing overhead:

- 33% faster than hardware encryption for real-time validation.
- 16.6% reduction in verification time, optimizing latency-sensitive tasks.

Optimized motor control:

- 60% accuracy boost in speed control, ensuring stability.
- ±2% deviation vs. ±5% in PID-based controllers.

Superior efficiency and scalability:

- Secure key storage eliminates caching delays for instant matching.
- 16.6% faster message parsing, minimizing CAN bus congestion.

6.3. Comparison with commercial automotive security solutions

To validate the practical applicability of SLCP, its performance was compared with Tesla, Toyota, and BYD's CAN security mechanisms. SLCP outperforms commercial solutions in real-time authentication speed (3.2 ms vs. 12.5+ ms). Consumes 70% less power than hardware-based HSM security models. Retains high security while maintaining computational efficiency, making it ideal for resource-limited EV microcontrollers. One critical factor in EV cybersecurity is whether a proposed security protocol can scale effectively in multi-node, high-speed networks. The SLCP model was evaluated in different scenarios, including single-node system (standard EV) – achieved 98% security validation with minimal processing overhead, multi-node EV network (autonomous vehicle simulation) – ensured 99.3% message integrity in high-traffic conditions. Comparison with commercial automotive security solutions as shown in Table 7.

Table 7. Comparison of the proposed system with commercially available

Manufacturer	Security approach	Message authentication time	Message authentication time
Tesla	HSM + AES Encryption	12.5 ms	High (hardware-accelerated processing)
Toyota	CAN gateway firewall + secure boot	15.8 ms	High (hardware-accelerated processing)
BYD	AI-driven anomaly detection + encrypted CAN frames	10.2 ms	High (AI processing overhead)
Proposed SLCP	HMAC authentication (Arduino-based)	3.2 ms	Low (software-optimized processing)

7. CONCLUSION

The SLCP introduced in this study represents a significant advancement in EV communication security, offering an efficient, low-latency, and cost-effective alternative to traditional encryption-based security solutions. By integrating HMAC authentication into an Arduino-based CAN protocol, the system successfully mitigates cyber threats such as message injection, replay attacks, and bus flooding, ensuring robust message integrity and authentication.

Enhanced security and communication integrity: Achieved 98% security validation, outperforming AES-based encryption by 3%. Improved message integrity accuracy to 98%, reducing error-prone transmissions. Optimized real-time performance for EV applications: 5x faster message authentication (3.2 ms) compared to AES (15.8 ms). Reduced CPU processing overhead by 70%, making it ideal for low-power EV microcontrollers. Reliable motor control and reduced latency: Ensured $\pm 2\%$ motor speed deviation, a 60% accuracy improvement over traditional PID controllers. Reduced message transmission delay by 20%, ensuring real-time EV response.

Despite its advantages, the SLCP system has certain limitations that require further research: Limited encryption capabilities – while HMAC ensures message integrity, it does not provide full data encryption like AES. Scalability concerns in ultra-high-speed networks – additional testing is required for multi-node EV systems with heavy data throughput. Potential memory constraints on low-resource microcontrollers – optimization techniques such as code compression and hardware acceleration could further enhance efficiency.

8. FUTURE SCOPE

Future enhancements focus on optimizing cryptographic algorithms by fine-tuning HMAC for lower authentication latency while maintaining security. Exploring hybrid techniques like AES-GCM + HMAC can provide both encryption and message integrity, while post-quantum cryptography ensures future-proof security. Integrating AI and ML will enhance anomaly detection through AI-driven IDS and predictive models analyzing CAN traffic patterns. Additionally, blockchain-based logging will secure autonomous and connected EVs with tamper-proof records.



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