Mini-MAC: Raising the Bar for Vehicular Security with a Lightweght Message Authentication Protocol

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Note: Footnotes not fixed yet. Cryptologia style not done yet.

Abstract

We propose Mini-MAC, a new message authentication protocol that works in existing automotive computer networks without adding any bus overhead.

Deployed in many vehicles, the CAN bus is a low-speed network connecting electronic control units, including those that control critical functionality such as braking and acceleration. The CAN bus is extremely vulnerable to malicious actors with bus access. Traditionally, Message Authentication Codes (MACs) help authenticate the sender of a message, and variants prevent message replay attacks; however, standard MACs are unsuitable for use on the CAN bus because of small payload sizes. Restrictions of the CAN bus, including the need not to delay messages, severely limit how well this network can be protected.

Mini-MAC is based on a counter-seeded HMAC, augmented with message history and truncated to fit available message space. It causes no increase in bus traffic and incurs a very small performance penalty relative to the provably secure HMAC. It is the first proposal to combine these two tenets for vehicle networks. Even though the CAN bus cannot be properly secured against a dedicated attacker, Mini-MAC meaningfully raises the bar of vehicular security, enhancing the safety of drivers and others.

Index terms— CAN bus, automotive security, message authentication code, Mini-MAC, vehicle security, applied cryptography.

1 Introduction

At the 2015 Black Hat conference, Miller and Valasek [REF] gained full control of a new Jeep, including its engine, brakes, and steering, by exploiting vulnerabilities in its computer network and WiFi implementation and by rewriting firmware on a controller connected to the car's entertainment system. This demonstration, and other similar projects [add refs on car insecurity], highlight the egregious state of vehicular security, including the lack of authentication of messages sent on the Controller Area Network (CAN).

To strengthen vehicular security in a simple and practical yet meaningful way—without replacing the CAN bus—we propose Mini-MAC, a new variable-length Message Authentication Code (MAC) for the CAN bus that works with small payload sizes without delaying messages. Based on the provably-secure HMAC, Mini-MAC protects against masquerade attacks. Mini-MAC also incorporates a counter and message history to protect against replay attacks. To avoid sending separate messages to different recipients, Mini-MAC applies authentication keys shared among groups of communicating Electronic Control

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Units (ECUs). It is the first proposal to authenticate messages on the CAN bus without increasing bus traffic or delaying messages.

Traditional authentication protocols (including digitial signatures or full-length MACs) are unsuited for the CAN bus due to small packet size, limited computational power of the ECUs, and the need not to delay messages (e.g., by time-consuming computations or by increasing bus traffic).

Mini-MAC improves on previous proposals, including Lin-MAC [LSV12], by not increasing bus traffic. Furthermore, Mini-MAC is easy to implement, requires no fundamental change to the underlying functionality of the ECUs, and requires no special hardware.

Our work includes a protoype implementation of Mini-MAC and preliminary timing studies of Mini-MAC for three component hash functions (MD5, SHA-1, SHA-2). For fastest speeds, we recommend using MD5.

Our contributions include:

- Mini-MAC, an authentication protocol suitable for vehicular systems, including the CAN bus, that require short message sizes and no message delays.
- Mini-MAC meaningfully raises the bar on authentication strength for the CAN bus, protecting against masquerade and replay attacks.
- Experimental demonstration of Mini-Mac, including execution times for our three HMAC implementations using the MD5, SHA-1, and SHA-2 hash functions.

2 Background

This section briefly reviews essential background on vehicular security and message authentication codes. The experienced reader may wish to skip to Section 3. We assume the reader is familiar with cryptographic hash functions as explained, for example, by Stinson [Sti06] and NIST [Nat15].

2.1 ECUs

Electronic Control Units (ECUs) found in an automotive computer network are low-power, single-purpose devices. ECUs on the CAN bus control many components in a modern automobile, from headlights and window controls, to brakes and engine. They are not typically designed with security in mind and frequently comprise a basic CAN bus transceiver, basic message processor, and an actuator. The message processor identifies whether or not a message being broadcast is interesting to the ECU and arbitrates bus rights with the other ECUs.

2.2 The CAN Bus

The CAN bus is a simple, low-speed bus designed to network simple nodes. In an automotive environment, it typically runs at 500 kbps.[1] As shown in Figure 1, a frame contains an 11-bit identifier field and a data payload, as well as some control bits. Figure 1 shows the data payload as 8 bits, but it can be 8 to 64 bits and is typically 64 bits. [ref?] The payload of up to 8 bytes is the most important element, as any MAC must fit into this frame or use a more complex multi-frame data transmission protocol that may or may not be supported on all ECUs.

We use the term "message" to refer to the data payload of one logical transmission. Any payload longer than 64 bits must be sent as a multi-frame transmission.

Ideally, and in the case of Mini-MAC, the MAC tag can fit into the payload together with the data, thus not increasing bus utilization. In test data captured by the authors from a 2010 Toyota Prius, approximately 61% of messages contain at most four data bytes (20% contain 4 bytes; 16% contain 3 bytes; 17% contain 2 bytes; and 8% contain 1 byte). Approximately 35% of messages contain a full 8 data bytes, and 4% contain 7 bytes. Thus, for most messages, there are at least four bytes of space available for a MAC tag.

We observed approximately 25 messages sent per second on average (40 maximum per second).

[1] kilobits per second (kbps).

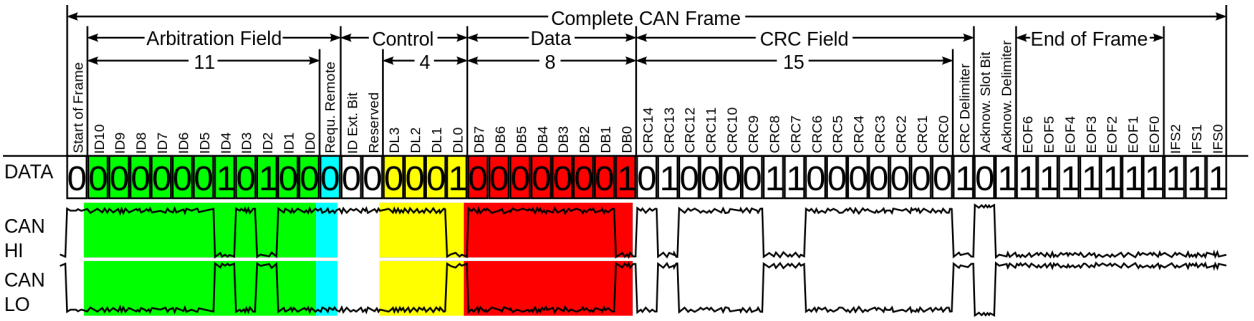

Figure 1: The CAN frame [**?**] [need to cite fig]. Each transmission on the CAN bus is a structured sequence of 55–111 bits including 8–64 data bits.

2.3 Bus Access

To spoof or replay messages on the CAN bus, the attacker must have access to it. There are several ways to access the CAN bus: (1) There is a physical connection through the On-Board Diagnostic (OBD-II) port, typically located underneath the steering wheel. An attacker might hide access to this port by splicing into unexposed wires. (2) An attacker might corrupt an ECU by rewriting its firmware. An attacker might do so while the car is being serviced or by entering the car while it is parked. (3) An attacker might gain access to the CAN bus by exploiting or corrupting a peripheral device connected to it, such as a cellular phone, audio system, or Bluetooth radio. For example, Checkowa [CMK+11] gained bus access by packing malware into a WMA audio file played on the car stereo. [give another example of wireless access from drive-by attacker]

Despite many demonstrated security flaws, automotive manufacturers have been unreasomnably hesitant to acknowledge the vulnerabilities inherent to the CAN bus, sometimes wishfully claiming that undetected bus access is difficult.

2.4 Message Authentication Codes

Given a message and optionally a key, a Message Authentication Code (MAC) computes a short string (called a tag) that a recipient can use, together with the message, to verify the authenticity of the message. The recipient verifies the tag by recomputing it.

The Keyed-Hash Message Authentication Code (HMAC) [BCK96, Nat08] is a well-known MAC construction that keys an underlying component hash function. Breaking it is as hard as breaking the component hash function.

HMAC is computed as

$$H((k \oplus \text{opad}) \parallel H((k \oplus \text{ipad}) \parallel \text{message})), \qquad (1)$$

where k is the key, and opad and ipad are the outer and inner hash padding strings, respectively. These strings are constant strings defined by 0x5C and 0x36, repeated until the hash input is of the appropriate length. H is the component hash function used. The symbols $\oplus$ and $\parallel$ represent exclusive-or (XOR) and concatenation, respectively.

3 Problem Statement

Our task is to create an authentication mechanism suitable for use on the CAN bus in vehicular environments. The mechanism must improve security over the standard non-secured bus, while not increasing bus traffic nor delaying messages. The mechanism must protect against replay and masquerade attacks as defined in Section 5. It must function in the highly constrained vehicular environment, which includes slow, low-power ECUs incapable of complex cryptographic functions.

4 Previous Work

Previous proposals to add authentication to the CAN bus violate the engineering constraints described in Section 3, increasing bus utilization and delaying messages. For example, pairwise key distribution among the ECUs and data that overflow CAN frame boundaries cause additional messages to be sent, delaying messages.

For example, Lin and Sangiovanni [LSV12] propose Lin-MAC, a keyed MAC with counter based on pairwise key distribution. Encrypting the same message to n different ECUs requires n messages to be sent. Using the full HMAC-MD5 requires 128 bits to be sent per message, requring two CAN frames per message.

Other recent CAN security projects suffer from similar limitations. Woo et al. [WJL15] propose a keyed MAC based on pairwise key distribution, packing the tag into the extended ID field (not used by all ECUs) and the CRC field in the CAN trailer (for a related proposal of ours, see Section 9.2). These bits fit only if the ECUs use the extended ID field. Their proposal requires a hardware redesign of CAN transceivers or rewriting a layer of message transmission firmware. Care should be taken when comparing their computation times because they assume a much more powerful message processor than we do.

Zalman et al. [ZM14] propose a fixed-size, timestamped MAC based on pairwise key distribution. Their tag overflows the CAN frame, increasing bus utilization, and as the authors acknowledge, delaying messages.

Xie et al. [XLL+15] propose packing multiple messages into one CAN frame using a keyed MAC with pairwise key distribution. They unrealistically assume that the messages and MAC tag are short enough to fit into one frame. Also, by queing messages into batches, their system delays messages.

[do we want to cite any other works on improving car security? If so, do it here.]

Many automakers and parts manufacturers are now members of the Open Alliance [need ref or URL], a non-profit group researching and encouraging the use of an Ethernet-based high-speed physical layer for use in vehicles. This approach would enable the use of established network security mechanisms in vehicle networks.

5 Adversarial Model

We consider three classes of adversaries:

Type 1 (*Strongest adversary*): A permanent entity on the CAN bus with a valid key for the MAC it wishes to generate.

Type 2 (*Strong adversary*): A permanent entity on the CAN bus without a valid key for the MAC it wishes to generate.

Type 3 (*Weak adversary*): A transient entity on the CAN bus without a valid key for the MAC it wishes to generate.

For example, a Type 1 adversary might be a compromised ECU on the CAN bus. A Type 2 adversary might be a malicious piece of hardware attached to the CAN bus. A Type 3 adversary might be a criminal who has gained temporary access to the CAN bus, perhaps via a wireless channel from another nearby car. For a Type 3 attacker, we assume the adversary's access to the CAN bus is limited to minutes, not hours. The differences among these attackers are what keys they know and for how long they have access to the CAN bus. This project aims to defend against Type 2 and Type 3 adversaries. Our techniques do not protect against a Type 1 adversary, who can spoof any message.

Motivation of the attacker includes criminal mischief (e.g., crashing car, destroying property) and theft. For example, spoofing messages on the CAN bus can unlock doors, disable brakes, and accerate the car. Goals of the attacker include spoofing or replaying messages on the CAN bus that will be accepted by an ECU as valid.

We assume the attacker posses complete knowledge of the CAN bus and ECUs, including all protocols, message IDs, and formats. We assume the attacker has substantial computing power, reliable access to the CAN bus, and is able to monitor and inject messages on the bus. We assume, however, that the

adversary cannot inject more than 40 messages per minute without detection.

We assume the ECUs are trustworthy and that the adversary cannot break standard cryptographic functions including encryption and hash functions.

This work does not address Denial-of-Service (DOS) attacks aimed at preventing a driver from using her vehicle. For example, our techniques do not prevent an attacker from flooding the CAN bus with messages. There are many simple physical DOS attacks, such as slashing a tire, cutting wiring, or draining fuel.

Although we assume the adversary has complete knowledge of the target technology, in practice the adversary must deal with the straightforward yet cumbersome task of learning this technology, which may include new ECUs and message formats.

6 Mini-MAC

Mini-MAC is a group-keyed lightweight variable-length truncated HMAC that depends on a counter and on recent message history. It does not increase bus traffic or delay messages. We explain Mini-MAC in three layers of abstraction: architecture, design, and implementation.

6.1 Architecture

Four core architectural elements characterize Mini-MAC: (1) Variable-size output to fit available space in the CAN packet. (2) Shared keys among groups of ECUs to avoid increasing bus traffic. (3) A counter to mitigate replay attacks. (4) Message history to defeat transient attackers, to mitigate replay attacks after counter resynchronization, and to serve as "salt" against possible unknown precomputation attacks. Elements (1) and (2) trade authentication strength for performance; see Section 8.2 for a discussion of this tradeoff.

To avoid sending long tags using additional messages, Mini-MAC truncates the HMAC tag to fit available space in the CAN frame (typically the resulting truncated tag is approximately four bytes).

To avoid increasing bus traffic by separately authenticating the same message to different recipients, Mini-MAC uses long-term shared group keys instead of pairwise keys. For example, in Figure 2, ECUs 2, 3, and 4 share the group key k_3. Group key distribution is possible because, at system design, the designer knows which ECUs communicate with which others. There is no need for a dynamic group key update capability because group membership will never change. Details about how these keys are initially set, and possibly later updated, are beyond the scope of this paper.

Using a counter is a simple, standard, and effective way to mitigate replay attacks.

Each ECU saves recent messages sent on the bus and XORs them into the HMAC input. More specifically, each ECU saves a separate message history for the successfully authenticated messages received for each group key. Thus, the adversary cannot insert a message into any message history without successfully forging message.

There are three reasons for the message history architectual element: First, it adds protection against any transient attacker (even one who knows the group keys) who cannot deduce enough of the message history. Second, it adds an additional layer of protection against replay attacks. This layer is useful if the counters need to be resychronized (see Section 9.1). Consider what happens if a group of ECUs reset their counters and message history to a previously stored synchronized state. Without message history, the network is potentially vulnerable to a replay attack of messages sent from a time the reset counter state was previously used. With message history, it is extremely likely that the unfolding message history will rapidly differ. Third, the history adds an unpredictable "salt" that might mitigate some possible precomputation attacks. Whereas counter values are predicable, message history is not.

6.2 Design

Figure 3 shows how to compute Mini-MAC$(k, M_n, s, C, \text{History})$, where k is the group key, M_n is the current message, s is the number of available bits in the current CAN frame, C is the

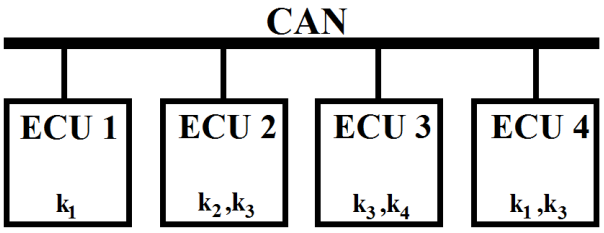

Figure 2: Mini-MAC key distribution. Each group of ECUs shares an authentication key.

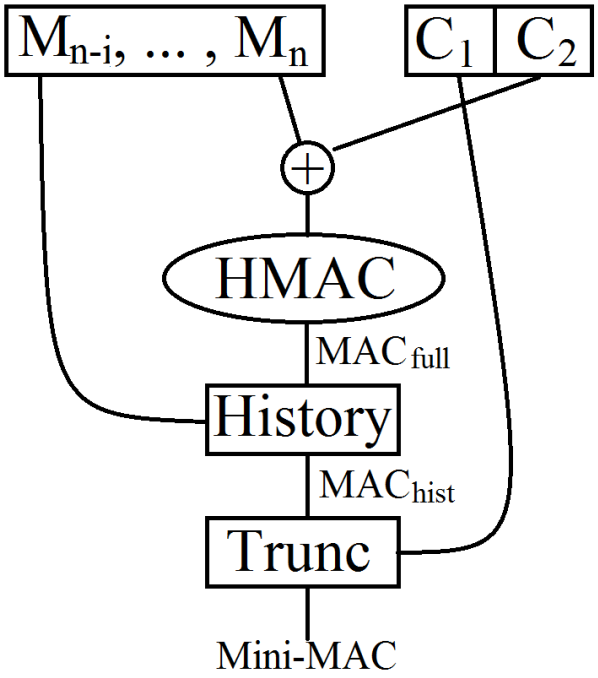

Figure 3: Mini-MAC. The Mini-MAC tag of a message M_n is a truncated keyed HMAC of the XOR of M_n, a counter C, and the most recent λ messages.

message counter, and History $= (M_{n-\lambda}, \ldots, M_{n-1})$ is the sequence of the most recent valid λ messages for key k.

The Mini-MAC tag is computed as

$$\text{trunc}(s, \text{HMAC}(k, \text{Input})), \tag{2}$$

where HMAC is the underlying HMAC and $\text{trunc}(s, \cdot)$ extracts s bits from its input. The input to HMAC is computed as

$$\text{Input} = M_n \oplus C \oplus (M_{n-\lambda} \oplus \cdots \oplus M_{n-1}). \tag{3}$$

6.3 Implementation

We implemented Mini-MAC using three different component hash functions (MD5, SHA-1, and SHA-2) to compare the resulting running times. Each group key is 128 bits. The $\text{trunc}(s, \cdot)$ function extracts the first s bits of its input.

We recommend a 64-bit counter, which (assuming at most 40 message per second) ensures no repeated counter state for 20 years of continuous operation (32 bits would prevent counter roll-over for 20 years with four hours of driving a day).

For **HMAC-MD5**, we adapted Peslyak's [Pes09] implementation of MD5 [Riv92] for the MSP430 platform, producing a 128-bit output. Despite known collision attacks on MD5 [WY05], we consider MD5 for Mini-MAC for its very fast speed.

For **HMAC-SHA-1**, we adapted Conte's [Con06a] SHA-1 [Nat15] implementation for the MSP430 platform, producing a 160-bit output. As for MD5, despite known security vulnerabilities in SHA-1 [WYY05], we consider SHA1 as a potential candidate.

For **HMAC-SHA-2**, we also adapted Conte's [Con06b] SHA-2-256 implementation for the MSP430 platform, producing a 256-bit output. A member of the SHA-2 family of hash functions, SHA-2 is still in use and is recommended by NIST as a cryptographic hash function, though SHA-3 will soon replace it [Nat15]. We did not use SHA-3 because we did not find an implementation of it for the MSP430. Throughout, we shall refer to SHA-2-256 as SHA-2.

7 Testing

We measured the execution time and RAM usage of our three Mini-MAC implementations running on the Texas Instruments MSP430F5529 microcontroller. In speed and power this device is representative of vehicular ECUs.

7.1 Purpose

The purpose of our tests is to measure the time and space usage of our Mini-MAC implementations, and more generally, to evaluate the performance suitability of Mini-MAC for authenticating messages on the CAN bus.

7.2 Methods

For each implementation we measured code size, memory usage, execution time, and bus utilization, collecting for each implementation metrics from 1000 inputs of various typical sizes (1 byte, 2 bytes, 4 bytes).

We measured code size and RAM usage at compile time using the Texas Instruments Code Composer v6. The RAM usage is know at compile time because there is no dynamic memory allocation.

We measured execution time using a counter register on the MSP430, whose 32 kHz clock provides timing values to approximate millisecond (ms) accuracy. As a very minor point we note that, due to a limitation in the hardware's support for timing measurements, there may be a $+/-0.03$ ms inaccuracy in each reading due to the time it takes to read the counter.

We collected statistics on message traffic from a 2010 Toyota Prius with a CAN-bus sniffer program based on an Arudiuno Uno platform and connected via an OBD-II CAN transceiver shield.

8 Results and Analysis

We analyze Mini-MAC for performance and security. Mini-MAC must be able to authenticate messages without compromising the performance of the real-time, safety-critical systems.

Table 1: Additional bus traffic for various authentication mechanisms, for one key group with n recipients. Mini-MAC adds no additional bus traffic

Algorithm	**Add. Traffic (b)**
HMAC-MD5 (Group)	128
HMAC-MD5 (Pairwise)	128*n
Lin-MAC	128*n
Mini-MAC	0

Table 3: Mean execution time of Mini-MAC implementations. Only the MD5 implementation meets our engineering requirement of at most 25 ms per message.[add STDs]

Hash	**Exec. Time (ms)**
MD5	7.5
SHA1	28.0
SHA2	69.6

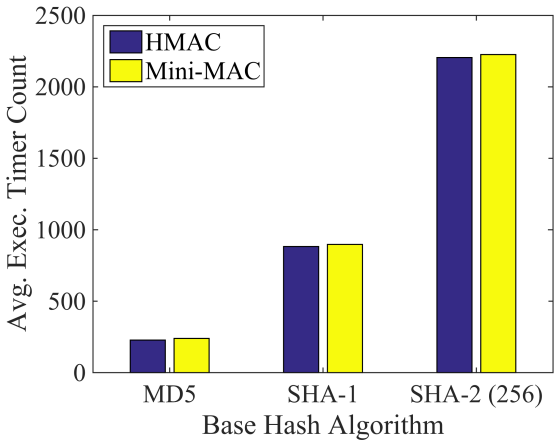

Figure 4: Mean execution time for our Mini-MAC implementations, in cycles on a 32 kHz clock.

Table 2: Mean additional time and RAM to compute Mini-MAC implementations over HMAC.

Hash	Code Size (B)	RAM Use (B)	Execution Time (ms)
MD5	835	5	0.38
SHA-1	850	5	0.42
SHA-256	766	5	0.68

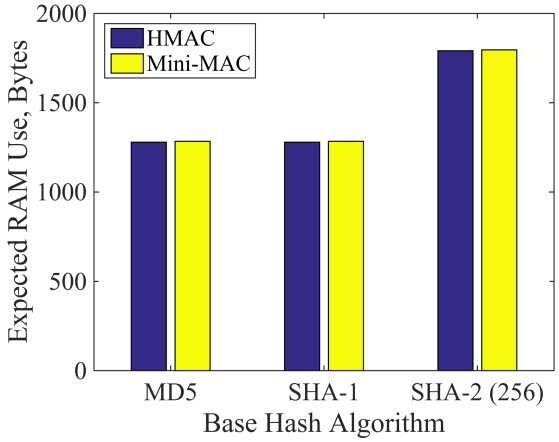

Figure 5: RAM usage for our Mini-MAC implementations.

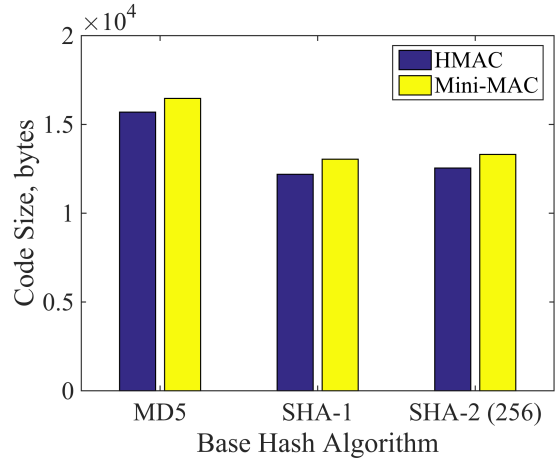

Figure 6: Code size of our Mini-MAC implementations.

8.1 Performance

Tables 1–3 and Figures 4–6 show the message traffic, execution time, code size, and RAM usage of our unoptimized implementations of Mini-MAC and their underlying HMACs. Time and space are dominated by the HMAC computation.

Table 1 shows that Mini-MAC adds no additional bus traffic. By contrast, HMAC-MD5 adds 128 bits (two CAN frames) per authentication, due to the 128-bit tag. Similarly, the pairwise-keyed Lin-MAC generates two additional CAN frames per recipient ECU in each group communication.

Table 3 shows the mean execution time [add standard deviations] for each of our implementations of Mini-MAC. Using MD5 is much faster than using SHA-1 or SHA-2. As shown in Table 2, the overhead in time to compute Mini-MAC beyond HMAC is very little (approximately 0.38–0.68 ms). Similarly, Figure 4 shows the mean execution times for Mini-MAC measured in number of cycles on a 32 kHz clock.

Importantly, Table 3 shows that only our MD5 implementtion of Mini-MAC runs fast enough to satisfy our requirement of authenticating at least 40 messages per second (approximately 25 ms between messages). While highly optimized code might run faster, on the basis of our timing measurements, we recommend implementing Mini-MAC using MD5.

Figure 5 shows the RAM usage for our implementations of Mini-MAC. As shown in Table 2, the overehead in RAM usage to compute Mini-MAC beyond HMAC is very low (about 5 bytes).

Figure 6 shows the code size of our Mini-MAC implementations. As shown in Table 2, the additional code size for Mini-MAC beyond HMAC is very small (approximately 800 bytes).

8.2 Authentication Strength

Mini-MAC detects spoofed messages by using a keyed HMAC. It detects replay attacks by incorporating a counter and recent message history into the HMAC input. Using message history also complicates a transcient attacker who may be unable to observe a sufficient number of recent messages. The 128-bit keys are sufficiently long to withstand exhaustive key-search attacks. The 64-bit counter is sufficient to prevent counter rollover within the lifetime of the car.

A security-enhancing feature of the CAN bus is, ironically, its slow speed of at most approximately 40 messages per second. Figure 7 shows a histogram of message interarrival times that we collected from a 2010 Toyota Prius. The slow speed of the CAN bus limits the rate at which an attacker can inject messages into the bus.

Another defensive feature is that there is no simple fast way for an adversary to test if a candidate tag is valid. The only way we are aware of is to inject a message into the bus and observe if the receiving ECU accepted the message.

Limitations imposed by Mini-MAC include its use of group keys and truncated HMAC tags. Using group keys means that a single compromised ECU learns all of the keys to which groups it belongs. We consider this limitation an acceptable design tradeoff given that Mini-MAC does not increase bus utilization and the compromise of any critical ECU is a devastating security failure.

One potential attack is for the adversary to inject messages into the bus with the hopes of trying a tag that verifies correctly. We shall call this attack the "trial injection attack." A downside of this attack is that it would be easy to detect such an attack involving many messages.

Table 4 lists for various tag lengths L two reference times that are useful in assessing the effectiveness of this attack. Column X gives the expected time to find a particular tag of length L by randomly guessing tags. Column Y gives the expected time to find a collision[2] in Mini-MAC with tag length L, exploiting the Birthday Paradox. The times are computed assuming that the enemy is limited to trying 40 tags per second.

[2]A collision is any pair of different inputs that produces the same output.

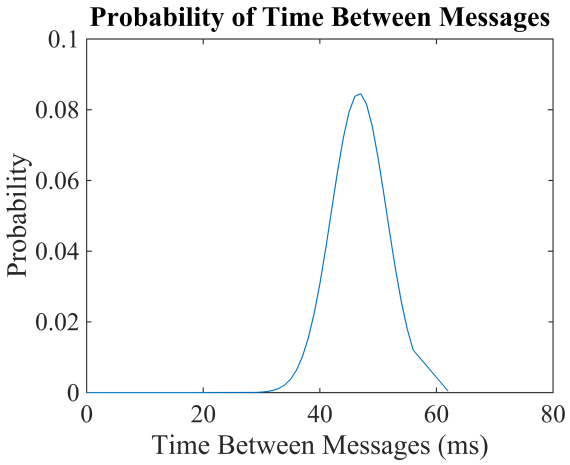

Figure 7: Histogram of message interarrival times observed by the authors from a 2010 Toyota Prius.

In Table 4, Column X is the expected time for a straight-forward implementation of a trial injection attack to succeed. We do not see how an adversary could mount a more clever version of this, or any other, attack to achieve the optimistic times given in Column Y. We include Column Y simply as a conservative reference.

For example, with a four-byte tag, the expected time for a straight-forward message injection attack to succeed is approximately 27.3 mins. For this reason we suggest that the message history window be set for at least 30 mins.

Another potential attack is to observe bus traffic with the hopes of finding statistical regularities that would significantly improve the chances of success of the aforementioned attack. We conjecture that this attempt is unlikely to yield significant advantage, given the strong properties of HMAC and some desirable (albeit imperfect) characteristics of the component hash functions.

Given that the CAN bus does not authenticate messages, we conclude that Mini-MAC meaningfully raises the bar of vehicular security.

9 Discussion

In this section we discuss how to resynchronize ECUs, how to lengthen the mini-MAC tag as an optional improvement, and we list some open problems.

9.1 Resynchronization

Our mini-MAC proposal requires the ECUs to have synchronized counters and synchronized message-history states. Therefore, a mechanism is needed to resynchronize the ECUs in case they ever lose synchronization, as might happen, for example, by a fault in the ECU or a disruption in message transmission.

Two common solutions are to reset the state to a specified initial state, or for one ECU to select a new state and communicate that state to the other ECUs (encrypted by a shared secondary communication encryption key).

Instead, for enhanced security we propose that each ECU periodically save its state in persistent memory. In the initial attempt to resynchronize, each ECU loads its most recent state. If that fails, then the aforementioned mechanisms could be applied. Section 6.1 explains how message history helps guard against replay attacks upon resynchronization.

A limitation of the CAN bus is that it provides no mechanism for detecting when ECUs are out of synchronization. In some cases, by monitoring observable conditions on the bus, an ECU might detect that another ECU is not responding to a message, which might be the result of a synchronization failure. A tradeoff in our design is that, by using counters and message history to athenticate messages, mini-MAC increases the opportunities for possible synchronization failures.

9.2 Lengthening the Mini-MAC Tag

Optionally, it is possible to lengthen the Mini-MAC tag by using the two bytes of space allocated for the CRC field in the CAM frame (see Figure 1), as suggested by Woo et al. [WJL15] in a related proposal. Because a MAC detects transmission errors (in fact, better than a simpler CRC), there is no need for a CRC in addition to a MAC.

Increasing the tag length greatly increases the time required for an adversary to forge a valid tag by finding a collision in the Mini-MAC by exhaustive search. Table 4 gives the expected time for an adversary to send a forged message that will be accepted by another ECU, for various tag lengths. Here, the main limiting assumption is the frequency with which messages can be sent on the CAN bus (approximately 40 messages per second. [in table, change b to bits] For example, increasing the tag from 32 to 48 bits increases this time from approximately 27.3 minutes to over four days.

Table 4: Expected time for some spoofed message to be accepted by an ECU for various tag lengths, assuming the adversary injects 40 forged messages per second.[add col for linear search]

Tag Length (b)	Time to Find Collision
16	6.40s
24	1.70m
32	27.30m
40	7.28h
48	4.85d

To implement this strategy one could modify the lower-level code in the CAN network stack, either to perform the MAC calculation there or to open the CRC field to the application level to calculate the MAC.

9.3 Open Problems

Our engineering decisions are driven by a desire to improve vehicular security by adding authentication to the CAN bus, without increasing bus traffic or delaying messages, and without making any disruptive changes. The egregious state of vehicular security, however, demands a radical disruptive redesign of vehicular computer networks carried out including security as a foundational design requirement. [should we cite any discussion like this from someone else? are we the first to say so?]

Design ideas for a replacement network to the CAN bus include the following: (1) Use a well-established high-speed network (such as 802.3 Ethernet) on which standard security mechanisms (such as IPsec) can be deployed. (2) Segregate nodes on the bus into task-defined groups. (3) Protect access to the bus by physically separating critical and non-critical systems. In particular, it should not be physically possible for malware or faults in entertainment or Bluetooth systems to affect braking, steering, or

acceleration.

A separate related problem is to detect vehicular network intrusions. [ref?] A challenge of such work is that there is no good reponse of what to do if an intrusion is detected other than to shut down the vehicle safely.

The Car-to-X network [FBZ+08] is an emerging interconnected collection of vehicles, buildings, signs, and road infrastructure to reduce congestion and enable more efficient traffic control. Cars of the future will have to be able to communicate securely with objects on such networks, requiring authentication and key management beyond Mini-MAC.

10 Conclusion

We propose Mini-MAC, the first variable-length MAC protocol for the CAN bus that adds no bus traffic overhead, allowing it to be used in vehicular systems with time-sensitive messages. The truncated HMAC protects against message injection by adversaries who do not know the ECU keys. The counter and message history protect against replay attacks.

Limited message size, the need not to delay messages, the limited computational power of the ECUs, and the relative ease of gaining access to the bus severely restrict how well the CAN bus can be protected. Mini-MAC meaningfully raises the bar on vehicular security, approaching (we conjecture) the limits of what is possible for authentication strength in this highly constrained environment.

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