The Cost of OSCORE and EDHOC for Constrained Devices

Extended Paper

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Abstract—Many modern IoT applications rely on the Constrained Application Protocol (CoAP) because of its efficiency and seamless integrability in the existing Internet infrastructure. One of the strategies that CoAP leverages to achieve these characteristics is the usage of proxies. Unfortunately, in order for a proxy to operate, it needs to terminate the (D)TLS channels between clients and servers. Therefore, end-to-end confidentiality, integrity and authenticity of the exchanged data cannot be achieved. In order to overcome this problem, an alternative to (D)TLS was recently proposed by the Internet Engineering Task Force (IETF). This alternative consists of two novel protocols: 1) Object Security for Constrained RESTful Environments (OSCORE) providing authenticated encryption for the payload data and 2) Ephemeral Diffie-Hellman Over COSE (EDHOC) providing the symmetric session keys required for OSCORE. In this paper, we present the design of four firmware libraries for these protocols especially targeted for constrained microcontrollers and their detailed evaluation. More precisely, we present the design of µOSCORE and µEDHOC libraries for regular microcontrollers and µOSCORE-TEE and µEDHOC-TEE libraries for microcontrollers with a Trusted Execution Environment (TEE), such as microcontrollers featuring ARM TrustZone-M. Our firmware design for the later class of devices concerns the fact that attackers may exploit common software vulnerabilities, e.g., buffer overflows in the protocol logic, OS or application to compromise the protocol security. µOSCORE-TEE and µEDHOC-TEE achieve separation of the cryptographic operations and keys from the remainder of the firmware, which could be vulnerable. We present an evaluation of our implementations in terms of RAM/FLASH requirements, execution speed and energy on a broad range of microcontrollers.

I. INTRODUCTION

CoAP is a widely used IoT application layer protocol. It was designed with two main goals: 1) to be efficient for large deployments of constrained devices communicating over constrained networks and 2) to integrate easily with existing Representational State Transfer (REST) [23] protocols, such as HTTP [22] [45] [20]. One of the strategies that CoAP uses to achieve these goals is to leverage proxy software executed on middle boxes, such as the border routers connecting the constrained IoT networks and the non-constrained networks, e.g., the Internet [45] [31]. For example, a proxy may serve incoming requests from a cache containing previously received data that is still valid in order to save the constrained communicational and computational resources of the device.

In other use cases, the proxy may act as a cross-protocol proxy and translate between CoAP and HTTP. Such cross-protocol proxies achieve integration of the constrained devices on the Internet that is independent of the application logic [20] [19] [29].

The CoAP specification [45] states that DTLS or TLS [18] [43] has to be used to secure CoAP. Although (D)TLS provides strong security guarantees, (D)TLS channels must be terminated at the proxies. This is because the proxies need to access certain fields of the CoAP or the HTTP message, which are encrypted at the transport layer. Decrypting the secured messages at the proxies makes the necessary fields available, but unfortunately also exposes the sensitive message payload [44] [32].

In order to circumvent this security issue, an alternative to (D)TLS consisting of the protocols OSCORE [42] and EDHOC [43] was recently proposed by IETF. In contrast to (D)TLS, OSCORE and EDHOC operate on the application layer, thus making proxy operations possible without decrypting the message payload. In addition, in order for both protocols to be well suited for constrained devices and networks, they leverage the low overhead encoding formats Concise Binary Object Representation (CBOR) [17] and CBOR Object Signing and Encryption (COSE) [41].

Previous work in the area of OSCORE and EDHOC implementations only considers early protocol drafts and therefore does not include all protocol modes [46]. The previous work also does not provide detailed evaluation in terms of memory, execution speed and energy on constrained microcontrollers [25]. We, however, describe the design of our libraries and provide the first detailed evaluation of the latest states of the specifications [42] [43]. Moreover, we consider all modes of operation. Furthermore, previous work does not consider the fact that IoT devices are often prone to software vulnerabilities, e.g., buffer overflows, which may compromise even the best-designed protocols. This is due to the fact the IoT devices often run firmware written in system languages such as C and C++. Moreover, such IoT firmware is often executed without an Operating System (OS) or on top of a Real-Time OS (RTOS) which provides very limited or even no security features. An attacker exploiting such a software vulnerability could, for example, leak the cryptographic keys used in the protocols and use them to impersonate the device. We address this issue.
by identifying the critical parts of the OSCORE and EDHOC protocols and placing them in a TEE. Such TEEs have become recently available on mainstream microcontrollers, for instance microcontrollers based on the Cortex-M23/33 cores featuring ARM TrustZone-M TEE [8, 9, 10, 7].

Contributions

We present the design of the firmware libraries µOSCORE and µEDHOC for regular microcontrollers. Our firmware designs consider all modes of operation of the final version of the OSCORE specification [42] and the latest EDHOC draft version [43]. The main feature of our designs is that they are completely independent of the CoAP library, embedded OS, the communication protocol stack and the crypto library. µOSCORE and µEDHOC are available as open source software [12].

We present the design of the firmware libraries µOSCORE-TEE and µEDHOC-TEE for microcontrollers featuring a TEE. These libraries separate the cryptographic keys and routines from the rest of the firmware, which could be vulnerable. We designed µOSCORE-TEE and µEDHOC-TEE especially for microcontrollers, but they can also be ported to more powerful computing environments, e.g., ARM Cortex A class of devices.

We provide the first detailed study about the applicability of the OSCORE and the EDHOC protocols on constrained IoT devices. More precisely, we provide a detailed evaluation of our libraries regarding RAM/FLASH requirements and execution speed on four broadly used low-end CPUs: Cortex M0, M4, M33 and Xtensa. We evaluate the overhead caused by using a TEE on the nRF9160 [9] radio SoC from Nordic Semiconductor featuring a Cortex-M33 CPU with TrustZone-M. In addition, we present an evaluation of the energy requirements of the protocols in an IPv6 over Bluetooth Low Energy (BLE) network [33].

II. BACKGROUND

This section provides background for the rest of the paper. The CoAP introduction provides details which are required for understanding the OSCORE internals. The TrustZone-M introduction is required for understanding the separation of code and keys.

A. CoAP

CoAP is a RESTful application layer protocol especially designed for the IoT domain [45]. It considers two types of devices – clients and servers, which communicate using requests and responses. The servers host resources such as sensors and actuators. The clients may access those resources using PUT, GET, POST and DELETE methods. Each resource is reachable through a Uniform Resource Identifier (URI). Each CoAP packet begins with a fixed 4-byte header carrying the method type (PUT, GET, POST, DELETE) or a response code, among other information. The header is followed by an optional token used to correlate requests and responses. The token is followed by optional options that contain additional parameters for the requests/responses. These are followed by an optional payload, prefixed with the payload.

B. TrustZone-M

A TEE is a state-of-the-art feature that has been available on application class processors for several years. Microcontroller class processors featuring a TEE called TrustZone-M were recently introduced by ARM with the ARMv8-M architecture. ARMv8-M chips such as nRF9160 and nRF5340 became recently available on the mass market.

TrustZone-M separates a microcontroller in two domains called secure world and non-secure world. RAM/FLASH memory regions and memory-mapped peripherals of the microcontroller are associated with one of those domains. Secure world code, data and peripherals are not accessible from non-secure world code or peripherals. Secure world code and peripherals can access secure world and non-secure world code and peripherals.

Functions in the secure world can call functions in the non-secure world without any restrictions. Secure functions are called by non-secure functions using a special type of secure memory region called non-secure callable. Only functions in the secure world defined with the non-secure callable attribute will contain a special secure gateway (SG) instruction, which allows them to be called from the non-secure world. Such functions are referred to as veneer functions [11]. This is the only way in which secure software can be accessed from the non-secure software.

By default, after power-up or reset the execution starts in the secure world. At that point, all memory regions are secure. The mapping of memories and peripherals into the secure world and the non-secure world is done during the boot process before the non-secure application is called.

III. ADVERSARIAL MODEL

This paper considers scalable remote software attacks targeting IoT devices. Such attacks may leverage common software vulnerabilities such as buffer overflows to leak cryptographic keys or manipulate the cryptographic operations involved in the OSCORE and EDHOC protocols.

However, we assume that the attacker cannot break state-of-the-art cryptographic algorithms or disturb their execution when they are executed inside the TEE. We also assume that the attacker cannot gain any knowledge of keys stored inside of the TEE. This paper also does not consider physical attacks targeting the IoT devices such as physical side channels [30], fault injections e.g., glitching [34] or physical memory dumping [35] since such attacks require physical access to the devices which makes them less scalable.

IV. REQUIREMENTS AND DESIGN GOALS

In this section, we state several high level requirements, which our firmware designs and their implementations have to fulfill. Then we derive a set of precise design goals from these requirements.

R-I: Lightweightness: OSCORE and EDHOC are intended to be executed on constrained microcontrollers, e.g., microcontrollers based on the ARM Cortex M CPUs. Our firmware designs have to be suitable for this class of devices. Therefore,
the implementations should be fast, interruptible and have low FLASH/RAM requirements. Additionally, heap memory should not be used. Heap usage on a microcontrollers often leads to heap fragmentation, which in turn may lead to situation at runtime where no additional memory can be allocated [13].

R-II: Adoptability: Our firmware designs have to ensure the portability of the implementations to a variety of application environments, e.g., different RTOSS, radios and hardware platforms. Therefore, our firmware designs should not rely on any specific: 1) embedded OS, 2) CoAP library, 3) underlying protocol stack, 4) crypto library or 5) specific hardware features, e.g., crypto accelerators or radio transceivers.

R-III: Firmware and Key Isolation: For our firmware designs for microcontrollers featuring a TEE, we assume that an attacker exists that can exploit software vulnerabilities such as buffer overflows, and in this way can compromise the security of the protocols. In order to mitigate such attacks, our designs for microcontrollers featuring a TEE should reduce the possibility of such software vulnerabilities being exploited, as much as possible. Therefore, to achieve this requirement, the sensitive key material and crypto operations should be separated from the possibly vulnerable rest of the firmware. More precisely, only the bare minimum code should be placed in the TEE. In addition, the interface between the TEE code and the non-TEE code should be as narrow as possible.

V. OSCORE

In this section, we briefly describe the OSCORE protocol functionality. Then we introduce the design of µOSCORE and µOSCORE-TEE.

A. OSCORE Functionality

OSCORE secures CoAP by providing end-to-end authenticated encryption, replay protection and binding of requests and responses. At the same time, OSCORE allows proxy operations. More precisely, OSCORE protects: 1) the method/response code, 2) the URI of the requested resource and 3) the payload. An OSCORE packet has the same structure as a CoAP packet. The main difference between the two is that the payload of the OSCORE packet is encrypted and integrity-protected by using an Authenticated Encryption with Associated Data (AEAD) algorithm [28]. The AEAD algorithm uses a shared symmetric keys on the client and the server, which may either be pre-established or established with a key establishment protocol such as EDHOC [43]. OSCORE packets are identified by the OSCORE option field, which can also contain additional parameters.

1) OSCORE Security Contexts: Each OSCORE endpoint maintains all the information it requires in three security contexts: a common context, a sender context and a recipient context. The common context is, as the name states, common to both client and server. It consists of identifiers for the AEAD Algorithm [28] and the HKDF Algorithm [28], Master Secret, Master Salt, ID Context and Common IV. Algorithms that must be implemented are AES-CCM-16-64-128 [49] and HMAC-SHA256 [28]. Master Secret is the shared secret. In addition to

Figure 1: Converting OSCORE message to a CoAP message

the common context, both OSCORE client and server possess a sender and a recipient context. The parameters Sender ID and Sender Key of the sender contexts are identical to the parameters Recipient ID and Recipient Key of the recipient contexts. The Sender Key and the Recipient Key are symmetric keys derived from the Master Secret. Sender ID and Recipient ID are identifiers used to identify the sender/recipient contexts.

2) Conversion between CoAP and OSCORE and Vice Versa: A CoAP message is converted into an OSCORE message before it is sent, and vice versa when it is received. Figure 1 shows the conversion of a CoAP message to OSCORE. The Code field, some options that need to be protected (called E options) and the optional payload form a plaintext, which is to be encrypted and integrity-protected. The resulting cipher text is the payload of the OSCORE packet. The Code of the OSCORE packet is fixed – 0.02 (POST) for requests and 2.04 (Chaged) for responses. In addition, the OSCORE packet contains an OSCORE option field, which is used to distinguish an OSCORE packet from a CoAP packet. Moreover, in some cases the OSCORE option transports parameters used for the nonce generation and identification of the contexts at the receiving party.

B. µOSCORE Design

µOSCORE has a simple API, consisting of only three functions: oscore_init(), oscore2coap() and coap2oscore(). The oscore_init() function initializes the OSCORE contexts. The functions oscore2coap() and coap2oscore() convert OSCORE to CoAP packets and vice versa.

µOSCORE envisions a usage model in which the user’s CoAP application runs as usual using some CoAP library and embedded OS preferred by the user. The conversion to/from OSCORE happens just before a CoAP packet needs to be sent and just after an OSCORE packet is received, see Figure 2. The functions coap_request_pkg_create/process(), and coap_response_pkg_create/process() are provided by the CoAP library. The send() and receive() functions are provided by the OS. For example Zephyr OS which is the OS we used for testing our libraries, provides standard BSD sockets [26], which allow sending and receiving data over UDP or TCP.

The function oscore_init() derives the Common IV, Sender Key and Recipient Key from the Master Secret using an HKDF function. We use a callback function to an implementation of the HKDF function that is provided by the user.
When the keys are retrieved, the corresponding cryptographic algorithms are executed. In the case of \texttt{tee\_hkdf()} and \texttt{tee\_aead()}, the output of the function is either a cipher text or a plain text, which is returned in the non-TEE domain.

**VI. EDHOC**

In this section we give an overview of the EDHOC protocol functionality. Then we present the design of \( \mu \)EDHOC and \( \mu \)EDHOC-TEE.

**A. EDHOC Functionality**

EDHOC is a lightweight authenticated ephemeral Diffie-Hellman (DH) key exchange protocol based on the SIGMA-I protocol. EDHOC requires the exchange of three messages between an initiator and a responder endpoint. Additionally, each endpoint can indicate an error condition by sending an error message. EDHOC can use static DH keys or digital signatures for message authentication. Static DH keys and digital signatures may be used with Raw Public Keys (RPKs) or certificates. The authentication method used by the initiator may differ from the authentication method used by the server.

Before discussing the design of \( \mu \)OSCORE-TEE in detail, we first state which assets need to be protected and what are the consequences of potential attacks on them.

1) **Sensitive Assets:** By analyzing the OSCORE specification we identified the Master Secret, Recipient Key and Sender Key as sensitive key material. Leaking these keys will make Man-in-the-Middle attacks at the protocol level possible. Also, sensitive are the AEAD and HKDF routines, which use these keys. If an attacker has access to these routines, he may manipulate them in a way that they leak their keys.

2) **Firmware and Key Isolation:** \( \mu \)OSCORE-TEE reuses the main part of the \( \mu \)OSCORE design. However, several important differences exist. First, the OSCORE contexts are split between the TEE and the non-TEE domains. For each OSCORE endpoint, the TEE domain maintains a data structure consisting of \textit{ID Context}, Master Secret, Recipient Key and Sender Key. The non-TEE domain holds the contexts as discussed in Section VI-A excluding the Master Secret, Recipient Key and Sender Key. Second, a narrow interface between the TEE domain and the non-TEE domain is provided by two functions \texttt{tee\_hkdf()} and \texttt{tee\_aead()}. These functions implement the key derivation function and the AEAD algorithm respectively. Instead of any sensitive keys, they take \textit{ID Context} as an argument. When they are called, \textit{ID Context} is passed to the TEE domain, where it is used to retrieve the cryptographic keys corresponding to the contexts in the non-TEE domain. When the keys are retrieved, the corresponding cryptographic algorithms are executed. In the case of \texttt{tee\_hkdf()}, the output of the function is the Recipient Key or the Sender Key, which is stored in the TEE domain. In the case of \texttt{tee\_aead()}, the output of the function is either a cipher text or a plain text, which is returned in the non-TEE domain.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{api_usage_model.png}
\caption{API usage model}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{conversion_functions.png}
\caption{\texttt{coap2oscore()} and \texttt{oscore2coap()} conversion functions}
\end{figure}

The conversion functions \texttt{coap2oscore()} and \texttt{oscore2coap()} execute a series of operations as shown in Figure 3. In the \texttt{coap2oscore()} function, first, the options contained in the CoAP packet are extracted. Then the options that need to be protected (E options), the payload and the code field form the plaintext of the new OSCORE packet, see also Figure 1. After that, the OSCORE option is created. When \texttt{coap2oscore()} is called on the client side the OSCORE option carries parameters used for the AEAD nonce generation. Otherwise, the OSCORE option is empty. The parameters carried in the OSCORE option are saved locally in a state variable. After that, a nonce is created and the plaintext is encrypted. For the encryption, we use a callback function to a user-provided implementation of the AEAD algorithm. Then the OSCORE packet is created.

In the \texttt{oscore2coap()} function, the OSCORE packet is parsed. If the packet does not contain an OSCORE option, the packet is a regular CoAP packet. In this case, \texttt{oscore2coap()} returns with a status code indicating to the caller that the received packet is a CoAP packet and can be processed as usual. If the packet contains an OSCORE option, it is an OSCORE packet. Then, the OSCORE option is parsed in order to retrieve the parameters for the nonce generation. Note that these parameters are only carried in the OSCORE option when \texttt{oscore2coap()} is called on the server side, otherwise they are retrieved from the local state variable. Afterwards, the payload is decrypted using a callback function to a user-provided implementation of the AEAD algorithm. Next, a CoAP packet is created.

**C. \( \mu \)OSCORE-TEE Design**

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\centering
\includegraphics[width=\textwidth]{conversion_functions.png}
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The implementation of those functions may use any protocol. The second set of parameters consists of credentials belonging to potential communication peers, e.g., root public keys of the CA when certificates are used, 3) intermediate EDHOC keys and 4) the result of the EDHOC protocol. An attacker having access to one of those keys may: 1) impersonate the device by leaking its long-term authentication keys, 2) fool the device into believing that it is talking to a legitimate peer by changing the peer’s public key or the root public key of the CA and 3) compromise the security of EDHOC by leaking or manipulating its intermediate keys or the end result of the protocol.

Also sensitive are all cryptographic routines using the keys. If these routines are manipulated, they may leak the keys or allow the EDHOC protocol to succeed although the communication peer is not authentic.

2) Firmware and Key Isolation: µEDHOC-TEE reuses a main part of the µEDHOC design. In the following, we only discuss the relevant aspects of the key and crypto code isolation.

In the TEE, we use security contexts, which are data structures containing keys. Each device has at least two security context instances, one for its own keys, which we refer to as an own context, and at least one for the credentials of the communication peers, which we refer to as peer context. If certificates are used for the peer authentication, one peer context containing the root public key of the CA is sufficient for authenticating many peers. However, when the peers authenticate with RPK, or the peers use certificates issued by different CAs, a separate context for each credential is used.

Each security context is identified with a context ID. Each key in a given context is identified with a key ID. In our firmware design, crypto routines are called outside of the TEE by using the context and key IDs. Inside the TEE, the IDs are used to retrieve the keys. Then the crypto routine is executed.
with the retrieved key in the TEE. If the crypto routine produces new keys, e.g., if the crypto routine is a HKDF function, the new keys are stored in the own context of the device.

µEDHOC-TEE uses the following interface functions between the TEE and the non-TEE domains: aead(), asymm_verify(), asymm_sign(), hkdf_extract(), hkdf_expand(), dh_secret_derive(), hash() and xor().

Special attention is given to the functions aead() and asymm_verify(), which verify the authenticity of a message. In the event that the authentication verification fails, these functions delete all intermediate keys, which prevents further protocol execution. If this is not done and the protocol logic outside the TEE is simply informed that the verification has failed, the protocol execution will not necessarily stop. A protocol logic outside the TEE controlled by an attacker will continue the protocol execution, which will lead to a situation where a key is exchanged with a non-authentic peer.

VII. REQUIREMENTS AND DESIGN GOALS DISCUSSION

Our designs and their implementations need to be suitable for constrained devices, see R-I in Section IV. We address this by using the language C for our implementations and following the best practices for developing firmware for microcontrollers. In particular, we are not using dynamic memory allocation. All variables that we use are placed on the stack. The low memory requirements and low computational times of our implementation are demonstrated later in Section VIII.

Our designs need to ensure that the implementations can be transported to a variety of application environments, see R-II in Section IV. Our usage models allow the independence of the embedded OS and the employed CoAP library. In order to be independent on the OS, our designs do not rely on any OS-specific functionalities. In the case of OSCORE in order to be independent of the CoAP library, we integrated the minimal required subset of CoAP message encoding and decoding functionalities (see Section V-A2) within our designs. In the case of EDHOC, we achieve independence of the CoAP library by using callback functions for to send and receive messages. We use the same strategy to achieve independence of the crypto implementation in all presented designs.

In order to minimize the chance of software attacks on the protocols (see R-III in Section IV) we put all keys and the bare minimum code, consisting only of the crypto routines and minimal key handling, in a TEE domain. Additionally, µOSCORE-TEE and µEDHOC-TEE have a narrow interface between the TEE domain and the non-TEE domain. In the case of µOSCORE-TEE, it only consists of two functions and in the case of µEDHOC-TEE, eight. The parameters of all interface functions have primitive types. This allows us to avoid the need for complex parsers in the TEE domain, which are often prone to exploitable vulnerabilities.

VIII. EVALUATION

In this section we evaluate our implementations in terms of FLASH/RAM requirements, computational time and energy requirements. For the evaluation of the protocols regarding their energy requirements we selected a communication stack using IPv6 over BLE as a representative low power IoT communication stack.

A. Scope of the Evaluation

In the following, we describe the scenarios in which we evaluate OSCORE and EDHOC.

1) OSCORE: Instead of trying to evaluate many scenarios with different payloads and combinations of protected and unprotected options, we decided to evaluate one representative scenario. This scenario comprises an OSCORE server, which handles a complete message roundtrip – the server receives an OSCORE request, converts it to CoAP, creates a new CoAP response packet, converts it to an OSCORE packet, and sends it. In our tests, we used small payloads typical for IoT applications. The OSCORE request and the response messages are both 35 byte. The corresponding CoAP messages are 24 byte.

2) EDHOC: EDHOC can use one of 16 combinations of initiator and responder authentication methods, see Figure 2. Our implementations are capable of handling all possible variants correctly. However, in this paper we present an evaluation of the modes in which both parties authenticate the same way: signatures with RPK, signatures with certificate, static DH keys with RPK and static DH keys with certificates, i.e., the modes on the diagonal in Figure 2. The RAM/FLASH, computational time and energy cost for the other modes can be estimated for the presented results. For example, if the initiator authenticates with a static DH key with RPK and the responder authenticates with a signature key with certificate the costs for this method will be higher than when both authenticate with DH key with RPK but lower than if both authenticate with signature key with certificate.

In addition, in order to demonstrate the best possible EDHOC performance, we use native CBOR certificates as proposed in a current IETF draft [39]. CBOR certificates are certificates in which the certificate information is CBOR encoded, thus these certificates can be parsed easily on constrained devices and are shorter in size. All CBOR certificates used in our evaluation are 135 byte long. A summary of the EDHOC message sizes for the different authentication modes is given in Table I.

| Authentication mode         | Msg 1 | Msg 2 | Msg 3 |
|-----------------------------|-------|-------|-------|
| Static DH keys / RPK        | 37    | 46    | 20    |
| Signature keys / RPK        | 37    | 117   | 91    |
| Static DH keys / Certificate| 37    | 186   | 160   |
| Signature keys / Certificate| 37    | 243   | 217   |

Table I: EDHOC message sizes in bytes

B. Evaluation Setups

The RAM, FLASH and computational time evaluations of µOSCORE and µEDHOC were conducted offline in a unit test environment where no messages were sent. Those evaluations were performed on four widely used microcontroller architectures: Cortex M0, M4, M33 and Xtensa. This set of
architectures covers a broad range of low-end CPU performance classes with CPU frequencies ranging from 16 MHz to 160 MHz.

To evaluate the energy requirements of the protocols, we set up an IPv6 over BLE network consisting of an nRF52832 BLE SoC, a Raspberry Pi acting as a border router and a Linux workstation. We used BLE version 4.1 which allows 20 byte of application payload data to be sent in a single link layer packet. Data can be sent and received only during connection events in which it is possible to exchange several link layer packets per event. In our setting, the connection event interval was set to 50 ms and the TX power was set to 0 dBm. In the case of OSCORE on the nRF52832 SoC, we run an OSCORE server, and on the Linux workstation we run a OSCORE client. In the case of EDHOC, the energy requirements of the initiator and the responder were evaluated on the nRF52832 SoC in a series of experiments for the different authentication modes.

We evaluated µOSCORE-TEE an µEDHOC-TEE on the nRF9160 SoC from Nordic Semiconductors featuring a Cortex M33 CPU and a TrustZone-M extension. The nRF9160 SoC can be configured in two different ways: 1) the TrustZone is used, which means that all memories and peripherals are split in a secure and a non-secure world and 2) the TrustZone is not used, which means that the SoC behaves as regular microcontroller. We compare µOSCORE and µEDHOC with µOSCORE-TEE and µEDHOC-TEE respectively by leveraging these two configuration modes.

For our OSCORE evaluation, we used the default algorithms AES-CCM-16-64-128 and HMAC-SHA256 as AEAD and HKDF algorithm respectively. For our EDHOC evaluation, in addition to these algorithms we used c25519 and ed25519 as DH and signature algorithms respectively. We refer users interested in doing so to the detailed evaluations of, e.g., wolfcrypt [1] and mbedTLS [47] and µNaCl [21].

For all experiments, we used a GCC compiler and set the optimization to -Os (optimized size).

For the RAM evaluation, we measured the stack usage by filling the stack with a known pattern (0xaa) at boot time and checking how much of the pattern was overwritten just before and after the protocols were executed.

For all setups, we used the embedded OS Zephyr OS [14] on the microcontrollers with the Zephyr’s CoAP library [15]. On the Linux workstation, we used the CoAP library cantcoap [3].

### C. OSCORE Evaluation

In the following, we present the µOSCORE and µOSCORE-TEE evaluation results.

1) µOSCORE FLASH, RAM, Computing Time and Energy Requirements: The µOSCORE FLASH and RAM requirements for the four different Cortex M0, M4, M33 and Xtensa architectures are shown in Figure 5 and Figure 6 respectively. The FLASH requirements are split between requirements for the OSCORE logic and requirements for the cryptographic operations. µOSCORE requires in total ≈ 10 KB FLASH and ≈ 1.8 KB RAM. Approximately 6.3-7.0 KB FLASH are required for the OSCORE logic and 3.5 KB for the crypto library. The FLASH requirements for the crypto library are very small since OSCORE requires only AES-CCM and HMAC functions. The FLASH requirements for the crypto library can even be completely eliminated if a hardware crypto accelerator is used, thus the FLASH size can be reduced to ≈ 6.3-7.0 KB. Furthermore, the figures show that the differences due to the different CPU instruction sets are very small. In summary, the

![Figure 5: µOSCORE FLASH requirements](image-url)

![Figure 6: µOSCORE RAM requirements](image-url)

µOSCORE FLASH and RAM requirements are very small, thus µOSCORE is very well suited for constrained microcontrollers.

The µOSCORE computing time measurements are given in Figure 7. Figure 7 shows that the most time-consuming function is the oscore_init() function. However, this function needs to be executed only once in order to set up the sender and recipient contexts. During the regular OSCORE operation, only the functions coap2oscore() and oscore2coap() are used. Figure 7 shows also that, depending on the CPU architecture and clock frequency, the conversion functions convert a 35 byte OSCORE packet to CoAP and vice versa in between 500 µs and few milliseconds, which shows that
µOSCORE is suitable for constrained microcontrollers also regarding computing time.

We measured the power consumption of µOSCORE running an nRF52832 BLE SoC in an IPv6 over BLE network while conducting two experiments. In the first experiment, we received and sent unprotected CoAP packets 24 byte in length. The power consumption of the device in this case is given in Figure 8.(a). In the second experiment, the nRF52832 SoC received a 35 byte OSCORE request then the request was converted to CoAP. Afterwards, a response CoAP packet was constructed and converted to OSCORE, then sent back to the client, see Figure 8.(b). In Figure 8 we see spikes in the power consumption of the SoC every 50 ms. This is due to the BLE connection events during which the radio is active and sends and receives data. By integrating the measurements in Figure 8 over the time we calculated that the CoAP roundtrip requires 352.97 µJ and the equivalent OSCORE protected roundtrip requires 352.00 µJ. The µOSCORE overhead is therefore only 3.87%, which means that µOSCORE is well suited for battery-powered devices. This means also that the OSCORE energy costs are mainly (96.13%) due to the radio transmission.

2) µOSCORE-TEE FLASH, RAM and Computing Time: Figure 9 shows the FLASH sizes of the split between the secure and the non-secure world µOSCORE-TEE implementation on an nrf9160 SoC. Additionally the FLASH size of the µOSCORE when the TrustZone is not used is given for comparison. The code in the secure world is reduced to 3,962 byte where the crypto library is 3,238 byte and the OSCORE logic is 724 byte. On the other hand the non-secure world contains only OSCORE logic code. In total µOSCORE-TEE requires 9,921 byte on a Cortex M33 CPU which is 3.13% more than µOSCORE which requires 9,611 byte.

Figure 10 shows the RAM requirements for the secure and non-secure world stacks, as well as the sum of both, and the stack requirements of µOSCORE. In total, the secure and non-secure stack require 2,376 byte which is 33.18% more than µOSCORE, which requires 1,784 byte. This is because the secure world and the non-secure world have separated stacks, so memory cannot be reused as efficiently as when the complete implementation runs with a single stack. Although this increase appears extreme, the amount of RAM required by µOSCORE-TEE is very low in the context of the total 256 KB RAM available on the nRF9160 SoC.

Figure 11 shows the computing time of the three OSCORE API functions for µOSCORE and µOSCORE-TEE. The computing time overhead µOSCORE-TEE is very low – 3 to 5% depending on the API function.

We provide no measurements of the energy consumption for µOSCORE-TEE since we have shown that the OSCORE energy costs are caused mainly by the radio transmissions (see energy evaluation for µOSCORE), which depend only on the protocol stack and not on the OSCORE library.

In summary, µOSCORE-TEE is well suited for constrained devices as well, since it has very small overheads in terms of FLASH and computing time when compared to µOSCORE. On the other hand, µOSCORE-TEE has significantly higher RAM requirements, which, however, is still unproblematic for modern IoT SoCs such as nRF9160.

D. EDHOC Evaluation

In the following, we present the µEDHOC and µEDHOC-TEE evaluation results.
1) µEDHOC FLASH, RAM, Computing Time and Energy Requirements

The µEDHOC FLASH requirements are summarized in Figure 12. In total, µEDHOC requires between 17 KB and 20 KB depending on different CPU architectures, i.e., instruction sets. Approximately half of the FLASH is required for the protocol logic and the other half for the crypto library. The RAM requirements of µEDHOC are summarized in Figure 13. Depending on the authentication mode, µEDHOC requires between 2.4 KB and 4.5 KB RAM. The differences caused by the different CPU architectures are negligible. Initiator and Responder have also negligible differences. The differences in the different modes are due to the usage of memory buffers for the intermediary operations, which are bigger in the certificate modes and smaller in the RPK modes. In summary, the FLASH and RAM requirements of µEDHOC are reasonable for constrained microcontrollers.

The µEDHOC computing time on the four different platforms is shown in Figure 14 (notice the logarithmic scale of the x axis). The left part of the figure shows the computing times of the initiator and right part those of the responder. In Figure 14, we see that the computing times of initiator and responder are roughly equal. The total computing time is mainly defined by the crypto operations that require several thousand times more time than the protocol logic itself.

Authentication with static DH keys with RPK is 45-50% faster than authentication with asymmetric signatures with RPK. Authentication with static DH keys with certificates is 25-30% faster than authentication with asymmetric signatures with certificates. The usage of static DH key authentication with certificates causes 75-80% overhead compared to static DH key authentication with RPK. The usage of asymmetric key authentication with certificates causes 50-55% overhead compared to asymmetric key authentication with RPKs. In Figure 14, we can also see that on weaker devices such as nRF51422 (Cortex M0 running at 16 MHz) the asymmetric authentication modes may be prohibitive for some applications since they require between ≈17 and ≈39 seconds. For devices that are more powerful, such as ESP32, nRF52832 and nRF9160, the computing times are lower and therefore acceptable for wider range of IoT applications.

The µEDHOC energy costs for the initiator and responder in an IPv6 over BLE network are summarized in Figure 15. The energy costs are split into energy required for the calculation and total energy required for the complete protocol run, including the sending and receiving of messages. In Figure 15, we see that the main part of the energy required is spent on the calculations.

In order to estimate whether these numbers are prohibitive for some battery power application, we considered an example in which we assumed that an IoT device is powered by a typical CR-2032 coin cell battery with a capacity of 2,322 J [4]. The energy capacity of 2,322 J allows ≈28,000 to ≈67,000 protocol runs, depending on the authentication mode, therefore µEDHOC is well suited for the majority of battery-powered IoT devices.

E. µEDHOC-TEE FLASH, RAM and Computing Time

µEDHOC-TEE FLASH requirements for the secure and non-secure worlds are given in Figure 16. In Figure 16, we see that µEDHOC-TEE requires in total 7.17% more FLASH than µEDHOC. The percentual increase between the TrustZone and
the non-TrustZone implementations of 7.17% is higher as the equivalent percentual increase of 3.13% for OSCORE. This is because µEDHOC-TEE contains additional code in the TEE domain for handling the more complex security contexts.

We measured the RAM and computational time requirements of µEDHOC-TEE in the different authentication modes. The RAM overhead of µEDHOC-TEE is 30-40% and the computational time overhead is 1-2% when compared to µEDHOC.

We provide no detailed energy measurements of µEDHOC-TEE because we have shown on the one hand side that the energy costs of µEDHOC are caused mainly by the calculations, see Figure [15]. On the other hand side the computational overhead of µEDHOC-TEE compared to µEDHOC is only 1-2%. Therefore, the µEDHOC-TEE energy costs can easily be estimated by adding 1-2% to the results in Figure [15].

In summary, µEDHOC-TEE is well suitable for constrained devices as well, because of its low FLASH, RAM, computing time and energy requirements.

F. Combined OSCORE and EDHOC Usage

In this section, we discuss the case when EDHOC and OSCORE are used in succession. All consideration in the following apply for both combinations µOSCORE/µEDHOC and µOSCORE-TREE/µEDHOC-TREE. However, we provide details only for the combination µOSCORE/µEDHOC for the sake of clear presentation in this paper.

The combined µOSCORE and µEDHOC FLASH requirements are given in Figure [17]. The total FLASH requirements are the sum of the FLASH requirements for the protocols’ logics and the crypto library. When µOSCORE and µEDHOC are used with cipher suites relying on the same AEAD and HKDF algorithms, e.g., both use AES-CCM-16-64-128 and HMAC-SHA256 the combined FLASH requirements for the crypto library are equal to the µEDHOC FLASH requirements for the crypto library. Figure [17] shows that when µOSCORE and µEDHOC are used together they require in total ≈25 KB FLASH, which is reasonable for constrained microcontrollers.

When µOSCORE and µEDHOC are used together, the total RAM requirements are determined by µEDHOC. This is due to the fact that we use only stack memory, which, once µEDHOC finishes its operations is reused by µOSCORE.

When the protocols are used in succession, the total computing time and energy requirements can be calculated as the sum of the individual protocols.

IX. RELATED WORK

In this section, we give an overview of the related work in the area of OSCORE and EDHOC evaluation and point out the differences to our paper.

OSCORE, DTLS and NDN protocol evaluation in single and multi-hop scenarios are presented in [25]. In this paper,
the authors use the OSCORE implementation libOSCORE \[5\]. The main difference between libOSCORE and µOSCORE is that libOSCORE depends significantly on the CoAP library \[6\]. In contrast, our implementation contains the minimal required subset of CoAP parsing/encoding functionalities. Additionally, it uses callbacks for the crypto operations. This makes our implementation completely independent of the CoAP library, OS or crypto implementation (library or hardware accelerator). Moreover, \[25\] concentrates mostly on the effects of packets lost in single and multi-hop scenarios, and does not present evaluation in terms of FLASH/RAM requirements, computing time and energy. Also \[25\] does not consider the usage of a TEE for separating the security critical operations from the non-critical OSCORE parsing and data encodings.

In \[36\], an implementation and evaluation of EDHOC version 8 and an optimized variant of it relying on out-of-band parameter negotiation are presented. Both variants are evaluated only with Pre-Shared Keys (PSKs) and asymmetric signatures with RPK authentication. Note that the EDHOC PSK mode was removed from the later protocol drafts. The runtime and success rates of both EDHOC variants are evaluated through simulation, considering packet losses in single and multi-hop environments. Also, the message size of both variants are compared with the Datagram Transport Layer Security (DTLS) 1.3 handshake. In \[40\], the usage of EDHOC with PSK message authentication for updating session keys in LoRa networks is analyzed. The analysis concentrates on the message size overhead compared to DTLS and time-on-air. \[37\] presents an approach in which the EDHOC’s PSKs or RPKs are derived by an LO-CoAP-EAP bootstrapping process. In addition, an EDHOC evaluation regarding message sizes and transmission times is presented. The paper considers only PSK authentication and asymmetric signature authentication with RPKs. A detailed message size comparison between DTLS 1.2, DTLS 1.3, Transport Layer Security (TLS) 1.2, TLS 1.3, EDHOC and OSCORE is provided by the IETF in \[32\]. The previous work \[36, 40, 37\] in the area of EDHOC implementations lacks evaluation results of the more recently proposed authentication with static DH keys. The usage of certificates is also not evaluated. Moreover, previous work lacks detailed evaluation regarding the FLASH/RAM requirements, computation times and energy consumption. In contrast, we implement the latest version of EDHOC, taking into account all authentication modes. For those, we provide a message size comparison and an extensive evaluation of the FLASH/RAM requirements, computation times and energy consumption on state-of-the-art Cortex M and Xtensa microcontrollers. In addition, we leverage the TrustZone TEE for executing all cryptographic operations and storing keys. We provide an evaluation of the overhead caused by this separation.

X. CONCLUSION

In this paper we presented the design of µOSCORE and µEDHOC firmware libraries for constrained regular microcontrollers, which are based on the newest state of the OSCORE and EDHOC specifications and consider all modes of operation. Additionally, we presented the design of µOSCORE-TEE and µEDHOC-TEE firmware libraries for microcontrollers featuring a TEE, which provide protection against attackers exploiting software vulnerabilities. This is achieved by separating the cryptographic keys and routines from the rest of the firmware, which may be vulnerable. We evaluated our libraries extensively on several broadly used microcontroller architectures. Our evaluation shows that when µOSCORE and µEDHOC are used together they require a total of \(\approx 25\) KB FLASH and between \(\approx 1.8\) KB and \(\approx 4.2\) KB RAM depending on the EDHOC mode. We also show that a typical CoAP packet can be protected with OSCORE within a few milliseconds.
Our computing time evaluation of the EDHOC protocol shows that authentication with static DH keys is 45-50% faster than authentication with signatures, when RPKs are used. When certificates are used, static DH key authentication is 25-30% faster than authentication with signatures. Our libraries for microcontrollers with a TEE show low overhead in terms of computing time and FLASH requirements. However, the RAM overhead is 30-40%, which is still acceptable for the majority of IoT SoCs.

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