ERASMUS: Efficient Remote Attestation via Self-Measurement for Unattended Settings

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ABSTRACT
Remote attestation (RA) is a popular means of detecting malware in embedded and IoT devices. RA is usually realized as an interactive protocol, whereby a trusted party – verifier – measures integrity of a potentially compromised remote device – prover. Early work focused on purely software-based and fully hardware-based techniques, neither of which is ideal for low-end devices. More recent results have yielded hybrid (SW/HW) security architectures comprised of a minimal set of features to support efficient and secure RA on low-end devices.

All prior RA techniques require on-demand operation, i.e., RA is performed in real time. We identify some drawbacks of this general approach in the context of unattended devices: First, it fails to detect mobile malware that enters and leaves the prover between successive RA instances. Second, it requires the prover to engage in a potentially expensive (in terms of time and energy) computation, which can be harmful for critical or real-time devices.

To address these drawbacks, we introduce the concept of self-measurement where a prover device periodically (and securely) measures and records its own software state, based on a pre-established schedule. A possibly untrusted verifier occasionally collects and verifies these measurements. We present the design of a concrete technique called ERASMUS: Efficient Remote Attestation via Self-Measurement for Unattended Settings, justifying its features and evaluating its performance. In the process, we also define a new metric – Quality of Attestation (QoA). We argue that ERASMUS is well-suited for time-sensitive and/or safety-critical applications that are not served well by on-demand RA. Finally, we show that ERASMUS is a promising stepping stone towards handling attestation of multiple devices (i.e., a group or swarm) with high mobility.

1. INTRODUCTION
In recent years, embedded and cyber-physical systems (CPS), under the guise of Internet-of-Things (IoT), have entered many aspects of daily life, such as: homes, office buildings, public venues, factories and vehicles. This trend of adding computerized components to previously analog devices and then inter-connected them brings many obvious benefits. However, it also greatly expands the so-called “attack surface” and turns these newly computerized gadgets into natural and attractive attack targets. In particular, as recent incidents demonstrated, IoT devices can be infected with malware and used as bot-controlled zombies in Distributed Denial-of-Service (DDoS) attacks. Also, IoT-borne malware can snoop on device owners (by sensing) or maliciously control critical services (by actuation), as happened with Stuxnet.

One key component in securing IoT devices is malware detection, which is typically attained with Remote Attestation (RA). RA is a distinct security service that allows a trusted party, called verifier, to securely verify the internal state (including memory and storage) of a remote untrusted and potentially malware-infected device, called prover. RA is realized via an interactive protocol between prover and verifier. A typical example is described in [5]: (1) verifier sends an attestation request to prover, (2) prover verifies the request, (3) and computes a cryptographic function of its internal state, then (4) sends the result to verifier, and finally, (5) verifier checks the result and decides whether prover is infected.

This general approach is referred to as on-demand attestation and all current RA techniques adhere to it. In this paper, we identify two important limitations of this approach. First, it is a poor match for unattended devices, since malware that “comes and goes” (i.e., mobile malware) can not be detected if it leaves prover by the time attestation is performed. Second, for a device working under time constraints (real-time operation) or otherwise providing critical services, on-demand attestation requires performing a possibly time-consuming task while deviating from the device’s main function(s).

To address these issues, we design ERASMUS: Efficient Remote Attestation via Self-Measurement for Unattended Settings. ERASMUS is based on self-measurements. Basically, a device (prover) measures and records its state at scheduled times. Measurements are stored in prover’s insecure memory. Verifier occasionally collects and validates these measurements in order to establish the history of prover’s state. Notably, with this general approach, verifier imposes only negligible real-time burden on prover. It also offers

Since attestation is a potentially expensive task, this verification mitigates computational DoS attacks.
strictly better quality-of-service than prior attestation techniques, because verifier obtains prover’s entire history of measurements, since the last verifier request. In other words, ERASMUS de-couples (1) frequency of prover checking, from (2) frequency of prover measurements, which are equivalent in on-demand attestation. Finally, ERASMUS simplifies RA design (in terms of required features) for prover: authentication of verifier requests is no longer needed, since computational DoS attacks do not arise.

We also introduce the new notion of Quality of Attestation (QoA) which captures: (1) how a device (prover) is attested, (2) how often its state is measured, and (3) how often these measurements are verified. It is the temporal analogue of the concept of quality of swarm attestation (QoSA) introduced in [6] in the context of attesting groups of devices.

NOTE: ERASMUS is not intended as a replacement for on-demand attestation, mainly because for some devices and some settings, real-time on-demand attestation is mandatory, e.g., immediately before or after a software update or for secure erasure/reset. Also, on-demand attestation may be more flexible, e.g., if the verifier is only interested in measuring a fraction of prover’s memory. These two approaches are not mutually exclusive and may be used together to increase QoA, specifically, in terms of freshness of the latest measurements.

The last incentive for our self-measurement approach is its suitability for highly mobile groups of devices. RA protocols developed for “swarm attestation”, e.g., [2] [18] [11] [6], are designed to efficiently attest groups of interconnected devices on-demand, with a single verifier-prover interaction. However, they do not work in highly mobile swarms, since on-demand attestation requires topology to remain essentially static during the entire attestation protocol instance – the time for which is dominated by computation on all swarm devices. Since ERASMUS involves virtually no real-time computation for prover, it is much more suitable for high-mobility swarm settings.

After overviewing the state-of-the-art in Section 2, we introduce ERASMUS and QoA in Section 3. An implementation and experimental results are discussed in Sect 4. Issues arising in time-sensitive applications and partial mitigation measures are discussed in Section 5. Applicability of ERASMUS to swarm attestation is considered in Section 6.

2. REMOTE ATTESTATION (RA)

RA aims to detect malware presence by verifying integrity of a remote and untrusted embedded (or IoT) device. As mentioned earlier, it is typically realized as a protocol where trusted verifier interacts with a remote prover to obtain an integrity measurement of the latter’s state.

RA techniques fall into the three main categories. (1) Hardware-based attestation [24] [19] uses dedicated hardware features such as a Trusted Platform Module (TPM) to execute attestation code in a secure environment. Even though such features are currently available in personal computers and smartphones, they are considered a relative “luxury” for very low-end embedded devices. (2) Software-based attestation [21] [20] requires no hardware support and performs attestation solely based on precise timing measures. However, it limits prover to being one-hop away from verifier, so that round-trip time is either negligible or fixed. It also relies on strong assumptions about attacker behavior [1] and is typically only used for legacy devices where no other RA techniques are viable. (3) Finally, hybrid attestation [9] [13] [2], based on a software/hardware co-design, provides RA while minimizing its impact on underlying hardware features.

SMART [9] is the first hybrid RA design with minimal hardware modifications to existing microcontroller units (MCUs). It has the following key features:

- Attestation code is immutable: located in and executed from ROM.
- Attestation code is safe: its execution always terminates and leaks no information other than the attestation result (token).
- Attestation is atomic: (1) it is uninterruptible, and (2) it starts from the first instruction and exits at the last instruction. This is realized in SMART by using hard-wired MCU access controls and disabling interrupts upon entering attestation code.
- A secret key (K) is stored in a secure memory location where it can be accessed only from within the attestation code; K is stored in ROM and is guarded by specialized MCU rules.

[5] extended SMART to defend against denial-of-service (DoS) attacks that try to impersonate verifier. We refer to this extended design as SMART+. [9] additionally requires verifier to have a Reliable Read-Only Clock (RROC), which is needed to perform verifier authentication and prevent replay, reorder and delay attacks. To ensure reliability, RROC must not be modifiable by software. Upon receiving a verifier request, ROM-resident attestation code checks the request’s freshness using RROC, authenticates it, and only then proceeds to perform attestation.

The TrustLite [13] security architecture also supports RA for low-end devices. It differs from SMART in two ways: (1) interrupts are allowed and handled securely by the CPU Exception Engine, and (2) access control rules can be programmed using an Execution-Aware Memory Protection Unit (EA-MPU). TyTan [4] adopts a similar approach while providing additional real-time guarantees and dynamic configuration for safety- and security-critical applications.

HYDRA [8] is a hybrid RA design for medium-end devices devices with a Memory Management Unit (MMU). It builds upon a formally verified micro-kernel, seL4 [12], to ensure memory isolation and enforce access control to memory regions. Using these formally and mathematically proven features, access control rules can be implemented in software and enforced by seL4. Consequently, HYDRA stores K and attestation code in writable memory regions (e.g., flash or RAM) and configures the system such that no other process, besides the attestation process, can access those memory regions. Access control configuration in HYDRA also involves the attestation process having exclusive access to its thread control block as well as to memory regions used for K-related computations. The latter ensures the K protection property. To ensure atomic execution, HYDRA runs the attestation process as the initial user-space process with the highest scheduling priority, while the rest of user-land processes are spawned by the attestation process, with lower priorities. Finally, hardware-enforced secure boot is used to provide integrity of seL4 and the attestation process at system initialization time.

In this paper, we use SMART+ and HYDRA as the base security architecture for ERASMUS. However, ERASMUS should be equally applicable to other on-demand RA techniques, such as TrustLite [14] or TyTan [4].

3. SELF-MEASUREMENTS

As discussed in Section 1, all current RA techniques perform on-demand attestation, whereby prover computes verifier-requested measurements in real-time. This can be a time-consuming activity that takes prover away from its primary mission. However, prover performs no RA-related computation between verifier’s requests.

In contrast, ERASMUS divides RA into two phases. In the
measurement phase, prover performs self-measurements based on a pre-established schedule and stores the results. In the collection phase, verifier (whenever it chooses to do so) contacts prover to fetch these measurements. The collection phase is very fast since it requires practically no computation by prover. Furthermore, unlike in on-demand RA, there is no threat of computational DoS when prover sends these measurements to verifier. Furthermore, it requires practically no computation by prover. In particular, fetching these measurements. The collection phase is very fast since a pre-established schedule and stores the results. In the collection phase, SMART or HYDRA.

MAC represents prover’s memory at time $K$ where $H$ is a suitable cryptographic hash function and $mem_i$ represents prover’s memory at time $t$. The computation of $H(mem_i)$ and $MAC$ is done in the context of the security architecture, e.g., SMART or HYDRA.

From here on, $Vvr$ and $Prv$ are used to denote verifier and prover, respectively. Although ERASMUS assumes a symmetric key $K$ shared between $Vvr$ and $Prv$, a public key signature scheme could be used instead, with no real impact on security of the scheme except for higher cost of measurements.

3.1 Quality of Attestation

Quality of Attestation (QoA) is primarily determined by two parameters: (1) time $T_M$ between two successive measurements on $Prv$, and (2) time $T_C$ between two successive requests by $Vvr$ to collect measurements from $Prv$.

We assume that in most cases $T_C > T_M$. If it so happens that $T_C < T_M$, verifier will simply collect the same measurements more than once, which is redundant. Instead, $Vvr$ can explicitly request $Prv$ to perform a measurement before the collection. In that case, $Vvr$’s request would have to be authenticated and checked for freshness (as in SMART+ [5]) before the on-demand measurement is computed. These activities clearly incur additional real-time overhead and delays. We refer to this variant as ERASMUS+OD.

Exactly how $T_C$ and $T_M$ are determined clearly depends on specifics of $Prv$’s mission and its deployment setting. Security impact of these parameters is intuitive. Smaller $T_M$ implies smaller window of opportunity for mobile malware to escape detection. Smaller $T_C$ implies faster malware detection. If either value is large, attestation becomes ineffective. Meanwhile, though low values increase QoA, they also increase $Prv$’s overall burden, in terms of computation, power consumption and communication.

Without loss of generality, we assume that measurements and collections occur at regular intervals. Of course, in practice this might not work in scenarios that involve critical or time-sensitive applications (see Section 3.2). In fact, it might be advantageous to take measurements at irregular intervals, as doing so might give prover a bit of an extra edge against mobile malware (see Section 3.3).

Another ERASMUS parameter is the number of measurements (referred to as $k$) obtained by $Vvr$ in each collection phase. It can range between one (only the most recent measurement) and all. In a typical setting, $Prv$’s history size should be set such that each measurement is collected exactly once. That is, $k = \lceil T_C/T_M \rceil$.

Finally, the collection phase involves the notion of freshness, i.e., how recent is $Prv$’s latest measurement. Depending on the application, maximal freshness might be required, e.g., right before or after a software update. Maximal freshness is attainable via on-demand attestation In ERASMUS, freshness of a measurement (denoted as $f$) ranges between $T_M$ and 0, which correspond to minimal and maximal freshness, respectively. On average, we expect $f = T_M/2$.

Figure 1 shows an example with two malware infections. In the first, malware covers its tracks and leaves before any measurement takes place. In the second, malware persists on $Prv$. Although measurement occurs perhaps soon after infection, corrective action can be taken only after collection, thus illustrating the importance of a small $T_C$. Measurements and collections are shown as punctual events in Figure 1. Although they do take some time to complete (measurements, in particular), it is considered negligible even for low-end devices (see Section 4).

3.2 Measurements Storage & Collection

A na"ive way for $Prv$ to store measurements is to keep track of them indefinitely. However, this will eventually consume a lot of $Prv$’s storage. To this end, ERASMUS uses rolling measurements. A fixed section of $Prv$’s insecure storage is allocated as a windowed (circular) buffer for $n$ measurements. The $i$-th measurement is stored at location $Li \mod n$. However, it is expected that $Vvr$ collects measurements sufficiently often, such that no measurement is over-written. That is, the time between successive collections should be at most $T_C \leq n \cdot T_M$.

The interaction between $Prv$ and $Vvr$ is very simple: $Vvr$ asks for $k$ latest measurements, which $Prv$ simply reads from the buffer and transmits. The collection phase does not involve any change of state on $Prv$ and sent measurements are not encrypted. (Though recall that they are authenticated, since each measurement is computed using $K$). It also does not trigger any significant computation on $Prv$, i.e., in contrast with on-demand attestation, no cryptographic operations are required in the collection phase. However, this is not the case in the ERASMUS+OD variant mentioned in Section 3.1 where (1) $Vvr$’s request must be authenticated and checked for freshness, and (2) a current measurement must be computed.

Self-measurements can be stored in $Prv$’s unprotected storage. This allows malware (that is possibly present on $Prv$) to tamper with measurements, by modifying, re-ordering and/or Deleting them. However, since malware (by design of SMART) cannot access $K$, it cannot forge measurements. Thus, it is easy to see that any tampering will be detected by $Vvr$ at the next collection phase and malware presence would be immediately be noticed. For the same reasons, code that handles request parsing as well as storage and transmission of measurements does not need to be executed in a secure environment or stored in ROM. Code that performs self-measurement, however, must be protected by the underlying security architecture, as in on-demand attestation.

Scheduling in ERASMUS can be implemented in a very simple and stateless manner. Let $t$ be the value of RROC at the time of measurement $Mt$, and let $T_M$ be the time between two successive measurements, as configured in $Prv$. The windowed buffer slot $Li$, used to store $Mt$, is determined by: $i = \lfloor t/T_M \rfloor \mod n$.

ERASMUS collection protocol is shown in Figure 2. No operation involves the underlying architecture during collection; only during measurements. Notation $Li$ refers to contents of location $Li$. A sample memory layout is shown in Figure 3.

3.3 ERASMUS+OD: ERASMUS with On-demand Attestation

As mentioned in Section 3.1, ERASMUS may be combined
with on-demand attestation to benefit from advantages of both approaches. This variant, ERASMUS+OD, records Prv's state history to detect mobile malware, and uses on-demand attestation to obtain better freshness. Freshness is particularly relevant whenever real-time attestation is mandatory, e.g., immediately before or after a software update.

The measurement phase is not modified, while the collection phase is combined with on-demand attestation request as follows. First, as part of each attestation request Vrf now computes and includes an authentication token and specifies k. As in SMART+ [5], authentication of Vrf protects Prv against computational DoS. Then, only after checking that a request is valid, Prv computes a measurement. Finally, this real-time measurement is sent to Vrf, along with k previous measurements. This protocol is shown in Figure 4.

This anti-DoS protection incurs an additional cost for Prv which may interfere with its normal function. A major advantage of ERASMUS over ERASMUS+OD and regular on-demand attestation is that no such protection is required.

3.4 Security Considerations

Security of the measurement process itself is based on the underlying security architecture, e.g., SMART+ or HYDRA, which: (1) provides measurements code with exclusive access to K, (2) ensures non-malleability and non-interruptibility of the measurement code, and (3) performs memory-cleanup after execution. The timestamps used in the measurement process must be based on the RROC which (by definition) can not be modified by non-physical means. This is important since malware should not influence when measurements are taken.

If RROC value could be modified, the following attack scenario would become possible: malware enters at time t₀ and remains active long enough so that a measurement at time t₀ + δ (with δ < TM) is taken. Before leaving, malware discards that measurement and resets the counter to time elapsed since t₀. Though this example works for one TM window, it can be extended to arbitrarily many. It requires an additional assumption that no collection took place during the presence of malware.

Fortunately, RROC is already a requirement of the underlying SMART+ security architecture, for a totally different reason. In SMART+, RROC helps prevent replay and computational DoS attacks on Prv. Thus, ERASMUS does not require any changes.
to the underlying security architecture.

As mentioned earlier, measurements need not be stored in protected memory because tampering with them is detectable and indicates malware presence on $\Pr_v$. Likewise, the code to support the collection phase does not require any protection since measurements are not secret (they are unique for every device and every timestamp value), and their absence or alteration is self-incriminating.

3.5 Irregular Intervals

A natural extension to ERASMUS is to use irregular measurements intervals instead of a fixed $T_M$. The motivation is that mobile malware that is aware of fixed scheduling knows when to enter/leave the device in order to stay undetected.

One way to implement irregular intervals is to use a Cryptographically Secure Pseudo Random Number Generator (CSPRNG) initialized (seeded) with the secret key $K$. Output of the CSPRNG can be truncated such that

$$T_{M_{\text{next}}} = \text{map}(\text{CSPRNG}_K(t_i)),$$

where map is a function that maps CSPRNG output to seconds, e.g. map : $x \rightarrow x \mod (U - L) + L$, with $U$ and $L$ upper and lower bounds, respectively.

The timer itself must be read-protected to ensure that $T_{M_{\text{next}}}$ is unknown to malware potentially present on $\Pr_v$. CSPRNG code must be protected in the same way as the measurement collection.

4. IMPLEMENTATION

We implemented ERASMUS on two security architectures: SMART+ and HYDRA. The main difference between them is that the former targets low-end devices, and the latter – medium-end devices with a memory management unit (MMU).

4.1 Implementation on SMART+

Figure 5 shows the implementation of ERASMUS atop the SMART+ architecture. As in SMART+, measurement code and $K$ reside in ROM. However, the code is invoked periodically and autonomously, whenever a scheduled timer interrupt occurs. We now examine ROM size, hardware costs and run-time on SMART+ architecture.

### Table 1: Size of Attestation Executable

| MAC Impl.      | SMART+ | HYDRA |
|----------------|--------|-------|
| HMAC-SHA1      | 4.9KB  | 4.7KB |
| HMAC-SHA256    | 5.1KB  | 4.9KB | 231.9KB | 233.84KB |
| Keyed BLAKE2S  | 28.9KB | 28.7KB | 239.29KB | 241.17KB |

### Figure 6: Measurement Run-Time on MSP430-based Device @ 8MHz

ROM Size greatly depends on the choice of MAC algorithms. We implemented ROM-resident code in "C" using three MAC functions: HMAC-SHA1 [7], HMAC-SHA256 [22] and key BLAKE2S [17]. We then use open-source MSP430-gcc compiler [25] to compile the "C" code into an MSP430 executable. Table 1 shows the ROM size for each SMART+-based approach. As expected, ERASMUS requires slightly less ROM than on-demand attestation.

**Hardware Cost:** We implement the hardware part of ERASMUS by modifying the MSP430 architecture, using open-source OpenMSP430 core [10]. We modify the memory backbone module in the OpenMSP430 core to support atomic execution of ROM code and exclusive access to $K$. RROC is realized as a peripheral using a 64-bit register incremented for every clock cycle. To ensure write-protection, a write-enable wire is removed in the RROC module. For timer components, we use the unmodified version of omsp_timerA module provided by OpenMSP430. Note that hardware timers are not considered to represent additional hardware cost. This is because they are common and crucial components of embedded systems. Indeed, it is unusual to find an embedded device not equipped with at least one timer. Finally, we use Xilinx ISE 14.7 [27] to synthesize our modifications to the MSP430 core from a hardware description language to a combination of registers and look-up tables that serve as building blocks in FPGA.

As expected, our synthesized results show that ERASMUS utilizes the same amount of registers and look-up tables as the on-demand attestation. Compared to the unmodified MSP430 core, ERASMUS requires roughly 13% (655 vs. 579) and 14% (1,969 vs. 1,731) additional registers and look-up tables respectively.

**Measurement Run-Time:** Figure 6 illustrates run-time of the measurement phase for various memory sizes. Not surprisingly, it is linearly dependent on memory size and roughly equivalent to that of on-demand attestation.

4.2 Implementation on HYDRA

Figure 7 illustrates implementations of HYDRA-based ERASMUS and on-demand attestation. We implement these two techniques on an I.MX6 Sabre Lite [3] development board. RROC is implemented based on the software clock approach, suggested by Brasser et al. [5]. Specifically, we use a short-term counter from Sabre Lite’s General Purpose Timer (GPT) and our clock code in $Pr_{Att}$ to construct RROC. When the counter wraps around and causes an interrupt, our clock code handles it by updating higher-order bits of the clock in $Pr_{Att}$. Then, the clock value is constructed by combining these bits with the GPT counter. To ensure read-only property, $Pr_{Att}$ is given exclusive write-access to RROC components. Also, we utilize Sabre Lite’s Enhanced Periodic Interrupt Timer (EPIT) to schedule execution of ERASMUS measurement code.

We base the code of $Pr_{Att}$ on open-source seL4 libraries [13].

\(^3\)Note that HMAC-SHA1 is used for comparison purposes only. We exclude it in our actual implementations due to a recent collision attack in SHA1 [23].
Secure Boot

Attestation Process

| RAM/Flash | AuthRequest & Compute M | M | MN |
|-----------|-------------------------|---|----|
| ROM       | Secure Boot             | K | M1 |
| I/O       | Timer                   | Timer | Clock |

(a) On-Demand  
(b) ERASMUS

Figure 7: Memory organization of HYDRA-based on-demand attestation and ERASMUS

Table 2: Run-Time (in ms) of Collection Phase on I.MX6-Sabre Lite

| Operations                  | ERASMUS | ERASMUS+OD |
|-----------------------------|---------|------------|
| Verify Request              | N/A     | 0.005      |
| Compute Measurement         | N/A     | 285.6      |
| Construct UDP Packet       | 0.003   | 0.003      |
| Send UDP Packet             | 0.012   | 0.012      |
| Total Collection Run-time   | 0.015   | 285.6      |

Figure 8: Measurement Run-Time on I.MX6 Sabre Lite @ 1GHz

On 10MB memory using keyed BLAKE2S as the underlying MAC function.

5. AVAILABILITY IN TIME-SENSITIVE APPLICATIONS

In some cases, it might be undesirable to interrupt execution of the Prv's application process in order to obtain a measurement. This is particularly the case for time-sensitive or safety-critical applications. As discussed in Section 4, measurements can take non-negligible time, e.g., 7 seconds on an 8-MHz device with 10KB RAM. Making Prv unavailable for that long is not appropriate.

As is, pure on-demand attestation is poorly suited for such applications. At the same time, if Prv follows a strict schedule, ERASMUS is also not a remedy since it suffers from the same issue. However, it can be made more flexible.

One partial measure is for Prv to be self-aware of when time-sensitive tasks occur. That way, it can schedule measurements at appropriate times. If this knowledge is also available to Vrf, on-demand attestation could be used if Vrf adapts to Prv's schedule.

Another approach is to allow Prv to abort the measurement in progress, if the need arises. However, this has some caveats: First, the security architecture needs to be adapted to allow interrupts during measurements. Protection of keys (and cleanup in case of an interrupt) is still required; thus, there is still a need for some hardware support. Second, it would be trivial for malware to abort computation of measurements in order to avoid detection, or simply pretend, when queried by Vrf, that all attempted measurements have been aborted. Therefore, Vrf must use some external information or policy to decide whether there is a valid justification for each aborted measurement.

To handle such situations, we consider another ERASMUS variant that involves lenient scheduling. Instead of performing a measurement every TM, Prv has a window of w × TM where w ≥ 1. Under normal conditions, Prv behaves as usual, using the TM window. If something causes a measurement to be aborted, it can be rescheduled to the end of the current window.

These are certainly not ideal measures, the underlying problem seems quite difficult to address deterministically. As is typical for security/usability compromises, real deployment would likely involve policy-based decisions.

6. SWARM ATTESTATION

Some applications require attesting a group (or swarm) of interconnected embedded devices. In such a setting, it is beneficial to take advantage of interconnectivity and perform collective attestation using a dedicated protocol. Several swarm attestation techniques have been proposed. SEDA [2] is the first such scheme, which relies on hybrid attestation security architectures: SMART [9] and TrustLite [13]. SEDA combines them with a request-flooding and response-gathering protocol. SEDA was improved and further specified in LISA [6]. Other related techniques deal with report aggregation [18] or physical attacks [11].

A concept of Quality of Swarm Attestation (QoS) was introduced in [6] to capture the level of information that Vrf obtains as a result of swarm attestation. This can range from binary (“is the whole swarm healthy?”) to full (state of each individual device and topology information). QoA, as introduced in this paper, is an orthogonal measure that captures the state of a given device in time. QoA and QoS can be used in concert with one another.

ERASMUS could be used instead of on-demand attestation in the context of swarm RA protocols. In particular, Prv self-measurements can be coupled with a collection protocol, such as LISA-α, where the latter only relays reports and does not perform any computation. This would yield a clean and conceptually simple approach to swarm attestation, with all the benefits of ERASMUS.

An additional advantage of using ERASMUS in the swarm setting is support for high mobility. Prior swarm RA techniques, such as SEDA, SANA and LISA require swarm topology to remain almost static during the whole swarm attestation instance. This process may be long and prohibitive for applications where connectivity changes often. ERASMUS does not require external input and its collection phase is very fast, since it does not involve any computation; only reading and sending stored measurements.
This makes ERASMUS a very natural and viable technique for highly-mobile swarms.

Finally, related to the discussion in Section 4, we consider the scenario where availability of at least one in (or a part of) a group of devices is required at all times. This cannot be guaranteed by on-demand swarm attestation, whereas a large part of the network may be concurrently busy. Meanwhile, with ERASMUS, it is trivial to establish a schedule which ensures that only a fraction of the swarm computes measurements at any given time.

7. CONCLUSION

We designed ERASMUS as an alternative to current methods that perform on-demand RA for low-end devices. ERASMUS provides better QoA in that it allows for malware to detect mobile malware, which is not possible with on-demand techniques that only detect malware if it is currently on $P_{rv}$. ERASMUS makes it harder for malware to avoid detection. ERASMUS’s other major advantage is that it requires no cryptographic computation by $P_{rv}$ as part of its interaction with $V_{rf}$. This is particularly relevant in time-sensitive and critical applications, where $P_{rv}$’s availability is very important. We discuss partial mitigation measures for this problem.

We present the new notion of Quality-of-Attestation (QoA) as a measure of temporal security guarantees given by an attestation technique. We show that timing of measurements and timing of verifications (that are conjoined in on-demand attestation) are two distinct aspects of QoA. They are treated as distinct parameters in ERASMUS. We also discuss that the possibility of using on-demand attestation as part of ERASMUS collection phase to obtain maximal freshness.

We implemented ERASMUS on two hybrid RA architectures, SMART+ and HYDRA, and demonstrated its viability on both. ERASMUS does not require extra features or a larger ROM than what is needed in SMART+, and each measurement is faster than on-demand attestation since no authentication of $V_{rf}$ requests is needed. Finally, we show that ERASMUS is a promising option for highly-mobile groups/swarms of devices, for which no current RA technique works well.

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