Scalable Attestation Resilient to Physical Attacks for Embedded Devices in Mesh Networks

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ABSTRACT
Interconnected embedded devices are increasingly used in various scenarios, including industrial control, building automation, or emergency communication. As these systems commonly process sensitive information or perform safety critical tasks, they become appealing targets for cyber attacks. A promising technique to remotely verify the safe and secure operation of networked embedded devices is remote attestation. However, existing attestation protocols only protect against software attacks or show very limited scalability. In this paper, we present the first scalable attestation protocol for interconnected embedded devices that is resilient to physical attacks. Based on the assumption that physical attacks require an adversary to capture and disable devices for some time, our protocol identifies devices with compromised hardware and software. Compared to existing solutions, our protocol reduces communication complexity and runtime by orders of magnitude, precisely identifies compromised devices, supports highly dynamic and partitioned network topologies, and is robust against failures. We show the security of our protocol and evaluate it in static as well as dynamic network topologies. Our results demonstrate that our protocol is highly efficient in well-connected networks and robust to network disruptions.

1. INTRODUCTION
Nowadays, networked embedded devices are increasingly present in every aspect of our lives. This paradigm, often referred to as the Internet of Things (IoT), is expected to constantly evolve in scale and complexity, reaching 20.8 billion devices by 2020 [2]. Technologies like Bluetooth Smart, IEEE 802.15.4, Wi-Fi Direct, ZigBee, or Z-Wave enable embedded devices to form large wireless mobile ad hoc networks (MANETs). In MANETs, all devices cooperate in the distribution of data in the network, thus establishing a decentralized and self-organized network topology. Interconnected embedded devices are frequently used in industrial control, building automation, military communication, or sensor networks. As such systems often process privacy-sensitive information or perform safety-critical tasks, their malfunction or misuse can cause serious damage. Unfortunately, software for embedded systems is typically written in unsafe programming languages and often reluctantly maintained. Additionally, even though an adversary requires significant resources to physically tamper with a device [8], (secure) hardware on embedded systems is usually not hardened against physical tampering; thus, interconnected embedded devices are appealing targets for cyber attacks [27][30][34].

To detect and mitigate such attacks, it is important to monitor the correct operation of embedded devices and detect any malfunctioning or misuse as early as possible. For this purpose, attestation protocols have been introduced, which allow a third party, the verifier, to check the integrity of a remote device, the prover. Since traditional single device attestation protocols are impractical in large mesh networks due to their overhead of attesting each device individually, scalable attestation protocols have recently been proposed [5][7]. These protocols perform an efficient attestation of large networks by distributing the attestation burden across all devices in the network. All scalable attestation protocols are based on the assumption that an adversary can only manipulate the software of provers. Thus, they cannot withstand an adversary who is able to perform physical attacks and tamper with the hardware of provers. Yet, an adversary can rather easily capture a device and tamper with its hardware as devices forming MANETs are often distributed over wide public areas and consist of a multitude of devices. Hence, a scalable attestation protocol that is resilient to physical attacks is much needed.

Ibrahim et al. [22] presented a first approach to solve this problem by combining existing scalable attestation approaches [5][7] with absent detection [13] to detect both software and hardware attacks. The absent detection protocol is based on the assumption that a strong adversary, who physically tampers with a device, must temporarily take the device offline for a certain amount of time, e.g., to disassemble the device and extract secret keys [8]. To detect offline and thus physically compromised devices, each device periodically emits a heartbeat that needs to be received, verified, and logged by every other device in the network. Although a functional solution to the problem, the protocol suffers from several shortcomings. First, the amount of exchanged messages per heartbeat period scales quadratically
with the number of devices in the network. This causes scalability issues in large networks with respect to network communication, energy consumption, and runtime performance. Furthermore, the protocol is very error-prone, since a single defective transmission of a heartbeat suffices to cause a false positive, where a healthy device is mistakenly regarded as compromised. Aggravating this, the protocol is only able to attest the state of the overall network and cannot identify particular compromised devices. Hence, a single false positive causes the entire network to be considered as compromised. Finally, the protocol relies on the assumption that during protocol execution the network topology is static and connected, which is a very strong limitation for wireless mesh networks.

In this paper, we present the first scalable attestation protocol (SCAP) for interconnected embedded devices that is resilient to physical attacks. To protect against strong adversaries, we build on the established assumption that an adversary needs to take a device offline to physically tamper with it [8, 14, 22]. In our protocol, a single leader device periodically emits a new heartbeat that is propagated in the network. To obtain the newest heartbeat from a neighboring device, a device must authenticate itself with the previous heartbeat. Since a device that is under physical attack has to be absent for at least one heartbeat period, it will miss this period’s heartbeat and thus be unable to obtain any further heartbeats. To prevent a collusion between compromised devices, heartbeats are stored in lightweight secure hardware and transmitted encrypted via secure channels. During the actual attestation, devices that fail to authenticate with the newest heartbeat are regarded as physically compromised, whereas devices with a compromised software are detected based on existing software attestation techniques. In case of an outage of the leader, a new leader device is determined through a leader election process. By optionally storing the attestation result in each device, our protocol is able to efficiently attest highly dynamic and partitioned network topologies.

We show that our protocol is secure against an adversary who compromises all but one device in the network. Finally, we demonstrate the practicability of our protocol in static and dynamic networks. In summary, SCAP provides the following improvements over existing work:

- SCAP can precisely identify devices whose hardware and/or software is compromised, if less than half of all devices in the network are compromised.
- SCAP is very efficient. Compared to the best previous work [22], we reduce the number of sent messages per time period from $O(n^2)$ to $O(n)$, thus, achieving scalability to millions of devices (where $n$ denotes the total number of devices in the network).
- SCAP is robust against network and device failures by (1) relying on a one-to-many delay-tolerant link in contrast to a many-to-many continuous link, as used in the best previous work [22], and (2) offering a recovery mechanism, the leader election protocol, that minimizes the amount of false negatives.

- SCAP provides a novel efficient aggregation scheme, e.g., attests of 4,000 devices fit into 1kB. This allows to attest highly dynamic and partitioned network topologies efficiently.
- SCAP is the first scalable attestation protocol that is evaluated in dynamic network topologies.

Outline. The rest of the paper is organized as follows. In §2 we summarize existing work. In §3 the system model, device requirements, and adversary model are presented. In §4 we describe our novel attestation approach to detect physically compromised devices. Then, in §5 we extend the attestation protocol to execute a recovery protocol on failures, verify the software integrity of devices, and support dynamic topologies during attestation. The performance of SCAP is evaluated in §6. Finally, we conclude in §7.

2. RELATED WORK

Device Attestation. Remote attestation is a mechanism that allows a third party, the verifier, to check the integrity of a remote system, the prover. Protocols that target the attestation of a single embedded device are either software-based [25, 26] or hardware-based [11, 18, 28]. Software-based techniques require no secure hardware, but rely on assumptions that have been shown to be hard to achieve in practice [6]. Hardware-based attestation mechanisms provide much stronger security guarantees by relying on lightweight security architectures. Nevertheless, single-device approaches are impractical in mesh networks due to the large overhead of attesting each device individually.

Recently, protocols started to focus on an efficient attestation of multiple embedded devices. Park et al. [29] proposed to compare the integrity measurements of multiple devices. Yet, their approach requires identical devices and only enables a probabilistic attack detection rate. Asokan et al. [7] present a highly efficient attestation scheme for large-scale networks of embedded devices that requires only Read-Only Memory (ROM) and a simple Memory Protection Unit (MPU). In their scheme, each device attests its neighbors and reports the aggregated result back to its parent, eventually received by the verifier. Ambrosin et al. [6] enhance this work by introducing a novel signature scheme that enables anyone to publicly verify the attestation result and allows the network to contain untrustworthy aggregator devices, such as routers or cloud servers. Yet, besides the work by Ibrahim et. al [22], which has been discussed in §1, existing works consider the adversary to compromise only the software on devices. In mesh networks, this assumption may not hold, since an adversary can comparatively easy capture a device and physically tamper with it.

Capture Detection. Several works have been proposed on the detection of node capture attacks, where an adversary physically approaches and manipulates a device. They all build on the assumption that an adversary needs to take a device offline, in order to tamper with it [8]. Conti et al. suggested that a node is collaboratively flagged as captured if it fails to re-meet with any other node within a fixed time interval [14, 15]. In the approach by Ho [20], nodes use statistical methods to detect absent neighbor devices in static network topologies. Recently, Agrawal et al. proposed to deploy multiple TPM-equipped cluster heads in the network, which check the integrity of the software as well as
the physical presence of all nodes in the cluster. Nevertheless, existing approaches are unable to detect devices with compromised software, require the deployment of additional hardware, or lack scalability. Secure Data Aggregation. Since ad hoc networks are often deployed to collect sensory data, many efficient and integrity-preserving aggregation schemes for mesh networks have been proposed. Unfortunately, these schemes rely on very costly asymmetric cryptographic operations, require a specific network topology during aggregation, or need multiple communication rounds, which both is undesirable, as it leads to communication overhead in dynamic network topologies. Thus, a lightweight aggregation scheme suitable for remote attestation of embedded devices that supports dynamic topologies and allows the identification of compromised devices is missing.

3. PRELIMINARIES

System Model. In our model, we consider embedded devices that can be heterogeneous in terms of hardware capabilities and software resources, e.g., devices with different software, computational power, storage capacity, or security functionalities. All embedded devices are connected in a mesh network topology. This topology can be static, where devices remain stationary and the network is connected, or dynamic, where devices can move freely and the network can be temporarily partitioned. However, in dynamic network topologies, we assume that devices meet each other regularly due to their mobility. Devices that are unreachable for some time are regarded as compromised, since it is uncertain whether they will ever contribute to the network again. We further assume that each device gets initialized and deployed by a trusted network operator, once.

After deployment, the goal of the network operator is to ensure the correct and safe operation of all devices by executing the proposed attestation protocol. The attestation protocol determines all devices whose software is in a trustworthy, i.e., unmanipulated and up-to-date, state and whose hardware has not been tampered with. We refer to these devices as healthy devices, in contrast to compromised devices. Executing the protocol, is able to learn the precise identity of all healthy and all compromised devices. This may serve as a first step towards physically locating and recovering compromised devices. In order to perform the attestation protocol, requires a connection to at least one device in the network.

Device Requirements. We assume that each device provides the minimal hardware properties for remote attestation, according to the work by Francillon et al. In practice, these properties can be implemented with ROM and a simple MPU. ROM stores the protocol code and cryptographic keys, and the MPU ensures an uninterrupted execution of the protocol code and allows only protocol code to access the cryptographic keys. Recently, it has been shown that these minimal hardware properties are available even on many low-cost commodity embedded devices. Additionally, our attestation protocol relies on a write-protected real-time clock. Protected real-time clocks are already built-in many existing commodity embedded devices. We henceforth refer to the execution space, where all required hardware properties are fulfilled, as Trusted Execution Environment (TEE).

Adversary Model. In this work, we regard a powerful adversary who is able to mount attacks on the network as well as the software and hardware of devices. In detail, is granted full control over all messages in the network (Dolev-Yao model). Thus, can eavesdrop, modify, delete, or synthesize all message between any two entities. Moreover, is allowed to compromise the software of all devices in the network. This gives full control over the devices’ execution state and storage, yet, no access to the protected contents inside the TEE. We further allow to capture and physically tamper with up to all but one device in the network, when attesting the overall network state, and up to half of all devices in the network, when knowledge on the precise identity of compromised devices is required. For the physically compromised devices, is able to access device secrets and code inside the TEE and is allowed to manipulate the clock. We note that it is impossible to guarantee a secure device attestation, if all devices in the network have physically been compromised.

Finally, as in, we assume that mounting a physical attack requires at least a time in which the device is offline, e.g., to decapsulate the device and to launch a microprobing attack. Depending on the device’s level of tamper resistance and the adversaries resources, such attacks typically require hours up to weeks in specialized laboratory environments.

4. SCAP

In the following, we describe the SCAP protocol, which identifies devices in the network have physically been tampered with. Note that the detection of hybrid attacks, i.e., attacks that target hardware and software, is discussed in the next section. SCAP consists of three different phases. In the initialization phase, the trusted network operator initializes each device once, before the deployment of the network. The heartbeat phase is periodically executed during the operation of the network. In this phase, all physically uncompromised devices maintain a valid state by sharing a common group key, namely the heartbeat. We will show how the heartbeat is periodically regenerated and propagated in the network and demonstrate that physically compromised devices are unable to obtain the heartbeat. Finally, in the attestation phase, initiates an attestation of the network and obtains a report, which exhibits all physically compromised devices.

4.1 Initialization Phase

Preliminaries. Devices can either be in a healthy or compromised hardware state. We discretize the time into non-overlapping time periods of fixed length . We reference the starting times of each time period with , , , ..., . The real time can be read by any device.
from a reliable read only clock RROC(), which for simplicity is assumed to be synchronized between all devices. Each device keeps track of the current time period, running from time $T_t$ until $T_{t+1}$. In the remainder of this section, we assume an implementation of a function Checktime($t$) that returns a constant HB, if the real time is within the time period indicated by parameter $t$, i.e., $T_t \leq T_{\text{clock}} < T_{t+1}$ and otherwise false.

**Enrollment.** In the enrollment phase, the network operator $O$ initializes the TEE of all devices with the following secrets. First, devices store two initial heartbeats $hb_{cur}$ and $hb_{next}$, which function as a group secret between all healthy devices. Second, each device is equipped with a device-dependent symmetric key $dk_i$, used during attestation to generate a device unique attest, and an asymmetric key pair ($pk_i, sk_i$), employed to establish secure channels between devices. Finally, devices record the current time period $t$, their own device identifier $D_i$, and the identifier of the leader device $D_{min}$, which is the first device $D_i$ in the network. Table 1 provides a summary of relevant definitions.

For explanatory reasons, we assume an initial enrollment of all devices. However, SCAP also allows devices to be enrolled at any point in time by issuing the current heartbeat.

**Acronym Usage**

| Acronym | Usage |
|---------|-------|
| $\delta$ | length of heartbeat period |
| $t$ | current time period |
| $D_i$ | unique device identifier |
| $D_{min}$ | device identifier of the leader device |
| $hb_{cur}$ | current valid heartbeat |
| $hb_{next}$ | heartbeat valid in next time period |
| $pk_i, sk_i$ | key pair for channel establishment |
| $k_{ij}, k_{ik}, \ldots$ | channel keys with neighbors $D_j, D_k, \ldots$ |
| $dk_i$ | device key for attestation with operator |

Table 1: Overview of all secrets stored in the $D_i$’s TEE.

### 4.2 Heartbeat Phase

**Basic Idea.** The heartbeat protocol is the core protocol of our approach. It excludes devices from the network that are offline for more than one time period and, hence, are assumed to be physically tampered with. During protocol execution, a so-called leader device emits a new secret group key, named heartbeat, that is propagated in the network. Obtaining this heartbeat requires a device to authenticate with the heartbeat of the previous time period. Therefore, devices that are offline in an arbitrary time period $T_a$ miss the heartbeat that is propagated in $T_a$ and thus are unable to obtain a heartbeat in any subsequent time period $T_{a+1}, T_{a+2}, \ldots$. Since any communication between devices in all protocols is secured using the newest heartbeat as a key, physically compromised devices are unable to participate any more. In the following, we describe the heartbeat transmission protocol, formalized in Figure 1, which is run between two neighboring devices to transfer the heartbeat from one device to the other.

**Heartbeat Transmission Protocol.** The emission of the new heartbeat in every time period is initialized by the leader device. As soon as the leader observes that the real time $T_{\text{clock}}$ has reached the start of a new time period (Checktime($t$) returns HB), the leader first updates the heartbeat of the current time period $hb_{cur}$ to the most recently exchanged heartbeat $hb_{next}$. We remark that heartbeats could also be indexed by the time period in which they are active in, e.g., $hb_1, hb_2, hb_3, \ldots$. However, as only two heartbeats are relevant for any device, only these two, i.e., the current and next heartbeat, are stored and referenced. After updating the current heartbeat, the leader samples a new heartbeat $hb_{next}$ for the subsequent period $t + 1$ and increments its time pointer $t$ by one. Consequently, the time period described by the pointer is now ahead of the real time $T_t > T_{\text{clock}}$. A time pointer ahead of the real time indicates a device that it is in possession of a heartbeat for the upcoming time period. The leader initialization code is illustrated below.
Next, the leader informs its neighbors about the new heartbeat with a message $msg_{new}$. For simplicity, we henceforth assume that two neighboring devices have already established a shared secret $k_{ij}$ by performing a key exchange using their public keys authenticated with the current heartbeat.

On receiving $msg_{new}$ from any device $D_i$, a device $D_j$ will enter its TEE and check whether the next time period has been reached. If this is the case, $D_j$ will update its current heartbeat to the previously communicated one. Afterwards, $D_j$ encrypts a fixed string, e.g., '0', under the current heartbeat, XOR-ed with the channel key $k_{ij}$ shared by both devices and sends the result to $D_i$. We refer to this XOR-ed key, as the session key. A healthy $D_i$ can decrypt the message by also computing the session key. A successful decryption proves that $D_j$ is in possession of the current heartbeat (and the channel key) and is therefore eligible for the next heartbeat. Then, $D_i$ answers with a message $msg_{agg}$ containing the current heartbeat $hb_{next}$, also encrypted with the session key. On successful decryption, device $D_j$ stores the new heartbeat as $hb_{next}$. Afterwards $D_j$ increments its time period pointer and then announces this new heartbeat to its neighbors with $msg_{new}$. Figure 3a illustrates the heartbeat transmission phase in a network with 6 healthy devices and one adversarial device $D_A$ that was physically compromised in time period $t = 2$.

We note, that the heartbeat protocol relies on the availability of the leader device, which constitutes a single point of failure. In §4.2 we present an extension that makes the heartbeat protocol more robust against device outages, network partitioning, or targeted denial of service attacks.

### 4.3 Attestation Phase

**Basic idea.** The attestation protocol allows the operator $O$ to check the state of all devices in the network. For this purpose, $O$ issues an attestation request that is answered by all devices with an attestation report. Propagating the attestation request through the network arranges a spanning tree whose root is $O$. This enables an efficient transmission and aggregation of attestation reports along the spanning tree to $O$. SCAP supports two variants of attestation. The first variant allows to attest the overall network state and is secure against an adversary who compromises all but one device. However, it only outputs a Boolean result, namely whether all devices are healthy or not. The second variant precisely identifies compromised devices by id and in this way increases the protocol’s robustness and applicability in practice. Yet, it requires more than half of all devices in the network to be healthy.

**Attestation protocol.** The protocol is formalized in Figure 2. The operator $O$ initially connects to a device $D_i$ in the network and emits an attestation request. The request contains the concatenation of a current timestamp $ts$ and the number of devices $n$ in the network, encrypted under the device’s key $dk_i$, which is only shared between $D_i$ and $O$. By verifying the authenticity and timeliness of the request (isValidReq($ts$)), denial of service attacks through replays can be prevented. Next, the attestation request, consisting of the concatenation of $ts$ and $n$, is propagated by $D_i$ to its neighboring devices. This and all following communication between two devices is secured with the pairwise session key, i.e., the current heartbeat XOR-ed with the channel key. Any device that receives an attestation request first verifies the request and then also propagates the request to its neighboring devices. These steps are repeated until the attestation request reaches devices, whose neighbors already have received the request. In this way, a spanning tree is constructed. Leaf devices that cannot propagate the request any further return an attestation report to their parent device from which they initially obtained the attestation request. The attestation report contains their own attest, which consists of $ts$ encrypted under their own device key. Every non leaf device merges its own attest (and identifier) with all received attestation reports and propagates the merged report to its parent device. Eventually, $D_i$ merges a final report that contains all healthy devices in
the network. This final report is encrypted under $dk$, and transmitted to $O$, who verifies the report, as described in the next paragraph.

We note that the attestation must be completed in time $\ell_{\text{attack}}$ or $O$ has to periodically check the presence of $D_i$ during attestation. Otherwise, $Adv$ can physically tamper with $D_i$, to extract an aggregate and induce attests of physically compromised devices. Figure 3(a) illustrates the attestation phase in a network with 6 healthy devices and one adversary device $D_A$ that was physically compromised.

**Report Aggregation and Merging.** An aggregated attestation report consists of two parts. The first part contains a description of all device identifiers that are in the aggregate. The second part consists of the aggregated attests. For a small number of devices, the description is a list of device identifiers, else it is an $n$-bit vector, where a one at position $k$ indicates that $D_k$ is contained in the aggregate. The attests themselves are aggregated by XOR-ing all individual attests.

Multiple attestation reports are aggregated by merging their device descriptions and XOR-ing their aggregated attests.

When attesting the overall network state, the attestation report consists of only the aggregate, as a device identification is not required. This decreases the size of the report significantly ($\ell_{\text{att}} \ll \ell_{\text{net}}$). Therefore, to increase efficiency, it is useful to run the attestation with precise device identification only, if an attestation of the overall network state fails.

**Report Verification.** Given a device description, $O$ recomputes the attests for all devices, whose id is contained in the description. Given no description, $O$ recomputes the attests for all devices. If the recomputed aggregate equals the reported aggregate and if at least $n/2$ attests are included in the report, then the report is assumed to be valid. Only then, all attested devices are assumed to be healthy and the verification returns a bit vector, where a zero/one at position $k$ indicates that $D_k$ is compromised/healthy.

### 4.4 Security Analysis

Intuitively, an attestation protocol is secure, when the network operator $O$ will testify a healthy system state, if not a single device has physically been compromised. We refer to such an attestation scheme as non-informative secure.

Moreover, an informative secure attestation protocol allows $O$ to distinguish between healthy and compromised devices. We follow the idea of Asokan et al. [7] and prove the security of our protocol by an adversarial experiment $\text{SECATT}^{\text{Adv}}(k)$. In this experiment, the adversary $Adv$ is given access to a network of $n$ initialized devices Net that execute the heartbeat and attestation protocol. $Adv$ can interact with all devices according to the attacker model presented in §3. Moreover, we assume any adversary $Adv$ to be computationally bound (PPT). Hence, $Adv$ is able to interact a polynomial number of times $k$ with devices in the network (and the authenticated encryption scheme). Furthermore, $Adv$ is allowed to trigger and observe attestations by $O$. After at most $k$ interactions, a final attestation is initiated by $O$. The output of $\text{SECATT}^{\text{Adv},c}(k)$ is then a bit vector returned by $O$ after verification of the final request. A bit vector with only zeros indicates a compromised network, whereas every bit set to one indicates a healthy device, cf. §1.3. We capture the intuitive idea of secure attestation in the following definition.

**Definition 1. Secure Attestation Scheme.** An network attestation scheme for $n$ devices is secure if

$$\Pr[\text{SECATT}^{\text{Adv}}(k) = 1] \leq \negl(k)$$

for any PPT $Adv$ and $0 < c < n$, where $c$ is the number of compromised devices. An attestation scheme is informative and secure if

$$\Pr[\text{SECATT}^{\text{Adv},c}(k)[j] = 1] \leq \negl(k)$$

for any PPT $Adv$ and every compromised device $D_i$, where $[j]$ is the $j$'th bit in the result vector and the total number of compromised devices $c$ is less than $n/2$.

Note that the definition of a non-informative secure attestation scheme is similar to the definition given in [7], which is defined without device identification in mind.

**Security of SCAP.** The security of SCAP is summarized in Theorem 1.

**Theorem 1.** SCAP is an informative and secure attestation protocol when the length of a heartbeat period $\delta$ is
at most $t_{\text{attack}}/2$, assuming security of the PRNG and authenticated encryption scheme that guarantees confidentiality (IND-CPA) and authenticity (INT-CTXT).

In the following paragraphs, we sketch a proof to show that SCAP is an informative secure attestation scheme. The sketch is split in two parts. First, we sketch a proof for Theorem 2 which formalizes the security of the heartbeat protocol, before arguing the security of the full protocol.

**Theorem 2.** Any PPT Adv is unable to gain access to any heartbeat $hb_t$, which is used to secure the communication in time period $t$, before time period $t + 1$, assuming $\delta < t_{\text{attack}}/2$, security of the PRNG, secure channels between devices and an authenticated encryption scheme that guarantees IND-CPA and INT-CTXT.

Intuitively, the security of the heartbeat protocol is achieved by using an interactive protocol that requires the receiving device to prove its knowledge about the current heartbeat to the sending device. Only then, the next heartbeat is exchanged. This active participation makes it impossible for offline devices to follow the continuous ‘stream’ of heartbeats.

**Proof Sketch - Heartbeat.** We observe that no two heartbeats are linked. Hence, it is impossible to derive any $hb_t$ from $hb_{t-1}, hb_{t+1}, \ldots, hb_{t-1}$ without breaking the security of the PRNG. Moreover, assuming synchronized clocks, every healthy device stores at most two heartbeats in any time period $t$, namely $hb_{t-1}, hb_t$. When compromising a single device in time period $t$ and assuming an attack time of $t_{\text{attack}} \geq 2 \cdot \delta$, the attack will be successful not earlier than in time period $t + 2$. The TEE of the compromised device will then leak at most heartbeat $hb_{t+1}$, but no later heartbeats, as these are not present in the TEE. We observe that with any attack time $t_{\text{attack}} < 2 \cdot \delta$, Adv would be able to compromise a device without missing a single heartbeat period, and thus render the protocol insecure.

We show that Adv is unable to gain access to the current heartbeat by interacting with healthy devices without breaking the security of the authenticated encryption scheme. During the heartbeat exchange, all messages sent between two devices $D_i$ and $D_j$ are encrypted with a session key that is the XOR of the pairwise channel key $k_{ij}$ and the current heartbeat $hb_t$ at time $t$. Thus, the session key is only known to $D_i$ and $D_j$ at time $t$. We observe that with access to only one (or none) of the two keys, Adv is unable to create or to decrypt a message that is accepted by $D_i$ or $D_j$ without breaking the INT-CTXT and IND-CPA security of the encryption scheme. Hence, even when compromising further devices and extracting (past) heartbeats, Adv is unable to decrypt any past or future communication between $D_i$ and $D_j$, as Adv is missing the pairwise channel key $k_{ij}$. Similarly, after compromising a device and gaining access to all channel keys, Adv is still missing the current heartbeat to construct the session key, required to interact with neighboring devices. The same arguments hold for all messages sent between devices in the aggregation protocol, since they are all encrypted using the pairwise session key.

**Proof Sketch - Attestation.** The attest of a single device $D_i$ is the encryption of the timestamp $ts_i$ issued by $O_i$ under $D_i$’s device key $dk_i$. Thus, Adv is only able to forge an attest for a healthy $D_i$ with non-negligible probability when being able to break the IND-CPA security of the encryption scheme. Yet, to win SECATT$_{Adv}^{\text{cc}}$, Adv has to report at least $n/2$ (informative) or $n$ (non-informative) valid attests, while being allowed to only compromise up to $c < n/2$ or $c < n$ devices. Consequently, since Adv is unable to forge an attest for a healthy device with non-negligible probability, Adv has to merge the attests of compromised devices with attests created by healthy devices.

During the actual attestation protocol, two cases can be distinguished. First, the device $D_i$ that $O$ approaches for the attestation is compromised. In this case, Adv can create an attestation report for all compromised devices. However, without access to a valid heartbeat and thus session key, Adv can only create a valid attestation request message $msg_{\text{req}}$ with non-negligible probability, when breaking the INT-CTXT security of the encryption scheme. Hence, no healthy device will contribute an attest. Similar, in the second case, where $O$ first approaches a healthy device, Adv is, for the same argument as described above, unable to decipher or induce any message in the attestation protocol between healthy device. Furthermore, the security of a XOR aggregation scheme, as used here, is shown in [23] and consequently, SCAP is non-informative secure, when only accepting a complete aggregation report that includes the attests of all devices. Furthermore, it is informative secure, when accepting reports with at least $n/2$ attests, because attests can be attributed towards their device id. Finally, we remark that the ’honest majority’ assumption $c < n/2$ is required, as otherwise a dishonest majority could fake a healthy systems state.

### 5. PROTOCOL EXTENSIONS

In the following, we present three significant extensions to SCAP. First, we make the heartbeat transmission phase more robust against failures (§5.1). Next, we extend SCAP to verify the integrity of the software on all devices in the network (§5.2). Finally, we propose an extension that allows efficient attestation in highly dynamic and disruptive network topologies (§5.3).

#### 5.1 Leader Election Protocol

The leader election phase extends the heartbeat transmission phase, to make it more robust against failures. In particular, devices that fail to receive the current heartbeat elect a new leader device that takes over the tasks of the previous leader, i.e., the periodic emission of a new heartbeat. In this way, the heartbeat protocol is able to recover from device outages, network partitioning, or targeted denial of service attacks.

The leader election protocol is initiated by every device that fails to receive the heartbeat within a time $h_{\delta}$ that is shorter than the heartbeat period $\delta (\delta_{h_{\delta}} < \delta)$. Devices execute the leader election protocol inside their TEE and use the remaining leader election time $\delta_{\text{LE}} = \delta - \delta_{h_{\delta}}$ to determine the device with the smallest id, which then becomes the new leader device (bully algorithm). For this purpose, devices initially generate their own heartbeat and then announce this heartbeat together with their device id to all neighboring devices. Devices store the smallest device id that they received in the leader election phase, including the corresponding heartbeat. Whenever a device updates its smallest received id and heartbeat, it broadcasts both to their neighboring devices. Thus, the new smallest id and
heartbeat are quickly propagated in the network. A device recognizes itself as the new leader device, if it only receives messages from devices with higher device ids. Note that the original leader has the smallest id in the entire network, hence, the protocol also tolerates a return of the original leader. In Appendix A.1, we formalize the leader election protocol, describe it in more detail, and demonstrate its security.

5.2 Attestation of Software Integrity

In order to attest the correct and safe operation of all devices in the network, it is crucial to ensure that devices are in a trustworthy software state, free from malicious or broken software. For this purpose, we propose that the network operator \( \mathcal{O} \) defines a set of trustworthy software states \( ts \) in the attestation request, when initiating an attestation of the network. \( ts \) specifies all software configurations that are permitted by \( \mathcal{O} \), e.g., because they represent the correct and most recent software states. When devices perform the attestation protocol, they invoke the execution of a software integrity measurement function in their TEE. This function measures the integrity of installed software and compares these measurements to the reference values specified in \( ts \).

In this way, each device determines whether it is in a trustworthy or untrustworthy software state. Devices being in an untrustworthy software state immediately abort the attestation phase and instead execute a recovery routine that allows the device to restore a trustworthy software state, e.g., via secure code updates [21]. Since untrustworthy devices do not participate in the execution of the attestation protocol, \( \mathcal{O} \) receives a report which exclusively contains devices that are in a trustworthy software and uncompromised hardware state. In Appendix A.2, we extensively explain changes that need to be done to the enrollment phase and the attestation protocol to enable such a hybrid attestation. Furthermore, we discuss the security of the extension.

5.3 Attestation of Dynamic Networks

Approach. The attestation protocol in SCAP (§ 4.3) arranges a spanning tree, which allows for an efficient aggregation and transmission of the attestation report to the network operator \( \mathcal{O} \). This approach works efficiently as long as the network topology stays static during attestation, for instance, as devices in the network only move as a whole (herd mobility) or within local limits (micro-mobility). However, in dynamic network topologies with highly mobile devices and frequent link disruptions, it is impractical to maintain a spanning tree topology. In such networks, communication with a parent device could introduce a significant delay or become highly inefficient, as the parent device could move away. Even worse, the parent device may be temporarily out of range and thus be disconnected from the network.

Therefore, instead of routing the attestation along a virtual topology, we propose a distributed (greedy) aggregation, where attestation reports are collected and aggregated by all devices in the network. Thus, after \( \mathcal{O} \) initiates the attestation protocol, each device first generates its own attestation report, stores this report, and broadcasts it to all neighboring devices. When a device receives an attestation report, it merges this report with its stored report. On observing new attests, the device broadcasts the updated report to all its neighboring devices. In this way, all devices in the network eventually store the same attestation report and \( \mathcal{O} \) can obtain the attestation result from an arbitrary device in the network.

To reduce the communication complexity, an aggregation scheme for the above mentioned approach must allow to merge multiple reports with intersecting attests into one. This requirement renders the aggregation function described in § 1.3 inapplicable, because its XOR operation risks the removal of intersections of attests from the aggregate. Because of this and following the analysis of aggregation protocols in § 2, we present a novel aggregation scheme for dynamic networks that is particularly tailored to the application scenario.

Secure & Efficient Attestation Report Aggregation. The here proposed scheme achieves statistical security and is slightly less powerful than the spanning tree aggregation scheme, as it allows an adversary to compromise at most \( c < n/2 - s \) devices, with \( 2^{-s} \) being the statistical security level. In our scheme, an attestation report also consists of two parts, namely the device description and the secure aggregate itself. The device description is a \( n \)-bit vector where a bit is set for every device included in the aggregate. The aggregate consists of an \( n_2 \) = \( (n + s) \)-bit vector, where a single bit indicates the attest of a device. A device \( D_i \) that receives an attestation request with timestamp \( ts \), creates its own attest using a collision resistant cryptographic hash function \( H \) by computing \( a = H(dk_i||ts) \) in its TEE. Subsequently, \( D_i \) sets a bit at position \( i \) in the device identifier as well as a bit at offset \( \text{compress}(a) \) in the secure aggregate, where \( \text{compress} \) is a function that reduces the hash value to a value of length \( n_2 \) bits. Note that \( \text{compress} \) does not need to be cryptographically secure, but it should achieve a close to uniform output distribution for uniformly distributed input. All other bits in both vectors are set to 0. In order to merge multiple attestation reports, a device computes the bit-wise OR of all attestation reports. This can be done very efficiently and allows to aggregate reports with intersections of devices. Both the secure aggregate and the list of device identifier could be compressed, for instance, by using a run-length encoding. Nevertheless, even without compression, a very short attestation report is achieved with a length of only \( 2n + s \) bits, e.g., 266 bytes for 1000 devices and a security level of \( s = 128 \) bit, which is a significant improvement over a naïve concatenation of attests that requires more than 16k bytes. Even though, \( \text{Adv} \) has a good chance to guess a small number of attests correctly, the security of the scheme is based on the hardness to guess (at least) \( s \) attests correctly. A detailed security analysis of this scheme is given in Appendix A.3.

6. EVALUATION

Next, we evaluate SCAP (§ 6) and its three protocol extensions (§ 5). In § 6.1, we describe our setup, give details of the implementation, and present our measurements. Then, in § 6.2, we report on our network simulation results for both static (§ 5.2) and dynamic network topologies (§ 5.3).

6.1 Implementation & Measurements

Setup. We implemented our protocol on Stellaris LM4F120XL microcontrollers. The Stellaris is a low-cost embedded system from Texas Instrument which features an 80 MHz ARM Cortex-M4F microprocessor and 256 kB of Flash memory. To enable wireless mesh connectivity
Table 2: Crypto Runtime Performance on the Stellaris.

| Algorithm      | Function      | Runtime  |
|----------------|---------------|----------|
| ed25519        | genKey()      | 18 ms    |
|                | keyExchange() | 48 ms    |
| AES-128-GCM    | encrypt(16 bytes) | 0.1 ms  |
|                | encrypt(1024 bytes) | 1.8 ms  |
|                | decrypt(16 bytes) | 0.1 ms  |
|                | decrypt(1024 bytes) | 1.8 ms  |
| SHA-512        | hash(16 bytes) | 0.4 ms   |
|                | hash(1024 bytes) | 3.1 ms   |
|                | hash(30720 bytes) | 81.9 ms  |

We configured the attestation protocol to use the software attestation extension (§5.2) and thus to attest the hardware and software state of all devices in the network. To verify the integrity of installed software, devices compute a SHA512 digest over a 30 kB software and compare the digest to an expected value that is specified in the attestation request. For attestation we used the spanning tree attestation approach (§6.3).

Figure 3 shows the runtime for a binary and 8-ary tree topology with up to 550,000 devices, where the heartbeat protocol on the application layer and used computational and network delays based on our measurements (see §6.1).
that reporting precise device identifier introduces a notable overhead. When reporting the overall network state, attestation runtime increases barely with the number of devices in the network, remaining below 2 seconds even for networks with multiple million devices in almost any tree topology. Yet, when reporting precise device ids, runtime increases to more than 152 seconds for 500.000 devices due to the large size of the attestation report, which increases proportionally with the network size. Nevertheless, we consider that 2.5 minutes is an acceptable timeframe to obtain a report that precisely lists which devices are in a compromised state.

**Communication Costs.** During heartbeat transmission, all devices, except for the leader device, receive $msg_{new}$ (1 byte), send $msg_{req}$ (17 bytes), and receive $msg_{att}$ (17 bytes) to obtain the newest heartbeat, using a one byte message identifier. If devices need to (re-)establish a secure channel key, they need to mutually exchange their public keys, which causes an additional message overhead of 32 bytes. For instance, in a binary tree topology, devices transmit in total 104 bytes, or 296 bytes with the initial key.

During the execution of the attestation protocol, all devices receive one $msg_{att}$ (17 bytes) or $msg_{agg}$ (17 bytes). Also, devices send a $msg_{att}$ to all neighbor devices that have not yet received $msg_{att}$ and afterwards receive a $msg_{agg}$ from them ($\leq n/2 + 16$ bytes). If the device's software integrity is attested \([1, 2]\), $msg_{agg}$ and $msg_{att}$ contain the set of trustworthy software states $\mathit{tss}$, in our evaluation a 64 bytes hash digest. In short, assuming a binary tree topology and $n = 1000$ devices, during a run of the attestation protocol, each non-leaf device transmits at most 666 bytes and each leaf device 222 bytes.

**Summary.** We demonstrated that our protocol is highly efficient in static network topologies. In comparison to the previously best attestation protocol that is secure against physical attacks \([22]\), we reduce the number of transmitted messages per time period from $O(n^2)$ to $O(n)$. To illustrate this advantage, in binary-tree topologies our approach is 27 times faster with 2000 devices and 3800 times faster with 500,000 devices when interpolating their results. The comparison already considers the fastest variant presented in \([22]\), which requires each device to store and manage $n$ symmetric keys. In our protocol, devices must only store the keys of neighboring devices, e.g., 3 in a binary tree topology.

When attesting the state of the entire network, both protocols \([22]\) and SCAP show a runtime that scales logarithmically with $n$. Nevertheless, in contrast to \([22]\), SCAP also allows to determine the ids of compromised devices with low overhead even in larger networks.

### 6.3 Simulation Results for Dynamic Networks

**Setup.** We further evaluated our protocol in highly dynamic and disruptive networks to investigate its robustness in complex scenarios. To model device mobility, we randomly deployed devices in a 1000m x 1000m square area and applied a random waypoint mobility model, which is commonly used in literature on absence detection \([10, 14]\). Consequently, each device repeatedly selects a random speed as well as a random destination within the area and then moves towards the destination at the selected speed. The random device movement causes the network to be constantly partitioned, especially for sparse networks. In order to investigate effects like link disruptions, varying network delays, and signal interference that emerge due to the movement of devices, we modeled an 802.15.4 physical and medium access control layer using the ns-3.25 lr-wpan module. Modeling both layers as well as device mobility requires a lot of computational power. This is a known issue in MANET simulations, which leads to huge simulation runtimes \([10]\). For these reasons, we were only able to run simulations with a few hundred devices. Nevertheless, as we will show in this section, the main hurdle of our protocol is to perform well in sparse networks. Scalability of our approach in dense networks, where all devices are permanently interconnected, is shown in the previous section. In addition to the above mentioned simulation parameters, we set the wireless communication range to 50m (50% of the distance specified in the ZigBee standard), the device speed to a random value between 5 and 15 m/s, and the heartbeat as well as the leader election period to 2.5 minutes (detecting physical attacks that require more than 10 minutes).

**Heartbeat Protocol Robustness.** We investigated the robustness of the heartbeat protocol in worst cases, which are highly dynamic and disruptive network topologies. In particular, we examined the time until the protocol produces false positives, i.e., healthy devices that are regarded as physically compromised, because they did not receive the heartbeat on time. Figure 6 illustrates the average runtime of the heartbeat protocol until a certain amount of false positives occur. The figure shows that the number of devices in the network has a vital influence on the robustness of the
heartbeat protocol. Since devices move completely at random, the network must be sufficiently dense so that devices meet each other frequently enough to exchange the newest heartbeat on time. In fact, there is an exponential correlation between robustness and device density, which causes the average error-free heartbeat runtime to quickly increase from 2.4 days for 60 devices to weeks with more than 90 devices. To illustrate the sparseness in this scenario, 60 statically connected devices could cover at the maximum 29% of the area and 90 devices 43.4%. Nevertheless, as shown by the boxplot, the runtime between multiple simulation results differ widely. This makes it hard to guarantee robustness for sparse network scenarios. Investigating the false negatives, we identified the main cause in the random movement of devices. Commonly, a single device hides away, i.e., does not encounter other devices, and thus has no chance to receive the newest heartbeat on time. This cannot be prevented by faster computations or smaller communication delays in our protocol, but only be increasing the duration of the heartbeat phase. We also observed that this hiding of a single device has barely any cascading effect on other devices. Hence, as shown in Figure 6, if tolerating a minimal amount of false positives, significant longer protocol runtimes are possible.

Next, we analyzed the effectiveness of the leader election extension by simulating an outage of the heartbeat leader device. Figure 7 shows the largest fraction of devices that agreed on a common new leader with an increasing time interval for the leader election phase. It again illustrates the importance of the network density. In dense networks, leader election information can spread faster and thus reach more devices in shorter time. Nevertheless, even in relatively sparse networks with 60 devices, a time interval of 150 seconds is on average sufficient to let all functioning devices agree upon a new common leader. This also highlights our robustness against targeted DoS attacks, where an adversary attempts to disrupt the heartbeat protocol by breaking the heartbeat leader device.

**Attestation Protocol Runtime.** For the evaluation of the attestation protocol in dynamic networks, we used our dynamic attestation extension (§ 6.2) with a statistical security level $s$ of 128 bits. Figure 8 shows a boxplot of the elapsed time between the emission of the attestation request and the moment when all devices in the network store the final attestation result, i.e., a report that contains all devices, for an increasing number of devices in the network. With an increasing network density, attestation reports spread faster and the overall attestation protocol runtime decreases. However, this effect is not as distinct as with the heartbeat protocol, where we observed an exponential correlation between protocol performance and network density. This is because, in contrast to the heartbeat protocol, where a single message is flooded in the network, each device must contribute with a message, i.e., its individual attestation report, to a global attestation aggregate. Furthermore, the size of the attestation report increases proportional with the network size, though, being reasonably small for common network sizes (e.g., 2.5kB for 10,000 devices). Figure 8 also shows that the runtime of the attestation protocol varies little. This guarantees that the final result is with high probability reached within a certain time frame, e.g., 5 minutes for 100 devices.

**Communication Costs.** Message costs in dynamic network topologies are, except for the attestation report, the same as in static network topologies (§ 6.2). However, due to link failures, some messages are transmitted more often in dynamic topologies. In our simulations, we varied the network size between 40 and 100 devices and let devices actively poll their neighbors for the newest heartbeat after 10 seconds. Our results revealed that, depending on the network size, each device sends on average 19.4 to 21.0 msg hb (poll heartbeat) and 1.04 to 1.12 msg req as well as msg hb messages. Hence, in total, devices transmit on average 114 bytes in each heartbeat transmission phase. Compared to static network topologies (§ 6.2), this is less than 10% communication cost overhead.

Nevertheless, because the attestation result is distributed to all devices, the actual attestation consumes considerably more communication in disruptive networks. Conducting the same simulations as described above, we observed that each device exchanges on average 12.4 attestation reports in networks with 40 devices, 16.0 with 60 devices, 18.9 with 80 devices, and 21.5 with 100 devices. Each exchange requires a device to send one msg req and receive one msg agg. Note that the dynamic attestation report in msg agg has a size of at most $n/4 + 16$ bytes. Thus, in total, devices transmit on average 1375 bytes in networks with 100 devices, which is 4.2 times more than in static network topologies.

**Summary.** We showed that our heartbeat and attestation protocols are robust and efficient, even in highly partitioned and unpredictably changing network topologies. In fact in an exemplary low connectivity scenario, with a maximum possible area coverage of 43% for randomly moving devices, the heartbeat protocol still runs on average 65 days without producing a single false positive with $t_{\text{attack}} = 10$ min-
utes. We further illustrated the effectiveness of the leader election protocol, by completely recovering networks from device outages in less than 130 seconds in the same setting. Finally, we demonstrated the robustness of our attestation protocol in dynamic networks and showed that its performance is dominated by network connectivity as opposed to the protocol’s communication complexity.

7. CONCLUSION & FUTURE WORK

We presented the first scalable attestation protocol SCAP for mesh networked embedded devices that is resilient to physical attacks. Compared to existing solutions, our protocol reduces the number of transmitted messages per time period from $O(n^2)$ to $O(n)$, thus scaling to millions of devices and outperforming existing solutions by orders of magnitude. In addition to attesting the overall state of the network, SCAP is able to precisely identify devices that run compromised software or have been physically manipulated. We demonstrated that our protocol is robust and efficient, even in very dynamic topologies, as it can perform an attestation or recover from device outages within minutes.

In future work we plan to investigate our protocol in specific network application scenarios, such as drone-based delivery systems or wireless sensor networks. Moreover, we want to make use of MANET simulators that are optimized for scalability and/or parallelism, in order to be able to simulate thousands of moving devices.

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APPENDIX

A. PROTOCOL EXTENSIONS

A.1 Leader Election Extensions

Heartbeat Transmission Protocol. The leader election protocol is shown in Figure 3 and extends the heartbeat transmission phase described in §4.1. We henceforth divide each time period $T_1, T_2, T_3, \ldots$ of length $\delta$ in two phases: the heartbeat phase, whose length is $\delta_{hb}$ (formerly $\delta$), and the leader election phase, whose length is $\delta_{le} = \delta - \delta_{hb}$. Furthermore, we assume that the function Checktime(t) returns the constant HB if $T_1 \leq T_{clock} < T_1 + \delta_{hb}$, the constant LE if $T_1 + \delta_{hb} \leq T_{clock} < T_{clock} + \delta_{le}$, and false otherwise.

Every device $D_i$ that did not receive a heartbeat within $\delta_{hb}$, indicated by Checktime(t) = LE, will generate its own heartbeat $hb_{i,next}$, set the current leader device id to its own id ($D'_{min} \leftarrow D_i$), and update its time pointer by one. In a next step $D_i$ will inform its neighbors about the new heartbeat with a message $msg_{hb}$.

Two devices that already initialized the leader election phase negotiate the heartbeat as follows. First, a leader election request message $msg_{req,req}$ is generated by $D_i$ that contains a session key to secure the remaining communication. Then, $D_i$ sends the smallest received device id $D'_{min}$ and the corresponding heartbeat to $D_j$. Initially these are $D_i$’s own id and generated heartbeat. Device $D_j$ will then compare its previous smallest id $D'_{min}$ with the just received id. If $D'_{min} < D'_{min}$, $D_i$ will update $D'_{min}$ to $D'_{min}$ and set $hb_{i,next}$ to $hb_{i,next}$. Finally, $D_j$ will inform $D_i$ of the result of the comparison, which is also stored by $D_i$. Both devices will then continue to further broadcast the new heartbeat. The protocol terminates implicitly, once the smallest device id has been identified. We note that a leader, who is absent during the heartbeat phase, can rejoin by participating in the leader election phase. In §4.3 (3), we analyze the effectiveness of the leader election protocol.

Security. The leader election protocol uses the same two-key mechanism, i.e., the session key constructed by heartbeat and channel key, as the original heartbeat protocol to secure all messages. This makes it impossible for an adversary $Adv$ to synthesize or to decrypt a message that is accepted or sent by healthy devices. Otherwise, $Adv$ could break the IND-CTXT or IND-CPA security of the encryption scheme. Hence, the actual leader election process can only be hindered, yet not controlled by $Adv$.

A.2 Attestation of Software Integrity

To achieve a secure attestation of hardware and software the following extensions to SCAP are required:

Enrollment Phase Extension. In the enrollment phase, the network operator selects an arbitrary software integrity measurement function Measure() and stores its implementation in the TEE of each device $D_1, \ldots, D_n$ in the network. Traditionally, these mechanisms measure the integrity of a software by computing a hash value over its binary code [32]. Though recent approaches are also able to measure the runtime behavior of a software, for the purpose of detecting sophisticated code-reuse attacks [3]. In the following, we abstract from these implementation details and use Measure() as a black box that takes an input $i$, e.g., a description of what to measure, and generates a measurement $m$, which represents the current software state of a device ($D_i$: Measure($i$) $\rightarrow m$).

Attestation Protocol Extension. Before invoking the attestation protocol, $O$ specifies a set of trustworthy software states $tss$. $Tss$ consists of multiple (input, measurement)-pairs ($tss =$ \{($i_1,m_1$), ($i_2,m_2$), ..., ($i_e,m_e$)\}) and a description which network device should use which input (e.g., devices from type 1 should use $i_1$, etc.). A pair ($i_k,m_k$) in $tss$ indicates that the expected measurement for the input $i_k$ is $m_k$ (Measure($i_k$) = $m_k$). In this way, $tss$ specifies all measurements that are permitted by $O$, e.g., because they represent the correct and most recent software states.

During the execution of the attestation protocol, $tss$ is distributed to all devices in the network. For this purpose, $O$ initially incorporates $tss$ into msg$_V$ ($msg_V \leftarrow$ AEnc($dr_{key}$, $ts||n||tss$)). In a similar way, by incorporating $tss$ into msg$_{att}$ ($msg_{att} \leftarrow$ AEnc($k_{att},ts||tss$)), devices forward $tss$ to neighboring devices. Afterwards, each device $D_i$ measures its local software configuration by extracting its appropriate ($i_k,m_k$) pair and executing the measurement function Measure() with the input $i_k$ in its TEE. Subsequently, $D_i$ checks whether the output generated by Measure() matches $m_k$ and if this is the case continues with the execution of the attestation protocol, as explained in Section 4.4. If both values do not match, $D_i$ invokes a recovery routine, which allows the device to restore to a trustworthy state by performing a secure code update protocol with $O$. Executing this extended attestation protocol, $O$ receives a msg$_{agg}$, that only contains ids of devices that are in a trustworthy software and uncompromised hardware state. Note that the protocol could easily be further extended to precisely report devices which are in an untrustworthy software but uncompromised hardware state, e.g., by introducing an additional msg$_{agg,ss}$ and msg$_{agg,ss}$ that is specifically generated and aggregated by untrustworthy devices and transmitted to $O$.

Security. The security of the protocol extension results from the security of the main protocol (§4.4), the secure hardware properties (§3), and the adversary model (§3). Since the protocol extension is executed in the TEE of devices, malware is unable to tamper with the protocol code, execution, or any stored protocol data (e.g., secret keys). Thus, an adversary, who compromises the software of a device, is only able to prevent protocol execution or manipulate the input/output to/from the protocol. However, preventing protocol execution has no influence, since untrustworthy devices stop executing the attestation protocol, anyway. Manipulating the input or output to or from the protocol has no affect, as all inputs and outputs are secured using authenticated encryption with secrets that are only accessible within the TEE. Additionally, all inputs and outputs are dependent on a session-specific timestamp $ts$ issued by $O$. Therefore, replay attacks are likewise worthless. These measures also prevent Dolev-Yao network adversaries from compromising security. By contrast, a physical attacker is able to tamper with the protocol code, data, or execution. However, as explained in the security analysis of the main protocol (§4.4), a physical attacker is unable to obtain the current heartbeat $hb_{i,cur}$, which is required to participate in the attestation protocol or heartbeat protocol.
A.3 Efficient Attestation Report Aggregation

Security. As already shown in the security analysis of the aggregation protocol (§4.4), \textit{Adv} is unable to exchange any message with healthy devices during attestation. This argument also holds for the efficient aggregation scheme, as only the aggregation inside the TEE is modified and not the protocol itself. Consequently, the security of the efficient aggregation scheme, depends on the hardness of attestation report itself. An attestation report is accepted if at least \(n/2\) valid attests are contained in the report. By assumption \textit{Adv} is only allowed to compromise up to \(c < n/2 - s\) devices and thus, can only compute up to \(c\) valid attests. The remaining \(n/2 - c\) attests have to be guessed by \textit{Adv}. The security of our aggregation scheme is formalized in Theorem A.3.

**Theorem 3.** Assuming collision resistance of the hash function, any PPT \textit{Adv}, compromising up to \(c < n/2 - s\) devices can successfully forge an efficient attestation report that is accepted by \(\mathcal{O}\) with probability of at most \(2^{-s}\) for any \(n > 2 \cdot s\).

**Proof Sketch.** The attestation report consists of two bit vectors, the first vector annotates the devices included in the network and the second vector annotates the actual attests (each attest is a single bit in the attest vector). To successfully include one additional attest into the report, \textit{Adv} has to set an additional bit in the device vector and to guess the correct bit in the attest vector. A single mismatch between the aggregate computed by \(\mathcal{O}\) and the reported aggregate results in a reject of the attestation report. As the position of an attest bit for a single device is computed by \(\text{compress}(H(dk_i \| ts))\), we observe that \textit{Adv} could break the collision resistance of the hash function, if \textit{Adv} would achieve non-negligible advantage in guessing an attest bit correctly without access to the device key. Assuming a uniform distribution of the attest bit, \textit{Adv} will guess its position correctly with probability \(1/n\). However, \textit{Adv} can follow a better strategy than randomly guessing all positions of the \(n/2 - c\) bits that are required for a valid attestation report.

We note that due to the relatively small set of bit positions, collisions between multiple devices are likely. The best strategy the \textit{Adv} can follow is thus, to guess collisions with the \(c\) bits that \textit{Adv} can set correctly in the attest vector. A collision with any of the attest bits occurs with probability of at most \(1/n\) (collisions within the attests of compromised devices are also possible). With this strategy, \textit{Adv} can achieve a winning probability of at most \((1/n)^{n/2-c}\). We observe that \(1/n = n^{2-s} \leq 1/2\) and by assumption \(n/2 - c \geq s\) and thus, \textit{Adv} wins the game with probability of less than \(2^{-s}\).

We remark that for the sake of technical simplicity of the proof, the attest vector is set to a fixed length \(n_s = n + s\). This is required to make it a hard task for \textit{Adv} to guess the zero bits in the attest vector for smaller \(n\), when setting all bits in the device vector. For larger \(n\), \(n_s\) could be chosen smaller than \(n + s\).
Heartbeat Leader Election Protocol (after secure channel establishment)

Sender device $D_i$
Secrets in TEE: $t$, $hb_{cur}$, $hb_{next}$, $k_{ij}$, $D_{min}$

Receiver device $D_j$
Secrets in TEE: $t$, $hb_{cur}$, $hb_{next}$, $k_{ij}$, $D_{min}$

Execute in TEE:
if Checktime($t$) = LE:
  $hb_{cur} \leftarrow hb_{next}$
  $hb_{next} \leftarrow \{ 0, 1 \}^n$
  $t \leftarrow t + 1$
  $D_{min} \leftarrow D_i$
  broadcast($msg_{new}$)

Execute in TEE:
if Checktime($t$) = LE:
  $hb_{cur} \leftarrow hb_{next}$
  $hb_{next} \leftarrow \{ 0, 1 \}^n$
  $t \leftarrow t + 1$
  $D_{min} \leftarrow D_i$
if Checktime($t-1$) = LE:
  $msg_{le\_req} \leftarrow AEnc(hb_{cur} \oplus k_{ij}, 0)$

Execute in TEE:
if Checktime($t-1$) = LE:
  $z \leftarrow ADecOrAbort(hb_{cur} \oplus k_{ij}, msg_{le\_req})$
  if $z = 0$:
    $msg_{le\_hb} \leftarrow AEnc(hb_{cur} \oplus k_{ij}, hb_{next} || D_{min})$

Execute in TEE:
if Checktime($t-1$) = LE:
  $hb_{\parallel} D_i \leftarrow ADecOrAbort(hb_{cur} \oplus k_{ij}, msg_{le\_hb})$
  if $D_i < D_{\min}$:
    $hb_{next} \leftarrow hb_{\parallel} D_i$
    $D_{\min} \leftarrow D_i$
  $msg_{leader} \leftarrow AEnc(hb_{cur} \oplus k_{ij}, hb_{next} || D_{min})$

Execute in TEE:
if Checktime($t-1$) = LE:
  $hb_{\parallel} D_{\min} \leftarrow ADecOrAbort(hb_{cur} \oplus k_{ij}, msg_{leader})$

Figure 9: Leader election protocol.