SAFE$^d$: Self-Attestation For Networks of Heterogeneous Embedded Devices

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ABSTRACT
The Internet of Things (IoT) is an emerging paradigm that allows to set large networks of small and independent devices. To ensure their integrity, practitioners employ so-called Remote Attestation (RA) schemes. Classic RA schemes require a central and powerful entity, called Verifier, that has mainly two duties: (i) it manages the entire process of attestation, and (ii) it contains all the proofs for validating the devices’ integrity. However, having a central Verifier makes the network dependent upon an external entity and introduces a single point of failure for security.

In this work, we propose SAFE$^d$, the first RA schema that allows a pair of IoT devices to validate their integrity without relying on an external Verifier. Our approach overcomes previous limitations by spreading the proofs among multiple IoT devices and using novel cryptographic mechanisms to ensure secure communications. Moreover, the entire IoT network can collaboratively isolate tampered devices and recover missing proofs in case of anomalies.

We evaluate our schema through an implementation for Raspberry Pi platform and a network simulation. The results show that SAFE$^d$ can detect infected devices and recover up to 99.9% of proofs in case of faults or attacks. Moreover, we managed to protect up to 10K devices with a logarithmic overhead on the network and on the devices’ memory.

CCS CONCEPTS
• Security and privacy → Security protocols; Trusted computing.

KEYWORDS
security, distributed hash table, chord protocol, remote attestation

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1 INTRODUCTION
Internet of Things (IoT) refers to a set of new technologies that allow building sophisticated applications by using groups of small and interconnected devices. IoT world revolves around three cardinal concepts: (i) a decentralized network which can be accessed remotely through the Internet, (ii) heterogeneous devices that collaborate autonomously, and (iii) interaction with the physical environment via sensors and actuators. This paradigm has several applications that range from industrial control systems [31] to small home-appliances [33].

To enhance the security guarantees of IoT networks, practitioners use Remote Attestation (RA) schemes that allow a trusted entity (i.e., Verifier) to validate the hardware and software integrity (i.e., verifies) of a remote one (i.e., Prover) without the need of manual inspection. The Verifier sends a challenge to the Prover and receives a measurement of its status as a report (e.g., an application fingerprint). The Verifier then compares the measurement with a database of proofs previously saved to check the correctness of the Prover status. This approach, often defined as single-Verifier RA, is well-established but assumes a Verifier with powerful capabilities and physically isolated from the network, thus protected against any threat (e.g., a remote server in a controlled area). The Prover, instead, might be any device inside the network and can be tampered by a potential attacker. These assumptions, however, are incompatible in a scenario of independent IoT networks in which the devices cannot rely on an external Verifier for the attestation process. Moreover, an IoT network is usually composed by devices that are equipped with different hardware and run different applications. A naive solution for removing a central Verifier might be to keep a copy of all the proofs inside each device. However, this is not practical due to the resource constraints imposed by IoT devices themselves. Moreover, a dynamic network is composed by devices which continuously leave and enter the network itself, thus introducing additional proofs-management challenges.
First solutions for autonomous networks were recently proposed with [2, 19, 22]. However, we found some limitations in these works. In [2], the authors rely on heuristics and consider only homogeneous devices, while in [19, 22], they do not fully address scalability and still suffer from single point-of-failure issues. We provide more details in Section 2.

In this paper, we propose SAFE\textsuperscript{d}, the first concrete RA schema for autonomous networks of heterogeneous embedded devices. SAFE\textsuperscript{d} introduces a new approach that enables any IoT device in a network to validate the integrity of another random device without the need for a central Verifier. To achieve this goal, we design new solutions that fit the IoT realm. The main concept regards the decentralization of the Verifier’s duties by making all the network active during the attestation process. The distributed nature of our solution increases the effort required for an attack.

To implement our strategy, we built SAFE\textsuperscript{d} upon a Distributed Hash Tables (DHT) [46] that allows us to manage data structures spread over several entities. For our proof-of-concept, we opted for Chord [36, 37, 45] as DHT implementation, however, SAFE\textsuperscript{d} is agnostic from the type of DHT protocol chosen. Chord protocol has not been thought to be resilient against compromised devices. Therefore, we developed new solutions to improve DHTs security guarantees and to overcome their limitations. First, we design a new key exchange protocol which is based on Diffie Hellman [35] and is integrated inside the Chord mechanisms. It allows to issue a secure communication between any pair of devices inside the network without having to store cryptographic keys or using additional exchanged messages. Second, we improve data resilience by using parallel DHT instances (called overlays) that replicate the proofs in different and random devices. This avoids an attacker to infer the proofs position inside the network. Our schema requires every device to be equipped with small trusted anchors [24], which contain and protect the algorithms required to SAFE\textsuperscript{d}.

We implemented SAFE\textsuperscript{d} in the open-source Raspberry Pi 3 platform. We chose this solution because its chip supports ARM TrustZone [43], which is a standard trusted anchor largely used in other works [15, 24, 25]. Moreover, we performed a large-scale experimentation by simulating networks of 10K virtual devices through Omnet++ [41]. To validate our approach, we conducted several attacks against both the platforms, encompassing software tampering, lost packets and corrupted devices. SAFE\textsuperscript{d} recovered up to 99.9% of lost proofs and showed a logarithmic communication overhead and memory footprint.

SAFE\textsuperscript{d} overcomes previous attestation solutions for network of IoT devices because its performances are not affected by the number of devices connected and it completely removes single point-of-failure by design. Furthermore, solid experimental results are proposed to support our claims. We believe that SAFE\textsuperscript{d} will help developing more resilient networks of IoT devices and secure DHTs.

To sum up, SAFE\textsuperscript{d} is a novel collaborative attestation for networks of heterogeneous IoT devices that introduces the following contributions:

- **Self-protection**: the network can identify and react against corrupted devices.
- **Resilient network**: SAFE\textsuperscript{d} can recover its proofs in case of lost data or attacks.
- **Scalability**: the protocol can manage a large number of devices with minimal footprint.

The open-source proof-of-concept implementation of SAFE\textsuperscript{d} for Raspberry Pi 3 will be available at the link \textsuperscript{1}.

2 RELATED WORK

2.1 Remote Attestation for IoT Networks

The first attestation proposal for autonomous network was introduced by Abera et al. with DIAT [2]. In this work, the authors assume a network of homogeneous devices (e.g., a swarm of drones), which validate their own status without using a central Verifier. However, they mainly focus on runtime RA (i.e., they validate runtime device status) by using heuristics. In addition, they require a network of homogeneous devices. On the contrary, SAFE\textsuperscript{d} is based on analytical results and it can handle networks of heterogeneous devices in an autonomous fashion.

PASTA [22] is the first work that tries to spread the burden of verification across the entire network. In PASTA, the Provers periodically collaborate to generate the so-called tokens. Every token attests the integrity of all the nodes that participated in its generation and contains a timestamp to allow absence detection of a particular node. Tokens are validated using an aggregated signature built on a Schnorr-based multisignature scheme. However, we found some limitation to their approach since they require that each device maintains all the private keys of its neighbors, thus limiting the scalability. On the contrary, SAFE\textsuperscript{d} enables any pair of devices to issue a trusted channel without any pre-shared information.

Another line of research attempts to measure the integrity of the network through a single challenge/response interaction [6, 8, 13]. The common trait of these works is the logical organization of the devices using a spanning tree topology. An external Verifier initiates the attestation process and collects a cumulative response from the entire network. On the contrary, SAFE\textsuperscript{d} faces a different scenario and does not require a central Verifier to perform an attestation.

Other works investigate cumulative RA schemes to detect physical attacks [19–21, 44]. The intuition behind these solutions is that an adversary needs to remove a device from the network to perpetrate an attack, thus causing a temporary disconnection. In particular, Ibrahim et al. proposed US-AID [19] which combines continuous in-network attestation and Proofs-of-non-Absence to detect both software tampering and device disconnections. However, they require a reliable read-only clock (RROC) to achieve physical attacks detection. Yan et al. improved the work of Ibrahim by introducing EAPA [44], which performs RA physical attack resilient in a faster manner. SAFE\textsuperscript{d}, instead, can detect physical attacks directly using communication timeouts by design.

To sum up, SAFE\textsuperscript{d} overcomes previous related RA schemes for mainly three reasons: (i) we fully remove any central trusted authority in the network, (ii) we efficiently spread the proofs among

\textsuperscript{1}We are willing to share the source code with the community upon acceptance or to provide it to the reviewers upon request via conference chairs.
the nodes, (iii) we do not rely on synchronized clocks for absence detection.

2.2 Distributed Hash Tables
In general, all DHTs have been designed to decentralize information (e.g., a file) and improve network performances and robustness. Furthermore, they are thought to be deployed in large networks, such as the Internet. However, these protocols do not consider security issues in their design. In the last years, researchers investigated security limitations of DHTs [17, 23, 32, 34]. These works aim at improving different aspects of DHT protocols, however, they differ from SAFE\textsuperscript{d} for different reasons:

- **Context**: they assume a large and dynamic network such as the Internet, while we focus on a more restricted physical area. Thus, we can rely on a better control over the devices that compose the network.
- **Attacker model**: they consider dishonest or churn nodes. On the contrary, SAFE\textsuperscript{d} assumes honest behavior guaranteed by trusted anchors.
- **Defense strategies**: they rely on statistical and cryptographic schema to improve trust in nodes [4]. However, their approaches simply increase the effort required to a potential attacker without resolving the problem by design.

We are the first to tackle DHT security issues in the context of attestation protocols, which is more concrete and practical w.r.t. previous works.

Another crucial aspect of DHTs regards the privacy of the data stored inside of it [29, 38]. SAFE\textsuperscript{d} enhances the privacy constraint by entirely encrypting the traffic and protecting sensitive memory locations inside every device.

To sum up, SAFE\textsuperscript{d} improves DHT security guarantees by exploiting trusted computing for specific scenarios (i.e., IoT). Also, we believe that our solutions can be adopted to mitigate similar threats in more general scenarios.

3 BACKGROUND

3.1 Remote Attestation
Remote Attestation (RA) schemes refer to those protocols that allow verifying the integrity of a remote entity. Usually, they involve two distinct roles: *Verifier* and *Prover*. The *Verifier* is considered trusted and is usually physically protected from attacks (e.g., a remote server). Its duty is to verify the integrity of a *Prover* that may be corrupted (e.g., due to a malware). RA schemes require a *Verifier* to start the protocol by sending a challenge to the *Prover*, which measures some properties of its state (e.g., compute a hash of a piece of software) and returns a report. The *Verifier* is now able to validate the *Prover* status according to the returned report by comparing its value with a database of correct measurements (called *proofs*).

The classic approaches involve static measurements, such as software fingerprint or hardware integrity [16]. More recently, researchers proposed a dynamic type of RA defined dynamic [1, 2, 40], which tries to attest run-time properties such as execution-paths. SAFE\textsuperscript{d} focuses on static RA. However, we discuss possible dynamic RA integration strategies in Section 8.

3.2 Trusted Anchor
Modern RA schemes require devices to mount specialized hardware called trusted anchors. These technologies allow to define protected memory regions and build Trusted Execution Environments (TEE). A TEE provides useful functionalities like cryptographic algorithms and secure random number generators. In this work, we opted for ARM TrustZone [43] as trusted anchor due to its flexibility and its wide spread. A device equipped with TEE organizes its memory in two main zones: *untrusted and trusted*, respectively known in ARM TrustZone jargon as *normal world* and *secure world*. The *normal world*, as the name suggests, contains the general purpose software needed for running a classic operating system. The *secure world*, instead, contains the code strictly necessary for establishing a trusted execution inside the *normal world*, i.e., the *secure world* checks the execution of the *normal world*.

SAFE\textsuperscript{d} implementation is placed inside the *secure world* to protect its algorithms and critical variables (e.g., cryptographic keys). These technologies stand as the base of modern RA schema in IoT devices and classic IT infrastructure.

3.3 Chord
Chord [36, 37] is a lookup protocol to establish a DHT and is specifically designed for large peer-to-peer networks. This protocol allows to distribute hash tables (i.e., key/value pairs) over multiple devices. It uses consistent hashing for arranging the nodes in a circle and for distributing the keys among them. Each element (e.g., nodes and keys) is identified by an *m*-bit number computed by a hash function.

Every piece of data is saved inside the first node whose identifier is greater than or equal to its identifier. As a consequence of this setting, a device will store all the piece of data whose ID is between its ID and that of the preceding device. Each node is linked to its predecessor and successor, thus establishing a ring. To improve resilience, a device also maintains a list of immediate successors, called *successors list*.

Having the devices and data organized in a ring makes possible to implement a look up function as follows: (i) a device *A* sends a request with the data ID to its successor *B*, (ii) if *B* contains the data (i.e., ID < B), it is returned to *A*, otherwise it forwards the request to its successor. The step is repeated till finding the ID.

The complexity of this solution is linear with the number of nodes placed inside the ring. To improve the performances, Chord introduces a *finger table* that contains additional routing information. The *finger table* has *m* entries called *fingers*: the i-th finger is a reference to the 2\(^{i-1}\) position ahead the current node. As a result, the *finger table* allows an average searching complexity of \(O(\log_2 N)\), making the look up operation scalable with respect to the number of nodes \(N\).

Chord also provides procedures for adding new nodes to the ring and maintaining the order in case of failures. We referred to [45] for the implementation of a simpler yet correct version based on three distinct operations:

- **Join**: an outside node contacts a member of the ring (defined as the *entry*) to know which is its successor. It then contacts its successor to update the successor list.
Figure 1: Network architecture (considering a single overlay).

- **Stabilize**: the node asks to its successor information about the predecessor. It adopts this predecessor as its new successor if it is actually closer than the current successor in the ring order. In both cases, the node sends a final notification to the successor. The successors list is updated with the information coming from the contacted nodes.

- **Rectify**: in case of a received notification, the node checks if its current predecessor is still alive and then adopts the notifying member as new predecessor if it is closer than the current predecessor or if it has no live predecessor.

A node executes the `join` procedure just when entering the network. `Stabilize` and `rectify` procedures are instead periodically triggered during the protocol routine.

`SAFE^d` builds on top of an enhanced version of Chord, in which a joining node can save its attestation data inside the network and the routine operations take care of re-distributing the information when new nodes join the ring. More importantly, `SAFE^d` introduces redundancy of data by running several Chord instances at the same time, thus dealing with the loss of information caused by failures or attacks.

4 ASSUMPTIONS AND THREAT MODEL

4.1 Device Architecture

The devices considered in `SAFE^d` are equipped with a trusted anchor (i.e., ARM TrustZone), which is considered secure. The secure world is physically isolated from the rest of the system and its duties are twofold: (i) inspect and measure the device memory and (ii) communicate with the other trusted anchors in the network. The trusted anchor is used as a secure storage for all the variables needed by `SAFE^d` and it is protected from an attacker by design. The normal world runs different applications and can be compromised.

4.2 Network Context

In this work, we assume networks of fully interconnected devices that range from few elements to 10K devices. Our main use case is for industry, however, we can deploy `SAFE^d` to any type of autonomous system networks. `SAFE^d` can handle highly dynamic networks where nodes continuously enter and exit them. However, we allow only known devices to join the network. This is reasonable since we consider geographically restricted networks (e.g., factories or smart-homes).

4.3 Threat Model

`SAFE^d` faces attacks that target both the device and the network.

**Device Attacks.** The goal of the attacker is to load unauthorized binaries or inject malicious code inside the normal world by using different strategies, e.g., exploiting security flaws. We consider the secure world isolated from the normal one and therefore out of the attacker range. We also consider compromised devices that hide their presence in the network and physical attacks.

**Network Attacks.** An attacker can manipulate network traffic by following classic Dolev-Yao model [14]. Thus she can eavesdrop, insert, modify, delete messages, perform a replay attack, or forge attestation messages.

In general, we do not consider denial-of-service (DoS), however, we evaluate the resilience of `SAFE^d` in case of unavailable devices. These assumptions are coherent with previous works [2, 6, 8, 13, 19, 22].

5 `SAFE^d`

`SAFE^d` is an extension of a DHT that includes new mechanisms for dealing with the adversary described in Section 4.3.

In our schema, the devices are logically organized into two parallel networks (Figure 1). The first one is the normal network (dashed line), used by ordinary applications to communicate with other devices. The second one is `SAFE^d-net` (solid-line arrows), built on top of the normal network and used by the trusted anchors to perform the schema routines.

`SAFE^d-net` is composed by a fixed number of overlays which is defined at network creation time. Each overlay is an independent Chord instance (Section 3.3) that contains all the devices as well as a copy for each proof. The purpose of the overlays is twofold: (i) the number of overlays identifies the redundancy (i.e., X independent proof copies requires X overlays) and (ii) they helps keeping the proofs distribution balanced.

The location of objects inside `SAFE^d-net` is managed through two types of ID:
We can explain the usage of these IDs by means of an example. Assume \( \text{SAFE}^{d} \) has two overlays. We assign three IDs to a device \( D \), namely \( D_{\text{OID}_1}, D_{\text{OID}_2}, \) and \( D_{\text{UID}} \). The first two (i.e., \( D_{\text{OID}_1} \) and \( D_{\text{OID}_2} \)) identify the position of \( D \) inside the two overlays respectively. The last one (i.e., \( D_{\text{UID}} \)) identifies the position of its proof in each overlay. The OIDs are computed online when the device enters the network. In Section 5.5, we describe the OID creation process that makes them random and applicable as public keys in a secure communication protocol. The UID, instead, is computed offline and is used as the key for retrieving the proof from the various overlays during an attestation process. We indicate UID and proof as a key/value pair (UID, proof). As a result, even if the UID is predictable, an external attacker cannot foresee which device contains the proof linked with it.

### 5.1 Protocol Overview

In \( \text{SAFE}^{d} \), we strengthen the Chord protocol to achieve the following properties. First, we desire that only authorized devices join the network. Second, we need to spread multiple copies of the proofs among the overlays. The entire protocol is represented as a finite-state-machine in Figure 2, where the shapes (i.e., circle and squares) represent a device status, while the arrows represent the transaction from a status to the next one. More precisely, the new status introduced by \( \text{SAFE}^{d} \) are depicted as squares, while the new phases are labeled with bold underlined text. In the following subsections, we describe the additions in detail:

- **Device-setting** defines the initial device configuration.
- **Device-unknown and Certification** allow only recognized devices to join the network (Section 5.2).
- **Non-member and Proofs update** are used to enhance availability of data in our dynamic context (Section 5.3).
- **Attestation** is used to monitor the integrity of other devices inside the network (Section 5.4).

As a whole, the protocol of \( \text{SAFE}^{d} \) is composed by two distinct phases: Offline and Online.

During the Offline phase, we boot the devices and set the following parameters inside the trusted anchor:

- The pair (UID, proof), which will be saved inside the network and later used for attestation/verification.
- A public/private key pair which are signed by a certification authority (CA).
- The CA certificate for the key pair.

During the Online phase, a device in **Device-unknown status** connects to the network and starts the procedure to access \( \text{SAFE}^{d} \)-net. We introduced this phase because Chord does not handle authentication by default. After the Certification is done, a device enters the **Device-certified** status and it can join each overlay asynchronously. A device that does not pass the Certification cannot physically communicate with other devices because it does not receive any OIDs from the entry point. The following procedure is repeated for every overlay. During the join phase, a device finds its successor around the ring by following standard Chord algorithms. It then sends its pair (UID, proof) to be stored. After this task is completed, the device assumes a **Non-member** status, which means that: (i) the device is aware of its position around the ring, (ii) it has inserted its own proof inside the overlay and (iii) it has not received yet the proofs it has to store. At this point, the device performs its first stabilize operation, making its successor aware of its presence inside the overlay. This triggers the Proofs update, which consists in the successor sending a copy of the proofs that should be stored inside the new device. A node maintains **Non-member** status until it is completely integrated inside the ring, i.e., the preceding and following devices becomes aware of it. When this is the case, it has become officially part of the overlay and it can switch to the **Member** status. This allows the device to perform the **Rectify** operation as described in the original Chord protocol and permits to the successor to safely delete the proofs previously copied. It is fundamental to maintain different **Member** status for each overlay because the Attestation process involves all the overlays. Therefore, we require a device to become **Member** in all of them before being able to execute it, thus reaching **Member-and-Running** status.

### 5.2 Certification Phase

We desire that only authorized devices join \( \text{SAFE}^{d} \)-net network because this ensures an honest execution of the \( \text{SAFE}^{d} \)-net procedures (i.e., due to trusted anchor isolation). More precisely, an entry point \( N \) can recognize the identity of a device \( U \), which is in

![Figure 2: SAFE\(^d\) finite-state-machine. Addition of states and phases w.r.t. Chord are respectively shown with squares and bold underlined text.](image-url)
Device-unknown status, by using a public key infrastructure (PKI), as described in Figure 3. All the devices are initialized during the Offline phase and receive a private key (e.g., \( N_{PRV} \)) and the corresponding certificate (e.g., \( N_{CERT} \)), signed by a certification authority (CA). The procedure uses a generic asymmetric encryption scheme denoted as \( E \).

The protocol starts with \( U \) that generates a nonce \( r \) and sends it along with its certificate (i.e., \( U_{CERT} || r \)) to \( N \). After \( N \) correctly verifies the signature of \( U_{CERT} \), it encrypts all of its OIDs and the nonce \( r \) (i.e., \( \{N_{OID} || r\} \)) by first using the public key of \( U \) (i.e., \( U_{PUB} \)) and then its private key (i.e., \( N_{PRV} \)). Finally, \( N \) sends them back to \( U \) along with its certificate (i.e., \( N_{CERT} \)). At this point, \( U \) performs the following operations: (i) verifies the certificate of \( N \) (i.e., \( N_{CERT} \)) using the CA public key, (ii) verifies the public key of \( N \) using the certificate and removes first encryption with it, (iii) extracts the OIDs of \( N \) (i.e., \( \{N_{OID}\} \)) and nonce (i.e., \( r' \)) using its own private key, (iv) checks the nonce \( r \) and \( r' \) to avoid replay attacks, (v) generates its own OIDs (i.e., \( \{U_{OID}\} \)), and (vi) sets its status to Device-certified.

The double encryption guarantees two properties: (i) the public key of \( U \) ensures that only \( U \) can decrypt the message and, (ii) the private key of \( N \) ensures that the message has been sent by \( N \).

From this point ahead, \( U \) can communicate with the entry point by using the encryption schema described in Section 5.5. More precisely, \( U \) joins the overlays as described in Chord. A device that does not pass the Certification phase cannot receive the OIDs of the entry point and, therefore, cannot communicate with the other devices. To protect from the leakage of the private key during physical attacks, it is fundamental to implement a certificate revocation procedure. We discuss possible solutions in Section 8.

5.3 Multiple Device Entrance

SAFE\textsuperscript{4} maintains all the proofs available and consistent in all the overlays in case of groups of devices that attempt joining the network simultaneously. To achieve this, we introduce the Non-member status and the Proof update task.

Figure 4 shows the main four steps of Proof update, that begins when a new device \( C \) enters in an overlay. The rectangle before the node letter is a representation of the proofs stored inside of it. In step 1, we assume having two devices \( A \) and \( B \) correctly distributed around the overlay (i.e., \( A_{OID} < B_{OID} \)). In step 2, \( C \) has just joined and it has found its position between \( A \) and \( B \) (i.e., \( A_{OID} < C_{OID} < B_{OID} \)). In this step, \( C \) is in Non-member status and it can only perform stabilize. This allows us to handle the entrance of multiple devices simultaneously and will be described later. In step 3, \( B \) copies into \( C \) the relative proofs while keeping a temporary copy in \( B \) itself. Keeping a copy of the proofs into \( B \) enables the other devices to find the \( C \) proofs even though \( C \) has not entered the ring yet. In step 4, \( A \) performs rectify and inserts \( C \) as its successor. \( C \) is formally part of the overlay and consequently can shift to Member status, while \( B \) can delete its leftover proofs. After step 4, \( C \) starts performing rectify. When \( C \) becomes Member in all the overlays, it reaches Member-and-running status and starts performing/receiving attestations.

This approach allows us to handle group of devices that enter simultaneously. For instance, a new device \( D \) may attempt entering while \( C \) is a Non-member. Here, we distinguish two cases: (i) \( D \) is located between \( A \) and \( C \) (i.e., \( A_{OID} < D_{OID} < C_{OID} \)) and sets \( C \) as successor; (ii) \( D \) is located between \( B \) and \( C \) (i.e., \( C_{OID} < D_{OID} < B_{OID} \)) and sets \( B \) as successor. In both cases, \( D \) is kept as Non-member until its successor becomes Member as well.

The difference is just in the order in which the devices become Member. In case (i), \( D \) receives Member status from \( C \), therefore, the entrance order is \( C \), then \( D \). In case (ii), \( D \) receives Member status from \( B \), while \( C \) changes its successor to \( D \) after doing a stabilize to \( B \). Generally, Member status is assigned only by otherMember (or Member-and-running) devices, which are considered stable. We keep rectify disabled while a device is Non-member to avoid the formation of chains of devices that would cause some of them to have outdated list of proofs.

5.4 Attestation Protocol

SAFE\textsuperscript{4} attestation process is an extension of classic RA (Section 3.1). The main differences are essentially two: (i) all the devices can assume the role of either Prover or Verifier, and (ii) the proofs are spread among all devices. The entire attestation process is implemented in a dedicated phase, which is executed whenever a device

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**Figure 3:** Certification phase between an unknown device \( U \) and the entry point \( N \).

**Figure 4:** Main steps of a new device that enters the overlay. The device remains Non-member until its neighbours in the overlay become aware of it, i.e., it becomes Member of the overlay.
inside the network needs to verify the integrity of another device before starting a communication.

The attestation is composed by the following steps:

- **Verifier initialization**: when the attestation is triggered, the device enters in **Verifier mode**.
- **Attestation request**: the Verifier challenges the Prover.
- **Retrieve report**: the Prover measures itself and returns a report defined as (UID, HASH) to the Verifier. The UID is used to retrieve the proofs from the overlays, while the HASH is the current self-measure of the Prover, which can be corrupted.
- **Retrieve proofs**: the Verifier queries all the overlays to retrieve the proofs using the received UID. The proofs will be used to check the report validity.
- **Voting**: we use a First Past The Post (FTPT) voting schema [3] to decide the healthy status of the Prover. In case of compromised status, the Verifier reacts in a proper way (see Attack Reaction below).
- **Recovery**: in case of missing proofs, the Verifier uses the retrieved data to recover the information where it has been lost. In case no overlay returned the proof, the Verifier launches a warning of possible infection for that particular device.

Finally, the device exits from the Verifier mode.

**Voting**. FTPT is a plurality voting system thatelects the most voted choice as the winner. During the voting phase, the Verifier considers the proofs collected from the various overlays as a preference vote, i.e., which state each overlay thinks is the correct one. At first, the Verifier evaluates all the missing proofs as blank votes and it does not consider them in the counting. Then, the Verifier chooses the correct proof by picking the one that was returned the highest number of times. The elected proof is then used to verify the report sent by the Prover. The devices whose vote disagreed with the elected proof are considered infected as well.

Despite its simplicity, FTPT shows in our case resilience against manipulation. An attacker cannot foresee the location of the proofs in the network. As a result, the voting is robust till at least 50% devices are healthy. Due to the design of SAFE4, we can implement new type of voting schema [28].

**Attack Reaction**. The actual attack reaction strategy strictly depends by the network pursue. In our prototype, we isolate the corrupted devices. In other scenarios, for instance, we can implement an hard-reset of the device. This can be useful for malware such as Mirai [7]. It is also possible to save the attestation results in the overlays for future manual inspections.

### 5.5 Secure Device Communication

SAFE4 allows two devices to issue a secure communication channel by introducing a novel protocol that allows to share a symmetric key **K** with zero-message exchanged. Our approach overcomes the scalability limitations of previous ones [19, 22] that either requires a device to store every key needed for the communication or to execute a key exchange protocol to establish a secure channel. The protocol is based on Diffie Hellman [35] and exploits Chord properties. The main idea is that each OID represents the public key of a device that joined an overlay. In Section 5.2, we discuss our mechanism to allow only authorized devices to enter the network.

In our protocol, we assume that all the devices share two secure prime number **g** and **N**. During the join phase, a device randomly computes an OID as follows:

\[
X = \text{rand}() \pmod{N},
\]

\[
\text{OID} = (g^X) \pmod{N}.
\]

At first, a device randomly computes a number **X** (modulo **N**), which is kept secret within the trusted anchor. Then, it generates the OID by computing the exponentiation of **X** over **g** (modulo **N**). These two operations are repeated for each overlay. For the sake of simplicity, we continue the description considering a single overlay, however, it is possible to easily extend the approach to any number of overlays. We indicate the pair **X**, **OID** for a device **D** as follows:

\[
(D_X, D_{\text{OID}}).
\]

Two devices, namely **A** and **B**, that know the respective OIDs can compute a shared symmetric key **K_{AB}** as follows:

\[
K_{AB} = (\text{OID}_B)X_A = (g^{AX_B})X_A
\]

\[
K_{AB} = (g^{BX_A})X_A = (\text{OID}_A)^{AX_B} \pmod{N}.
\]

The key **K_{AB}** can now be used in a symmetric encryption schema **E**.

The design of Chord assures that each device knows the OIDs of its successors (e.g., finger list and successor list). Therefore, if **B** is a device following **A**, **B** cannot compute **K_{AB}** because it does not have knowledge of **AOID**. To overcome this problem, we need to send **AOID** to **B** avoiding unauthorized entities to read the OID. We achieve this by encrypting **AOID** such that only authorized devices can read it. The whole message structure is shown in the following:

\[
E_{\text{BOID}}[\text{SOID}] | | AOID | | E_{K_{AB}}[M] | | O,
\]

which comprises three parts:

- \(E_{\text{BOID}}[\text{SOID}] | | AOID\) is the header and is encrypted by using a symmetric encryption schema **E** and **BOID** as a key. This allows only the devices that are already participating the overlay (i.e., **B**) to read the content. The header contains two OIDs, called source and sender. The first identifies the device which originally sent the message (i.e., **SOID**), while the second identifies the device which is currently forwarding the message to **B** (i.e., **AOID**). Keeping the source OID permits a fast reply; this will be described later through an example.
- \(E_{K_{AB}}[M]\) is the message body. It contains the message **M** to deliver and is encrypted with the symmetric schema **E** and **K_{AB}** as a key.
- **O** indicates the overlay to which the message is meant to and is sent as plain text.

This structure enables **B** to decrypt an incoming message as follow:

- reads **O** and identify from which overlay is coming.
- uses its corresponding OID (i.e., **BOID**) to decrypt the header and to retrieve the sender OID (e.g., **AOID**).
- computes **K_{AB}** and decrypts **M**.

---

4Since the key space of **E** is generally smaller than the size of **BOID**, we use a hash function **H** to adjust the size, i.e., \(E_{H(BOID)}[\cdot]\)
A packet structured in such way has three interesting properties: (i) besides the overlay $O$, no information is shipped as a plain text, thus only devices inside SAFE$^d$-net (also called Member) can read the headers (see Section 5.2); (ii) only the intended recipient can successfully decrypt the message, thus any attempt to manipulate or reroute the message will generate an error; (iii) a symmetric schema is less expensive than an asymmetric one, thus more suitable for low-power devices.

Figure 5 shows a complete example of two devices that communicate. In this case, a device $A$ wants to send a message $M$ to device $C$, but $C$ is not directly reachable by $A$. Therefore, $A$ must pass through the ring. At the beginning, $A$ only knows the OID of $B$, because it is its successor. Therefore, $A$ asks $B$ to deliver $M$ to $C$ by creating packet (1) as follows:

$$E_{B_{OID}}(A_{OID}|A_{OID}) || E_{K_{AB}}(M) || O.$$

In this packet, source OID coincides with $A_{OID}$. $B$ decrypts the header with its OID, calculates $k_{AB}$ using the sender OID and obtains the message $M$. Since $B$ knows $C$, $B$ relays the message crafted as follows:

$$E_{C_{OID}}(A_{OID}|B_{OID}) || E_{K_{BC}}(M) || O.$$

$C$ follows similar steps to retrieve message $M$ and serves the request. At this point, $C$ replies to $A$ by using the source OID (i.e., $A_{OID}$) and crafting message (3) as follows:

$$E_{A_{OID}}(A_{OID}|C_{OID}) || E_{K_{AC}}(M) || O.$$

Finally, $A$ receives the response from $C$.

This approach brings three advantages: (i) we avoid spoofing attacks because the sender is automatically verified (unless the attacker steals its secret $X$), (ii) we can build a symmetric key without using extra messages, and (iii) a compromised device cannot choose its OIDs arbitrarily unless it resolves the discrete logarithm problem. We also mitigate reply attacks by using nonces [47].

Figure 6 shows the execution pipeline.

Figure 6: Execution pipeline.

6 IMPLEMENTATION

SAFE$^d$ workflow is composed by a number of independent steps, which are depicted in Figure 6. In the beginning, SAFE$^d$ waits for an incoming packet from the server socket (step 1). Once a packet arrives, it is sent into the trusted application (step 2). At this point, the packet is decrypted (step 3) and processed (step 4). After the response is created, it is encrypted (step 5) and written into the untrusted application along with the destination IP (step 6), which must be in plain text for correct routing. Finally, the packet is shipped by the client socket (step 7). The packets are built in such a way that the untrusted application knows only the destination IP, while the content is always encrypted as described in Section 5.5.

An attacker that alters the plain-text IP would simply lead to a crashed or lost message because the only device capable of decrypting it is the intended recipient (see Section 5.5). Moreover, blocking the message would cause the original sender to raise a warning for a timeout in its communications, thus exposing the attack.

Our prototype requires around 46KLoC for the untrusted application and around 49KLoC for the trusted application. We used AES-CBC [39] for symmetric encryption with keys 32B long, while we used RSA [10] for the asymmetric keys in the certification phase, with 1218B for the private key and 294B for the public one.

**Measurement Generation**. In our proof-of-concept, SAFE$^d$ protects the integrity of critical pieces of software inside the normal world by using a shared memory. However, it is possible to extend SAFE$^d$ to measure other device properties, such as hardware configuration. The location to protect is identified at the boot phase. For the sake of simplicity, our proof-of-concept can monitor memory regions that reside in the same process of SAFE$^d$. It is still possible to extend SAFE$^d$ to read arbitrary physical addresses and protect the integrity of different parts of the system [42].

**Omnet++ simulation**. We performed a large scale performance analysis using Omnet++ [27, 41] as support. We implemented our protocol at the application level and used time delays to simulate cryptographic operations and propagation time. Based on the

\[^3\]We used the commit f5172a5a993f64f4be0ebb3a6e88af8f0 of the official repository for the OP-TEE OS and server respectively.

\[^4\]We could have implemented a socket in the secure world as well, however, not all trusted anchor platforms support this feature so we opted for a more flexible solution.
Raspberry Pi’s measurements, we set a delay of 10 ms for the decryption/encryption of the messages. Moreover, we set the communication rate at 250 Kbps based on the defined data-rate of Zigbee, a widely used communication protocol for networks of IoT devices.

7 EVALUATION
In this section, we evaluate different metrics of SAFE\textsuperscript{d} by using two network settings:

- **Raspberry Pi**: we mounted a small network of Raspberry Pi 3 composed by 4 devices. This setting was used to test the efficacy of SAFE\textsuperscript{d} on real devices and to collect realistic parameters for the simulation.
- **Omnet++**: we used Omnet++ to simulate a network of IoT devices that contained up to 10K entities and with different number of overlays (from 1 to 3). We used this setting to evaluate the performances of SAFE\textsuperscript{d} in the presence of thousands of devices and with a different number of overlays.

7.1 Network Analysis
We measure the size of the message used by SAFE\textsuperscript{d}, the elaboration time, and the time elapsed to perform a complete attestation.

**Messages Size.** SAFE\textsuperscript{d} requires two types of message:

- **Certification messages**: they are used only during the certification phase (Section 5.2) and require 256 × o bytes, where o is the number of overlays (e.g., 1KB for 4 overlays). These messages are more expensive in terms of size but they are only used in the initial part.
- **Routine messages**: the other messages exchanged in our prototype have a fixed size of 384 bytes plus 68 × s bytes, where s is the successor list size (e.g., 520B with 2 successors). They compose the vast majority of the network communication. Furthermore, s is a fixed parameter of the network, thus the message size remains constant throughout the execution.

**Message Time Elapsed.** We measure the time required to process a single message in a Raspberry Pi. We did not consider the Certification messages phase because they are used only during the initial part of the protocol. As a result, any message required an average 9.1ms (with a standard deviation of 6.3) to be processed without using cryptography, while around the double, 18ms (with a standard deviation of 9.2), using the cryptography described in Section 5.5. As already observed in [19, 22], cryptography is the predominant part during the protocol execution.

**Attestation Performances.** Figure 7a shows the average time elapsed to perform a complete attestation (y-axis) over the number of devices present inside the network (x-axis). A complete attestation involves sending the challenge, collecting the report and querying all the overlays to retrieve the proofs. The graph shows a logarithmic growth with the number of devices, while the number of overlay does not affect the overall performances because the packets are processed by each device independently. Considering 10K devices and 3 overlays, an entire attestation process requires around one second to be completed.

7.2 Memory Footprint
Each device uses 64, 1218, 294 and 256 bytes respectively for the UID, the private RSA key, the public RSA key and the certificate. For each overlay, it uses 32 bytes for the secret, 68 bytes for its own OID and its predecessor OID, 68 bytes for each entry in the successor list, 68 bytes for the entries in the finger list and 128 bytes for each element inside the proof storage. The overall memory usage M, expressed in bytes, can be computed as follows:

\[
M = 1832 + [168 + 68 \times s + 68 \times f + 128 \times p] \times o,
\]

where s is the size of the successor list, f is the size of the finger table, p is the number of proofs and o the number of overlays. Variables s and o are parameters that remain constant during the protocol execution. In the following paragraphs, we show that the finger list size f has an upper bound of \(\log(n)\), with n the total number of devices inside the network, while the number of proofs p is small w.r.t. the network size.

**Finger Table Size.** Figure 7b shows the maximum number of entries in a finger table (y-axis) against the number of device in the network (x-axis). The graph shows a logarithmic growth with the number of devices and a linear pattern with the number of overlays. This is due to the design of the finger table and of SAFE\textsuperscript{d}. This table, in fact, is used by Chord to optimize packets routing (see Section 3.3) and contains at most a logarithmic number of entries with respect to the network size. Moreover, each node maintains a separate table for every overlay. The overall memory cost is then logarithmic in the number of devices and linear in the number of overlays.

**Proofs Distribution.** Figure 7d shows an empirical analysis of the proofs distribution in a simulated network with 10K devices and using different overlays (from 1 to 3). On average, each device should contain a number of proofs equal to the number of overlays. However, since the distribution is random, some device may contain more proofs than others. The number of overlays helps improve the proofs distribution. In fact, with 3 overlays the curve tends to be smoother. In the worst scenario, we measured only less than 5 devices that contained 25 proofs in a network with 10K elements and 3 overlays. In case of 3 overlays, a network contains 30K proofs, 3 for each device. Our approach allows to build a collaborative attestation by solely requiring a device to contain 25 proofs at most, which makes SAFE\textsuperscript{d} scalable.

To sum up, the number of proofs p that a device stores is bounded and can be forced to reach the ideal value (i.e., 1 proofs for each overlay). Considering the overall memory consumption, SAFE\textsuperscript{d} is a clear improvement with respect to previous works that are either an order of magnitude more expensive [22] or have a quadratic dependence on unpredictable parameters [19].

7.3 Resilience
The purpose of this experiment is to measure the ability of SAFE\textsuperscript{d} to recover missing proofs in case of attacks or faults. In this scenario, we modeled a powerful attacker that randomly destroys all the proofs of a device. In a real case, this simulates an adversary that physically destroys a device, interrupts the normal world scheduling, or simply a fault in the network. This attack is tuned by a drop rate
which indicates the number of devices that drops all their proofs on every simulation cycle. We experimented a drop rate of 20% with a simulation cycle of 10 seconds, which means that on average 20% of the entire network erased all of its proofs every 10 seconds. We tested a different number of overlays to observe the different responses. Figure 7c shows the results of our experiments in a simulated network that contains up to 10K devices and different number of overlays (from 1 to 3). The y-axis shows the resilience index, which is the ratio between the number of proofs correctly recovered and the number of lost proofs. The x-axis, instead, shows the number of devices in the network. According to the attestation algorithm (Section 5.4), in case of lost proofs, the Verifier attempts to recover the missing information from the other overlays. Therefore, the resilience index tends to 1 if all the proofs were correctly recovered, otherwise it goes to 0. The plot shows that with the increases of the overlays, the resilience index tends to reach 1 even in the presence of an high drop rate. More precisely, we manage to recover 99.9% of the proofs with 3 overlays. This experiment shows that the overlays can be effectively used to recover the network in the presence of attacks.

7.4 Security Consideration

We describe how SAFE\textsuperscript{d} reacts against different attacker scenarios.

**Tampered Devices.** An attacker may infect a device and take control of it. Since we use a trusted anchor, we consider the secure world as protected, while the normal world can be under attacker control. Therefore, SAFE\textsuperscript{d} protocol is protected by design. Moreover, all the packets that transit through the normal world are encrypted, thus outside the attacker range. However, an attacker may avoid invoking trusted anchor code compromising normal world scheduler. In this case, if the trusted world is not triggered, the Chord protocol cannot work properly, and the neighbour devices can realize the attack.

To test SAFE\textsuperscript{d} effectiveness, we verified that the other devices are able to spot the modified code inside the normal world.

**Attacks against the Network.** All the messages exchanged among trusted anchors are encrypted (Section 5.5) and only devices that joined the network can communicate among each other (Section 5.2). Man-in-the-middle [9] attacks are mitigated by design: (i) the body is protected by the symmetric key $K_{AB}$, (ii) the header can be manipulated only by the trusted anchors of authorized devices. We also include nonces to avoid replay attacks. This enhances
robustness even in case of corrupted devices as long as their trusted anchor remains intact.

**Physical attacks.** According to DARPA attacker model [20], a device which receives a physical attack is temporarily removed from the network. Previous authors [20–22] proposed to use a heartbeat to keep the devices synchronized. In this way, a device that goes temporarily off-line cannot get aligned with the heartbeat, and therefore, enables the detection of the attack. However, establishing a heartbeat protocol implies the presence of loosely synchronized and secure clocks in every device. SAFE\textsuperscript{d} overcomes this requirement by using the communication timeouts and nonces to detect network disconnections. During the protocol execution, each device periodically contacts its successor to assess its status. In case a timeout occurs, the device uses the successor list to contact the closest node following the old one. The contacted device will further check if its predecessor left the network, and if so, it will acquire the message sender as new predecessor, while launching an alert for a possible physical attack. The double check adds robustness against simple network malfunctions. To enhance the protection against physical attacks, we further propose a certificate revocation strategy that will be discussed in Section 8.

**Denial-of-Service.** We do not protect against denial-of-service in case of a network entirely compromised (e.g., all the messages are dropped). However, we can partially recover information loss by combining multiple overlays and our attestation protocol (Section 7.3).

8 DISCUSSION

**Certificate Revocation.** SAFE\textsuperscript{d} security properties can be further improved by adopting an efficient certificate revocation mechanism. This feature can be useful in at least three scenarios: (i) if the CA private key gets compromised (e.g., leaked), (ii) if a software is updated and (iii) if a device is corrupted. The design of a scalable and efficient certificate revocation procedure was already addressed by [18, 30] that proposed solutions based on Bloom filters [11]. Furthermore, [5] proposed a way to make a Bloom filter scalable, i.e., to make its capacity adaptable at runtime so that it can be increased without stopping the general execution. It is possible to implement in SAFE\textsuperscript{d} a certificate revocation protocol that is scalable and distributed based on the previous citations.

**Run-time Attacks.** An attacker could alter the application behavior without modifying the binary by using run-time attacks [12]. A way to cope with those threats is using run-time remote attestation [1, 40] that can verify run-time properties, e.g., the current execution path. Usually, these solutions require several proofs to be stored. We can use the DHTs in SAFE\textsuperscript{d} to spread the proof load among devices. We leave this as a future work.

**Run-time Software Upgrade.** In specific cases (e.g., industrial IoT), we need to upgrade devices software without interrupting the network. In SAFE\textsuperscript{d}, we do not deal with this case, but it is possible to mitigate this issue by using two main approaches: (i) we could introduce new upgraded devices in the network and remove the old ones until all the network is upgraded, (ii) we integrate specific upgrade protocols in SAFE\textsuperscript{d} that load new software and substitute the proofs in the DHTs. Regardless the strategy adopted, the software upgrade strategy should be integrated with a strong certificate revocation mechanisms to avoid an attacker to re-upload old and vulnerable software.

9 CONCLUSION

In this work, we proposed SAFE\textsuperscript{d}, the first concrete self-attestation schema for networks of heterogeneous embedded devices. SAFE\textsuperscript{d} maintains multiple copies of the proofs among the devices, which are equipped with small trusted anchors. We also designed and developed new techniques that enhance classic DHT protocols against powerful adversaries, which are typical of remote attestation scenarios.

SAFE\textsuperscript{d} allows performing remote attestations without the need of an external Verifier, and consequently removing a single point of failure. SAFE\textsuperscript{d} coordinates multiple devices to self-protect the network and also to self-recover missing or corrupted proofs in presence of attackers and faults.

We implemented a prototype of SAFE\textsuperscript{d} in the open-source platform Raspberry Pi 3, this allows us to show the technical challenges faced for the implementation of SAFE\textsuperscript{d} in the ARM TrustZone architecture. Moreover, we stressed SAFE\textsuperscript{d} performances by simulating a network of 10K devices. As a result, we showed that SAFE\textsuperscript{d} requires a logarithmic amount of memory and a logarithmic time to perform a complete attestation. Moreover, SAFE\textsuperscript{d} can recover up to 99.9% of proofs in case of attack or faults by using only three overlays.

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