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Cubedate: Securing Software Updates in Orbit for Low-Power Payloads Hosted on CubeSats

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Abstract—CubeSat design is facilitated by the increasing availability of open-source software in the domain, and a variety of low-cost hardware blueprints based on commodity microcontrollers. We attain the rock-bottom price to reach orbit as entities that design, launch and operate CubeSats started selling to multiple tenants tiny rack slots (typically 0,25U each) for low-power payloads that may be hosted on their CubeSat. The question arises of how to provide state-of-the-art security for software updates on a multi-tenant CubeSat, whereby mutual trust between tenants is limited. In this paper, we provide a case-study: ThingSat, a low-power payload we designed, is currently hosted on a CubeSat orbiting at 500km altitude operated by a separate entity. We then design Cubedate, a framework for securing continuous deployment of software to be updated on orbiting multi-tenant CubeSats. We also provide a highly portable open-source implementation of Cubedate, based on the IoT operating system RIOT, which we evaluate experimentally.

I. INTRODUCTION

Driven in part by the increasing involvement from public research and the academic community [1], more and more open source software and hardware is available, maturing and used on CubeSats.

Their availability has lowered the bar of entry, with the aim of designing low-cost CubeSats which can more reliably achieve a successful launch – until recently, the failure rate was still around 60% for first-time satellite builders [2].

With the same objective, another trend has been to buy tiny “rack-space” in orbit [3]. With this model, a stakeholder (a user) can place a small (<1U) payload slot hosted inside a CubeSat provided by an operator (a different stakeholder). The user only needs to design and operate this payload, instead of designing and operating the whole CubeSat, drastically reducing users’ costs and lead time. Typically, such a payload boils down to a printed circuit board (PCB) with sensors, a low-power CPU (sometimes with separate wireless communication capabilities) and a bus communication interface to the CubeSat main on-board flight computer (OBC). As such, a hosted payload on a CubeSat resembles small embedded devices usually found in the Internet of Things (IoT).

Nevertheless, even if the entry bar is lowered through the combination of a hosted payload and leveraging open source, software embarked on launched CubeSats tend to be minimalist (think: space rush, time pressure to meet hard launch deadlines...) and buggy, as most software is. In effect, hosted CubeSat payload software must typically be updated over-the-air (OTA) regularly, after it is deployed in orbit and

in operation. Beyond enabling OTA software updates on a hosted CubeSat payload, cybersecurity is a crucial emerging aspect. Indeed, on the one hand, software updates can be used to fix vulnerabilities but, on the other hand, tampering with software updates can be used as a cyberattack vector [4].

State-of-the-art has so far focused on single-stakeholder CubeSats use cases, where embarked software is managed by a single entity. In this paper, we instead focus on the challenge of securing software updates on low-cost multi-tenant CubeSats whereby the OBC and the payload are operated by different stakeholders which do not necessarily trust each other. In particular, we focus on payloads based on low-power microcontrollers, which are essential on low-cost CubeSats, where low power consumption is a key factor.

II. RELATED WORK

Open source hardware and software is increasingly used on low-cost CubeSats, including microcontroller parts. For instance pyCubed [2] proposes open source CubeSat hardware based on an Arm Cortex-M4 (atsamd51) microcontroller and matching Python (CircuitPython) based open source software. OreSat [5] designs microcontrollers based CubeSats, and provides the corresponding open source software. Organizations such as the Libre Space Foundation [6] harbor a number of open source software code basis for CubeSats, such as UPSat, Qubik.

Once the CubeSat is in orbit, during its lifetime, the embarked software will typically need updating. Some work such as [7] have focused on the reliability of the ground-flight link for firmware updates. Other work have focused on mitigating radiation effects corrupting firmware storage and on error correction, such as [8] or partly in [9]. A vanilla approach to securing low-cost CubeSat software updates, such as described in [10], uses weak security primitives (e.g., MD5 integrity checks) instead of strong primitives such as authentication with digital signatures and encryption. However, recent cyberattacks such as the ViaSat outage in Ukraine [11] suggest that CubeSat systems are more likely to become cyberattack targets. A crucial related challenge is thus **how to provide strong security for in orbit software updates**. Prior work such as NUTS [12] have focused on authentication and communication security over the ground-flight uplink.

However, to the best of our knowledge, no prior work exists on providing strong security for software updates on a low-

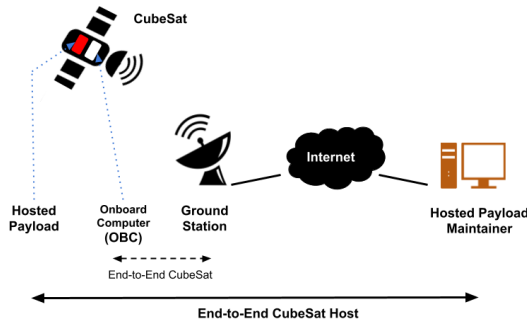


Fig. 1. CubeSat hosted payload software update security end-to-end.

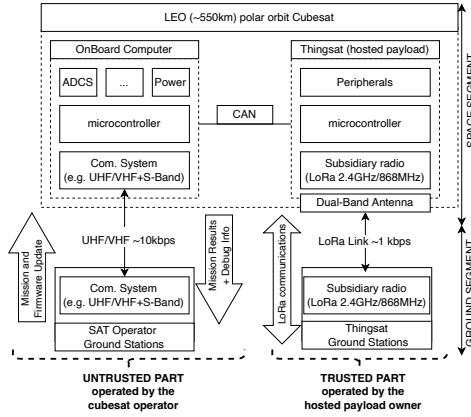


Fig. 2. ThingSat hosted payload: deployed components and architecture.

power CubeSat *payload*, via a satellite uplink and an OBC that are *both potentially untrusted*. This hosted CubeSat use-case is depicted in Figure 1.

The main contributions of this paper are the following

- We provide a case-study, ThingSat: a low-power, low-cost payload hosted on a CubeSat, currently in-orbit;
- We analyze its software update requirements and constraints;
- We define Cubedate, a generic architecture enabling standards-based, secure software updates for payloads hosted on a low-power CubeSat;
- We provide and evaluate an open source implementation of Cubedate.

III. CASE STUDY: THINGSAT

The ThingSat project [13] aims to benchmark ground-space LoRa links on different frequency bands and demonstrate the effectiveness of that technology inside a LEO (Low Earth Orbit) CubeSat.

ThingSat is deployed as a hosted payload on a shared 3U CubeSat: STORK-1 from the polish start-up SatRevolution. The CubeSat was launched on January 13th, 2022, currently in orbit at an altitude of 525km (see its Two-Line Elements).

A. Distributed System Architecture

Figure 2 describes the ThingSat deployment components. It gives an overview of a typical CubeSat ecosystem, whereby the interaction with this payload traverses untrusted elements.

Low-power Space Segment: The Space Segment comprises the on-board computer (OBC) and hosted payloads, whom, interconnected via a Controller Area Network (CAN) bus, which share resources on the CubeSat.

- The **OBC** provided by the satellite operator consists of a microcontroller with all its subsystems to operate the CubeSat: Attitude Determination and Control System (ADCS), communication subsystems (UHF/VHF/S-band for uplink/downlink and antennas) and power subsystem (Battery Management, Energy Harvesting with Solar Panels, Auxiliary Power Supply).
- The **ThingSat payload** we designed uses a STM32F405RG microcontroller featuring an ARM Cortex-M4 core and open source firmware based on RIOT [14]. It embeds both a SX1302 transceiver for communications on the 868MHz band and a SX1280 transceiver for communications on the 2.4GHz band. Furthermore we designed a corresponding dual-band patch antenna. When active and using the 868MHz band, the ThingSat payload consumes at 3.3V: (i) 90mA in standby, (ii) 110mA during a frame reception (RX) and (iii) 300mA during a frame transmission (TX) at the 27dBm maximum power. By operating in the mWatt range, our payload achieves low-power consumption what could not have been achieved with a raspberry pi or without the de-facto low-power LoRa technology.

Ground Segments: Ground Segment elements that communicate with the ThingSat payload are:

- **SatRevolution Ground Stations:** provided by the CubeSat operator ¹ to communicate via UHF/VHF with the OBC, and indirectly with the payload. This can be done directly through a Command & Control Center, which acts as a broker between payload maintainers and hosted payload (indirect access).
- **ThingSat LoRa Ground Stations:** that we designed, deployed and maintain, which can communicate via LoRa **directly** with the ThingSat payload. These stations are based on an ESP32 microcontroller, and a 2.4GHz SX1280-LoRa transceiver, also running an open source firmware based on RIOT.

B. Communication Characteristics Overview

ThingSat payload communicates either directly via low-power WAN (LPWAN), or indirectly via the UHF/VHF link provided by the CubeSat's OBC.

Direct communication patterns via LPWAN: ThingSat can communicate directly with LoRa. In principle, although it is not used as such so far, this communication link could also be used to transport software updates. The ThingSat payload may act as either: (i) a Sat-IoT end-device (ED) that will send

¹not necessarily owned by the CubeSat operator

LoRa frames to terrestrial LoRaWAN gateways or ThingSat ground stations (GS), or (ii) an in-orbit LoRa sniffer, or (iii) a store-carry-and-forward LoRa gateway.

Patterns (i) and (ii) allow to benchmark simple ground-space LoRa links by computing statistics over multiple sent/received frames. Pattern (iii) is a more complex scenario: the satellite stores packets received from ED (Steps 1-2 on Figure 3), carries them (Step 3) and delivers them once LoRa GS destinations are inside the footprint of the satellite (Step 4).

Indirect communication characteristics via UHF/VHF: CubeSat-GS communications are typically done on amateur frequency bands (UHF/VHF) with typically low data rates ranging from 9.6Kbps to 100Kbps. A polar LEO satellite will typically pass over a given ground station 2 to 4 times/day, each pass having a communication window of 5 to 10 minutes.

For ThingSat, the CubeSat Operator provides only 2 ground stations (both in Europe) communicating with the CubeSat via a 10-Kbps UHF/VHF link. Thus, the daily throughput is roughly 1500KB (corresponding to 2GS x 2 passes/day x 5-min pass duration x 10Kbps). However, this throughput must be shared between communications to/from the OBC (for telecommand/telemetry/update) and to/from hosted payloads. Therefore in practice, the total communication budget available for ThingSat via the UHF/VHF link is around 300KB/day.

Intermittent communication/power supply: Last but not least, the ThingSat payload is not constantly powered on. Typically, at any point in time, only one single hosted payload is powered on. For a 3U, 1U is dedicated to the OBC and the remaining 2U is available for hosted payloads (8 payloads slots of 0.25U in the case of ThingSat). Therefore, on average ThingSat is powered only 1/8th (12.5%) of the time (modulo other factors such as mission specificities, regulations, battery level etc.).

C. Hosted Payload Software Updates Requirements

Data exchanges between the Payload Maintainer and ThingSat (Step 5 on Figure 3) consist of **downlinks**: used by ThingSat to send mission results (radio metadata, frame stats, collected LoRa frames) and diagnosis data (debug info on failed missions/updates) and **uplinks**: used for software updates of two categories :

- 1) Firmware updates: to fix bugs, add/improve functionality (typically ~200KB per FW, 1 FW/month);
- 2) Mission updates: to configure scenarios (typically ~700B per mission scenario, 1 scenario/day);

IV. CUBEDATE: STANDARD SECURITY FOR CONTINUOUS DEPLOYMENT OF LOW-POWER CUBESAT SOFTWARE

In this section we describe Cubedate, a structured approach to securing heterogeneous software updates for in-orbit CubeSat software.

A. Security Requirements

The minimal security guarantees that we aim for with Cubedate are authenticity and integrity of software updates delivered over the network, during the lifetime of the satellite

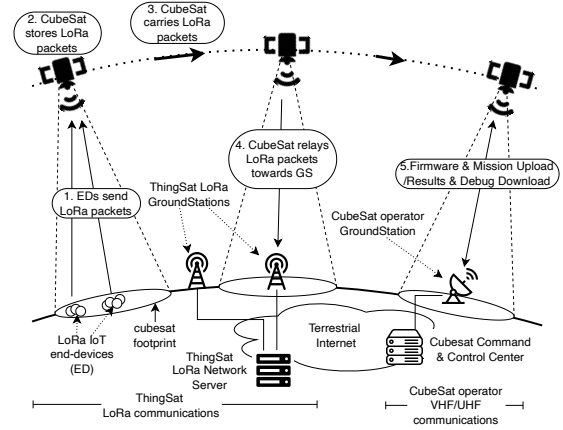


Fig. 3. ThingSat in-orbit communication patterns.

mission (5-10 years). Cubedate must allow for crypto agility, i.e. update the crypto primitives used to secure update to the satellite while in operation. This need can be dictated either by cryptography's evolving state-of-the-art (implementation/algorithm vulnerabilities are discovered) or by the need to transfer the trust anchor to a new entity (the authorized maintainer has changed). Additional guarantees beyond authenticity/integrity should also be possible with Cubedate, such as confidentiality, software update replay attacks, or software update mismatch attacks.

B. Trust Anchor

Our model is based on a single trust anchor: the secret key from the single authorized maintainer for the CubeSat hosted payload. There is no mitigation if this trust anchor used is compromised. We thus rely on the maintainers' ability to keep their private keys secure. Extensions using a (hierarchical) public key infrastructure are possible but out of scope for this paper.

C. Cubedate Software Life-Cycle Phases

The basic process we use for securing authenticity and integrity of software updates is decomposed in six phases shown Figure 4. During a preliminary, pre-flight phase (*Phase 0*) the authorized maintainer for the CubeSat-hosted payload produces and flashes the payload with commissioning material: a bootloader, the initial firmware, and authorized crypto material (a public key, and a cryptographic hash function). Once the hosted payload is commissioned it can be sent to the CubeSat operator of installation in the CubeSat.

Once the CubeSat is in orbit, the hosted payload maintainer can trigger iterations through cycles of Phases 1-5, whereby the authorized maintainer can build a new software update (*Phase 1*), hash the update and sign the hash (*Phase 2*) then push a network transfer (PUT) towards the hosted payload via the ground station and the OBC (*Phase 3.1*). The next time it wakes up, the hosted payload can then ping and fetch (GET) the update from the OBC (*Phase 3.2*), proceed to verify the signature and the hash (*Phase 4*), and upon successful

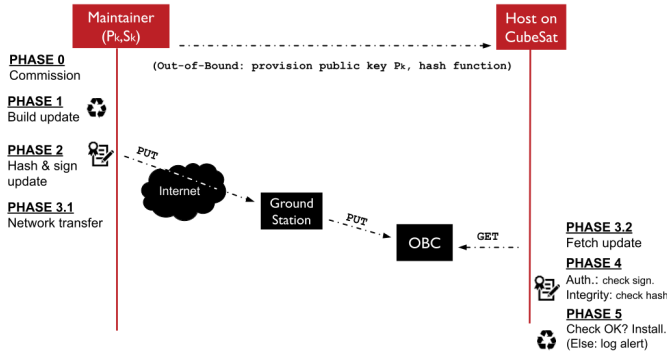


Fig. 4. CubeSat hosted payload secure software update process.

verification, install/boot the new software (*Phase 5*), otherwise the update is dropped.

D. Supporting Network Transport Heterogeneity

This aspect concerns *Phase 3.1* and *Phase 3.2* in Figure 4. Security guarantees on software updates must remain valid "end-to-end". Depending on the use-case, "end-to-end" spans differently, as depicted for example in Figure 1. In the most complex case we tackle in this paper, end-to-end means all the way from the hosted payload software maintainer to the payload hosted in orbit on the CubeSat. Software updates may be transported over one or more network links of varying nature:

- **Developer to Groundstation:** Internet;
- **Groundstation to CubeSat:** UHF/VHF, LoRa...
- **Intra-CubeSat:** CAN, I2C, RS-232...

Intermittent power supply, combined with orbiting and radio range limitations impacts the intermittence of network connectivity to/from the hosted payload: establishing a delay-tolerant path and in-network data caching might be required. To cope with this wide variety of network paths and links (including ultra-constrained low-power elements), different approaches can be envisioned at the network layer, the transport layer and the application layer. Approaches span from proprietary solutions to standards such as the low-power IPv6 protocol stack (6LoWPAN, UDP, CoAP [15]) or experimental stacks such as information-centric networking which benefits from in-network caching even with small caches on microcontrollers [16].

Nevertheless, in order to retain generality, Cubedate does not specify any particular approach at the network, transport and application layers to enable the delivery of software updates across the network. Cubedate only aims to guarantee end-to-end security properties for the software update binaries that are delivered, somehow, over the network.

E. Supporting Updated Software Heterogeneity

This aspect concerns both *Phase 1* and *Phase 5* in Figure 4. As seen in subsection III-C, software updates may be of various nature and size. Cubedate aims to support the same mechanism, workflow and guarantee to update the CubeSat (1)

firmware updates, (2) mission scenario files and (3) runtime configuration files.

For this reason, we choose not to rely on specialized approaches such as DFU (Device Firmware Update [17]) which assumes that the software is firmware and that the device is connected directly via some local bus connection (e.g. USB).

Instead, we aim to combine the use of generic and standard metadata characterizing software updates and state-of-the-art cryptographic primitives applicable on most low-power microcontrollers and a large variety of low-power networks, as described below.

F. Low-power End-to-End Security using SUIIT

Cubedate leverages the SUIIT manifest [18] which specifies a metadata format to describe software updates. This format uses Concise Binary Object Representation (CBOR) for data serialization, and a security wrapper which protects the metadata end-to-end, leveraging the CBOR Object Signing and Encryption (COSE) specification - all of which are IETF open standards for low-power communication security [19].

The Cubedate software update binary itself can be either encapsulated in the SUIIT manifest, or transferred separately based on the URI provided in the manifest. For instance, the metadata includes a sequence number (preventing unwanted rollbacks), the expected device type (preventing software mismatch), the SHA256 digest of the software update binary and of the manifest, and the ed25519 digital signature of the manifest (the metadata). As such, using Cubedate, software updates for payload hosted on CubeSats mitigate attacks including:

- **Tampered Software Update Attacks** – An attacker may try to update the IoT device with a modified and intentionally flawed software image. To counter this threat, Cubedate uses digital signatures on a hash of the image binary and the metadata to ensure integrity of both the firmware and its metadata.
- **Unauthorized Software Update Attacks** – An unauthorized party may attempt to update the IoT device with modified image. Using digital signatures and public key cryptography, Cubedate ensures that only the authorized maintainer (holding the authorized private key) will be able to update the device.

G. Supporting Crypto Agility

The first level of crypto agility enabled by Cubedate uses flexibility provided by the SUIIT standard specification: while keeping the same metadata and workflow, diverse crypto primitives backends can be used. For instance, to upgrade from pre- to post-quantum security, digital signature performed with ed25519 (elliptic curve crypto), can be swapped for hash-based signatures (LMS [20]).

The second level of crypto agility enabled by Cubedate leverages a dedicated embedded runtime architecture: on the one hand, we place the software update manager (implementing SUIIT-related operations) in the firmware image itself.

On the other hand, we perform cryptographic operations in software only.

Thus, changing the trust anchor stored is as simple as swapping a public key in the next firmware's update manager. Authorization to update the firmware can thus be easily delegated to another maintainer, who can take over the production and the roll out of authorized updates. Furthermore, the update manager in the next firmware image could implement and use upgraded cryptographic primitives.

H. Guarantees beyond Authenticity/Integrity

Cubedate may also guarantee confidentiality by encrypting (optional) software updates transmitted over the network. It is performed using the encrypt/decrypt mechanism provided by the SUIE specifications [21], using a symmetric cryptographic key commissioned in the update manager by the authorized maintainer. Confidentiality can mitigate additional cyberattacks leveraging analysis of CubeSat firmware/software binaries.

Going beyond authenticity, integrity and confidentiality guarantees for software updates delivered over the network, using Cubedate also mitigates other attacks including:

- **Software Update Replay Attacks** – An attacker may try to replay a valid, but old (known-to-be-flawed) software. This threat is mitigated by using a sequence number. Cubedate uses a sequence number, which is increased with every new software update.
- **Software Update Mismatch Attacks** – An attacker may try replaying a software update that is authentic, but for an incompatible device. Cubedate includes device-specific conditions, which can be verified before installing a software binary, thereby preventing the device from attempting to use an incompatible software image.

V. CUBEDATE IMPLEMENTATION

We implemented Cubedate by extending the open source ecosystem around RIOT, which we combined with our initial firmware running on the ThingSat payload, also open sourced, which we published and maintain online [22].

Communication Bus: To provide a simple socket-like API on top of the raw CAN bus connecting hosted payloads and OBC on the CubeSat, we used libCSP, a library implementing the CubeSat Space Protocol (CSP version 1), which we integrated into RIOT. This stack is deployed on satellites such as Nuts[12], GomSpace and used by SatRevolution. Roughly, CSP provides an 'equivalent' of the IP/UDP stack and static routing.

SUIE Implementation: To fully support the wide variety of software updates case required by Cubedate, we extended existing RIOT implementation of SUIE [23] which, initially, supported only firmware updates, internal storage, and WPAN network delivery. We generalized the SUIE state machine to add support for:

- **Heterogeneous update delivery mechanisms:** configurable {message model, network stack, network interface} bundle, or FileSystem *read/write* functions.

- **Heterogeneous storage destination:** configurable internal/external memory: Volatile (e.g. RAM for mission files, or for tiny runtime execution containers such as FemtoContainers [24]) or non-volatile (e.g. FileSystem or internal Flash).
- **Heterogeneous update data URI:** either a local file (e.g.: mounted USB device) or a remotely accessible file (eg CoAP or HTTP endpoint);

Network Pull Implementations: The client/server interaction is initiated by the hosted payload which pulls (GET) the software update data over the network from either the OBC, or a groundstation. The pull mechanism we implemented uses CoAP [25] an open standard low-power IPv6 protocol following a general-purpose REST architecture. In particular, it is not only applicable over the CAN/CSP link, but also usable over VHF links [26] or LoRa links [27], which paves the way for some Cubedate software updates over the direct link from a ThingSat LoRa groundstation to the ThingSat payload.

VI. CUBEDATE EVALUATION AND DISCUSSION

In the following, code measurements were generated compiling with ARM GCC 10.2.1, optimized for code size. As code base, we used RIOT release 2022.01 and SUIE configured with ed25519 digital signatures provided by the C25519 crypto library (which has a small footprint as shown in prior work [23]).

1) **Memory Footprint Overhead:** To evaluate the RAM and Flash footprint of our Cubedate implementation, we apply it to the ThingSat use-case, compiled for the hosted payload hardware described in subsection III-A.

In Table I we compare the RAM and Flash memory requirements for a ThingSat firmware with/without Cubedate-compliant updates. We observe that Cubedate requires a memory budget of ~4KB of RAM and ~19KB of Flash, which represents roughly a 10% increase in the total RAM and Flash memory budget for ThingSat.

TABLE I
CUBEDATE IMPLEMENTATION: MEMORY FOOTPRINT IN BYTES.

	ThingSat		ThingSat+Cubedate	
	RAM	Flash	RAM	Flash
CAN	10774	8762	10774	8762
Crypto	633	7386	64	13760
CoAP	1024	2192	1024	1632
CSP	8541	11771	8541	12653
SUIE	0	0	3200	7425
LoRa GW	22300	45688	22300	45688
Firmware	7008	108881	8225	114088
Total	50280	184680	54128	204008

TABLE II
CUBEDATE IMPLEMENTATION: SUIE METADATA SIZE.

Seq.Num.	Digests	IDs	URI	Auth.	Other	Total
4B	64B	32B	64B	64B	86B	314B

2) *Network Transfer Overhead*: On the UHF/VHF link at 1kb/s, the additional network transfer time induced by the Cubedate firmware size overhead (19KB) is roughly 15 seconds. This overhead is reasonable, but non-negligible considering that a connection to the CubeSat is segmented in time windows of ~ 300 seconds.

Next, in Table II we look in more details at the metadata (SUIT manifest) used to secure Cubedate software updates for ThingSat. As we can see, the metadata including all CBOR/COSE formatting, digests (SHA256 hashes) and authentication data (ed25519 signature) amounts to ~ 330 B. The metadata overhead thus incurs negligible overhead (+0,15%) in case of a ThingSat firmware update (of size 200KB on average, recall subsection III-C). However, for smaller software update such as updating a mission scenario (average size 700B) the metadata overhead is significant (almost +50%). Nevertheless, on the UHF/VHF link at 1kb/s, this overhead remains negligible in terms of additional network transfer time.

VII. DISCUSSION & PERSPECTIVES

1) *Portability*: Bolted on top of RIOT, our Cubedate implementation works out-of-the-box (or is trivially portable) on a very wide variety of low-power hardware built on Cortex-M microcontrollers: the bulk of the 200+ boards supported by RIOT. However, additional work would be needed to support other hardware based on different 32-bit microcontroller architectures (e.g. RISC-V).

2) *Network Stack Simplification & Standardization*: The use of CSP was mandated by the CubeSat operator. The purpose of CSP was to provide an ultra-low footprint equivalent of the IP protocol stack for CubeSats with legacy (8-bit) microcontrollers. However, on modern (32-bit) microcontrollers such as those used in ThingSat, this approach is can be discussed. More widely spread standard alternatives to CSP seems possible for a similar "price". For example, RIOT's default low-power IPv6 (6LoWPAN) stack used with static routing has a footprint in RAM/Flash memory that is comparable to libCSP memory footprint. The 6LoWPAN stack could run directly on the CAN bus or on LoRa (see 6LoCAN [28] and SCHC [29]).

3) *Alternative cryptographic primitives*: In our experimental evaluation, we used ed25519 (elliptic curve cryptography) digital signature providing 128-bit pre-quantum security. One can consider either alternative primitives, while remaining compliant with Cubedate and the SUIT standard. One compromise to significantly decrease network transfer and memory footprint with Cubedate is to use HMAC (symmetric crypto) instead of digital signatures for authentication. Another option would be to upgrade security to 128-bit post-quantum security by using hash-based signature instead of ed25519.

VIII. CONCLUSION

As the space race intensifies, rises the need for state-of-the-art security to protect software updates on multi-tenant cubesat in orbit. In this paper, we provided a corresponding case-study: ThingSat, a low-power payload we designed, hosted

on a cubesat operated by a separate entity, currently orbiting. We then designed and implemented Cubedate, a framework achieving strong security guarantees and low overhead, for continuous deployment of software over the air on multi-tenant cubesat. The open source implementation of Cubedate we provided and evaluated for ThingSat was built to be reusable on a wide variety of low-power cubesat hardware.

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