ANCHOR: logically-centralized security for Software-Defined Networks *

This is a subtitle†

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Software-defined networking (SDN) decouples the control and data planes of traditional networks, logically centralizing the functional properties of the network in the SDN controller. While this centralization brought advantages such as a faster pace of innovation, it also disrupted some of the natural defenses of traditional architectures against different threats. The literature on SDN has mostly been concerned with the functional side, despite some specific works concerning non-functional properties like 'security' or 'dependability'. Though addressing the latter in an ad-hoc, piecemeal way, may work, it will most likely lead to efficiency and effectiveness problems.

We claim that the enforcement of non-functional properties as a pillar of SDN robustness calls for a systemic approach. We further advocate, for its materialization, the re-iteration of the successful formula behind SDN – 'logical centralization'. As a general concept, we propose ANCHOR, a subsystem architecture that promotes the logical centralization of non-functional properties. To show the effectiveness of the concept, we focus on 'security' in this paper: we identify the current security gaps in SDNs and we populate the architecture middleware with the appropriate security mechanisms, in a global and consistent manner. ANCHOR sets to provide essential security mechanisms such as strong entropy, resilient pseudo-random generators, secure device registration and association, among other crucial services.

We claim and justify in the paper that centralizing such mechanisms is key for their effectiveness, by allowing us to: define and enforce global policies for those properties; reduce the complexity of controllers and forwarding devices; ensure higher levels of robustness for critical services; foster interoperability of the non-functional property enforcement mechanisms; and finally, better foster the resilience of the architecture itself. We discuss design and implementation aspects, and we prove and evaluate our algorithms and mechanisms.

CCS Concepts: • **Security and privacy** → **Systems security**; • **Networks** → **Network security**;

Additional Key Words and Phrases: Software-defined networking, SDN, non-functional properties, control plane, security, perfect forward secrecy, post-compromise security, post-compromise recovery, post-quantum secure

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1 INTRODUCTION

Software-defined networking (SDN) has moved the control function out of the forwarding devices, leading to a logical centralization of functional properties. This decoupling between control and data plane leads to higher flexibility and programmability of network control, enabling fast innovation. Network applications are now deployed on a software-based logically centralized controller, providing the agility of software evolution rather than hardware one. Moreover, as the forwarding devices are now directly controlled by a centralized entity, it is straightforward to provide a global network view to network applications. In spite of all these benefits, this decoupling, associated with a common southbound API (e.g., OpenFlow), has removed an important natural protection of traditional networks. Namely, the heterogeneity of different solutions, the diversity of configuration protocols and operations, among others. For instance, an attack on traditional forwarding devices would need to compromise different protocol interfaces. Hence, from a security perspective, SDN introduces new attack vectors and radically changes the threat surface [Dacier et al. 2017; Kreutz et al. 2013; Scott-Hayward et al. 2016].

So far, the SDN literature has been mostly concerned with functional properties, such as improved routing and traffic engineering [Alvizu et al. 2017; Jain et al. 2013]. However, gaps in the enforcement of non-functional properties are critical to the deployment of SDN, especially at infrastructure/enterprise scale. For instance: insecure control plane associations or communications, network information disclosure, spoofing attacks, and hijacking of devices, can easily compromise the network operation; performance crises can escalate to globally affect QoS; unavailability and lack or reliability of controllers, forwarding devices, or clock synchronization parameters, can considerably degrade network operation [Akhunzada et al. 2015; Kloti et al. 2013; Scott-Hayward et al. 2016].

Addressing these problems in an ad-hoc, piecemeal way, may work, but will inevitably lead to efficiency and effectiveness problems. Although several specific works concerning non-functional properties have recently seen the light e.g., in dependability [Berde et al. 2014; Botelho et al. 2016; Katta et al. 2015; Kreutz et al. 2015; Ros and Ruiz 2014] or security [Porras et al. 2012; Scott-Hayward et al. 2016; Shin et al. 2013, 2014], enforcement of non-functional properties as a pillar of SDN robustness calls, in our opinion, for a systemic approach. As such, in this paper we claim for a re-iteration of the successful formula behind SDN – 'logical centralization' – for its materialization.

In fact, the problematic scenarios exemplified above can be best avoided by the logical centralization of the system-wide enforcement of non-functional properties, increasing the chances that the whole architecture inherits them in a more balanced and coherent way. The steps to achieve such goal are to: (a) select the crucial properties to enforce (dependability, security, quality-of-service, etc.); (b) identify the current gaps that stand in the way of achieving such properties in SDNs; (c) design a logically-centralized subsystem architecture and middleware, with hooks to the main SDN architectural components, in a way that they can

inherit the desired properties; (d) populate the middleware with the appropriate mechanisms and protocols to enforce the desired properties/predicates, across controllers and devices, in a global and consistent manner.

Generically speaking, it is worth emphasizing that centralization has been proposed as a means to address different problems of current networks. For instance, the use of centralized cryptography schemes and centralized sources of trust to authenticate and authorize known entities has been pointed out as a solution for improving the security of Ethernet networks [Kiravuo et al. 2013]. Similarly, recent research has suggested network security as a service as a means to provide the required security of enterprise networks [Scott-Hayward et al. 2016]. However, centralization has its drawbacks, so let us explain why centralization of non-functional property enforcement brings important gains to software-defined networking. We claim, and justify ahead in the paper, that it allows to define and enforce global policies for those properties, reduce the complexity of networking devices, ensure higher levels of robustness for critical services, foster interoperability of the non-functional enforcement mechanisms, and better promote the resilience of the architecture itself.

The reader will note that this design philosophy concerns non-functional properties in abstract. To prove our point, in this paper, we have chosen *security* as our use case and identified at least four gaps that stand in the way of achieving the former in current SDN systems: (i) security-performance gap; (ii) complexity-robustness gap; (iii) global security policies gap; and (iv) resilient roots-of-trust gap. The security-performance gap comes from the frequent conflict between mechanisms enforcing those two properties. The complexity-robustness gap represents the conflict between the current complexity of security and crypto implementations, and the negative impact this has on robustness and hence correctness. The lack of global security policies leads to ad-hoc and discretionary solutions creating weak spots in architectures. The lack of a resilient root-of-trust burdens controllers and devices with trust enforcement mechanisms that are ad-hoc, have limited reach and are often sub-optimal. We further elaborate in the paper on the reasons behind these gaps, their negative effects in SDN architectures, and how they can possibly be mitigated through a logically-centralized security enforcement architecture.

To achieve our goals, we propose ANCHOR, a subsystem architecture that does not modify the essence of the current SDN architecture with its payload controllers and devices, but rather stands aside, 'anchors' (logically-centralizes) crucial functionality and properties, and 'hooks' to the latter components, in order to secure the desired properties. In this particular case study, the architecture middleware is populated with specific functionality whose main aim is to ensure the 'security' of control plane associations and of communication amongst controllers and devices.

In addition, in this paper we give first steps in addressing a long-standing problem, the fact that a single root-of trust — like ANCHOR, but also like any other standard trusted-third-party, like e.g., CAs in X.509 PKI or the KDC in Kerberos — is a *single point failure* (SPoF). There is nothing wrong with SPoFs, as long as they do not fail often, and/or the consequences of failure can be mitigated, which is unfortunately not the common case. As such, we start by carefully promoting reliability in the design of ANCHOR, endowing it with robust functions in the different modules, in order to reduce the probability of failure/compromise. Moreover, the proposed architecture only requires symmetric key cryptography. This not only ensures a very high performance, but also makes the system secure against attacks by a quantum computer. Thus, the system is also *post-quantum secure* [Bernstein 2009]. Second, we mitigate the consequences of successful attacks, by protecting past, pre-compromise communication, and ensuring the quasi-automatic recovery of

ANCHOR after detection, even in the face of total control by an adversary, achieving respectively, *perfect forward secrecy (PFS)* and *post-compromise security (PCS)*. Third, our architecture promotes resilience, or the continued prevention of failure/compromise by automatic means such as fault and intrusion tolerance. Though out of the scope of this paper, this avenue is part of our plans for future work, and the door is open by our design, since it definitely plugs the SPoF problem, as is well known from the literature, which we debate in Section 7.

To summarize, the key contributions of our work include the following:

(1) The concept of logical centralization of SDN non-functional properties provision.
(2) The blueprint of an architectural framework based on middleware composed of a central 'anchor', and local 'hooks' in controllers and devices, hosting whatever functionality needed to enforce these properties.
(3) A gap analysis concerning barriers in the achievement of non-functional properties in the security domain, as a proof-of-concept case study.
(4) Definition, design and implementation of the mechanisms and algorithms to populate the middleware in order to fill those gaps, and achieve a logically-centralized security architecture that is reliable and highly efficient, post-quantum secure, and provides perfect forward secrecy and post-compromise security.
(5) Evaluation of the architecture.

We show that, compared to the state-of-the-art in SDN security, our solution preserves at least the same security functionality, but achieves higher levels of implementation robustness, by vulnerability reduction, while providing high performance. Whilst we try to prove our point with security, our contribution is generic enough to inspire further research concerning other non-functional properties (such as dependability or quality-of-service). It is also worth emphasizing that the architectural concept that we propose in this paper would require a greater effort to be deployed in traditional networks, due to the heterogeneity of the infrastructure and its vertical integration. This will be made clear throughout the paper.

We have structured the paper as follows. Section 2 gives the rationale and presents the generic logically-centralized architecture for the system-wide enforcement of non-functional properties, and explains its benefits and limitations. In Section 3, we discuss the challenges and requirements brought by the current gaps in security-related non-functional properties. Section 4 describes the logically-centralized security architecture that we propose, along with its mechanisms and algorithms. Then, in Sections 5 and 6, we discuss design and implementation aspects of the architecture, and present evaluation results. In Sections 7 and 8, we give a brief overview of related work, discuss some challenges and justify some design options of our architecture. Finally, in Section 9, we conclude.

2 THE ANCHOR ARCHITECTURE

In this section we introduce ANCHOR, a general architecture for logically-centralized enforcement of non-functional properties, such as 'security', 'dependability', or 'quality-of-service' (Figure 1). The logical centralization of the provision of non-functional properties allows us to: (1) define and enforce global policies for those properties; (2) reduce the complexity of controllers and forwarding devices; (3) ensure higher levels of robustness for critical services; (4) foster interoperability of the non-functional property enforcement

mechanisms; and finally (5) better promote the resilience of the architecture itself. Let us explain the rationale for these claims.

Define and enforce global policies for non-functional properties. One can enforce non-functional properties through piece-wise, partial policies. But it is easier and less error-prone, as attested by SDN architectures with respect to the functional properties, to enforce e.g., security or dependability policies, from a central trust point, in a globally consistent way. Especially when one considers changing policies during system lifetime.

Reduce the complexity of controllers and forwarding devices. One of the most powerful ideas of SDN was exactly to simplify the construction of devices, by stripping them of functionality, centralized on controllers. We are extending the scope of the concept, by relieving both controllers and devices from ad-hoc and redundant implementations of sophisticated mechanisms that are bound to have a critical impact on the whole network.

Ensure higher levels of robustness for critical services. Enforcing non-functional properties like dependability or security has a critical scope, as it potentially affects the entire network. Unfortunately, the robustness of devices and controllers is still a concern, as they are becoming rather complex, which leads to several critical vulnerabilities, as amply exemplified in [Scott-Hayward et al. 2016]. For these reasons, a single device or controller may become a single point of failure for the network. A centralized concept as we advocate might considerably improve on the situation, exactly because the enforcement of non-functional properties would be achieved through a specialized susbsystem, minimally interfering with the SDN payload architecture. A dedicated implementation, carefully designed and verified, would be re-usable, not re-implemented, by the payload components.

Foster interoperability of the non-functional property enforcement mechanisms. Different controllers require different configurations today, and a potential lack of interoperability in terms of non-functional properties arises. Global policies and mechanisms for non-functional property enforcement would also mean an easy path to foster controller and device interoperability (e.g., East and Westbound APIs) in what concerns the former. This way, mechanisms can be modified or added, and have a global repercussion, without the challenge of having to implement such services in each component.

Better promote the resilience of the architecture itself. Having a specialized subsystem architecture already helps for a start, since for example, its operation is not affected by latency and throughput fluctuations of the (payload) control platforms themselves. However, the considerable advantage of both the decoupling and the centralization, is that it becomes straightforward to design in security and dependability measures for the architecture itself, such as advanced techniques and mechanisms to tolerate faults and intrusions (and in essence overcome the main disadvantage of centralization, the potential single-point-of-failure risk).

The general outline of our reference architecture is depicted in Figure 1. The "logically-centralized" perspective of non-functional property enforcement is materialized through a subsystem architecture relying on a centralized anchor of trust, a specific middleware whose main aim is to ensure that certain properties – for example, the security of control plane associations and of communication amongst controllers and devices – are met throughout the architecture.

ANCHOR stands aside the payload SDN architecture, with its payload controllers and devices, not modifying but rather adding to it. It 'anchors' crucial functionality and properties, and 'hooks' to the former components,

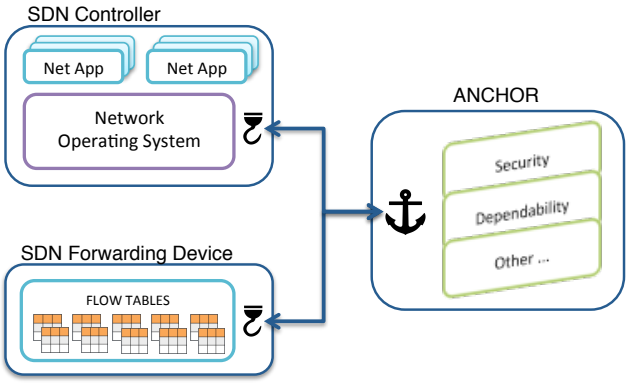

Fig. 1. ANCHOR general architecture

in order to secure the desired properties. So, on the devices, we just need the local counterparts to the ANCHOR middleware mechanisms and protocols, or HOOKs, to interpret and follow the ANCHOR's instructions.

After having made the case for logically-centralized non-functional property enforcement in software-defined networking, and presenting the outline of our general architecture, in the next two sections we introduce the use case we elected to show in this paper, i.e., *logically-centralized security*. We start with a gap analysis that establishes the requirements for the architecture functionality in Section 3, and then, in Section 4, we show how to populate ANCHOR with the necessary mechanisms and protocols to meet those requirements.

3 CHALLENGES AND REQUIREMENTS FOR SECURITY

To elaborate on our 'security' case study, in this section we discuss, with more detail, the challenges brought in by the previously mentioned gaps — (i) security-performance; (ii) complexity-robustness; (iii) global security policies; and (iv) resilient roots-of-trust — as well as the requirements they put on a logically-centralized approach to enforcing security, as a non-functional system property.

3.1 Security *vs* performance

The security-performance gap comes from the conflict between ensuring high performance and using secure primitives. This gap affects directly the control plane communication, which is the crucial link between controllers and forwarding devices, allowing remote configuration of the data plane at runtime. Control channels need to provide high performance (high throughput and low latency) while keeping the communication secure.

The latency experienced by control plane communication is particularly critical for SDN operation. The increased latency is a problem *per se*, in terms of reduced responsiveness, but may also limit control plane scalability, which can be particularly problematic in large datacenters [Benson et al. 2010a]. Most of the existing commercial switches already have low control plane performance on TCP (e.g., a few hundred flows/s [Kreutz et al. 2015], see Section V.A.). Adding crypto worsens the problem: previous works have demonstrated that the use of cryptographic primitives has a perceivable impact on the latency of sensitive

communication, such as VoIP [Shen et al. 2012] (e.g., TLS incurs in 166% of additional CPU cycles compared to TCP), network operations protocols such as SNMP [Schonwalder and Marinov 2011], NTP [Dowling et al. 2016], OpenFlow-enabled networks [Kreutz et al. 2017a,b], and HTTPS connections [Naylor et al. 2014]. Perhaps not surprisingly, the number of SDN controllers and switching hardware supporting TLS (the protocol recommended by ONF to address security of control plane communication [ONF 2014, 2015]) is still reduced [Abdullaziz et al. 2016; Scott-Hayward et al. 2016]. Recent research has indeed suggested that one of the reasons for the slow adoption to be related with the security-performance trade-off [Kreutz et al. 2017b].

Ideally, we would have both security robustness and performance on control plane channels. Considering the current scenario of SDN, it therefore seems clear the need to investigate lightweight alternatives for securing control plane communication. In the context of the security-performance gap, some directions that we point to in our architectural proposal ahead are, for instance, the careful selection of cryptographic primitives [Kreutz et al. 2017b], and the adoption of cryptographic libraries exhibiting a good performance-security tradeoff, such as NaCl [Bernstein et al. 2012], or of mechanisms allowing per-message one-time-key distribution, such as iDVV [Kreutz et al. 2017a,b]. We return to these mechanisms later.

3.2 Complexity *vs* robustness

The complexity-robustness gap represents the conflict between the current complexity of security and crypto implementations, and the negative impact this has on robustness and hence correctness, hindering the ultimate goal.

In the past few years, studies have recurrently shown several critical misuse issues of cryptographic APIs of different TLS implementations [Buhov et al. 2015; Egele et al. 2013; Razaghpanah et al. 2017]. One of the main root causes of these misuse issues is the inherent complexity of traditional cryptographic APIs and the knowledge required to use them without compromising security. For instance, more than 80% of the Android mobile applications make at least one mistake related to cryptographic APIs. Recent studies have also found different vulnerabilities in TLS implementations and have shown that longstanding implementations, such as OpenSSL[1], including its extensive cryptography, is unlikely to be completely verified in a near future [Beurdouche et al. 2015; Fan et al. 2016]. To address this issue, a few projects, such as miTLS [Bhargavan et al. 2013] and Everest [Bhargavan et al. 2017], propose new and verified implementations of TLS. However, several challenges remain to be addressed before having a solution ready for wide use [Bhargavan et al. 2017].

While the problem persists, the number of alarming occurrences proliferates. Recent examples include vulnerabilities that allow to recover the secret key of OpenSSL at a low cost [Yarom and Benger 2014], and timing attacks that explore vulnerabilities in both PolarSSL and OpenSSL [Arnaud and Fouque 2013; Brumley and Tuveri 2011]. On the other hand, failures in classical PKI-based authentication and authorisation subsystems have been persistently happening [Cromwell 2017; Hill 2013; PwC, CSO magazine and CERT/CMU 2014], with the sheer complexity of those systems being considered one of the root causes behind these problems.

[1]OpenSSL suffers from different fundamental issues such as too many legacy features accumulated over time, too many alternative modes as result of tradeoffs made in the standardization, and too much focus on the web and DNS names.

Considering the widely acknowledged principle that simplicity is key to robustness, especially for secure systems, we advocate and try to demonstrate in this paper, that the complexity-robustness gap can be significantly closed through a methodic approach toward less complex but equally secure alternative solutions. NaCl [Bernstein et al. 2012], which we mentioned in the previous section, can be rightly called again in this context: it is one of the first attempts to provide a less complex, efficient, yet secure alternative to OpenSSL-like implementations. Mechanisms simplifying key distribution, authentication and authorization, such as iDVVs [Kreutz et al. 2017b], could help mitigate PKIs' problems. By following this direction, we are applying the same principle of vulnerability reduction used in other systems, such as unikernels, where the idea is to reduce the attack surface by generating a smaller overall footprint of the operating system and applications [Williams and Koller 2016].

3.3 Global security policies

The impact of the lack of global security policies can be illustrated with different examples. Although ONF describes data authenticity, confidentiality, integrity, and freshness as fundamental requirements to ensure the security of control plane communication, it does so in an abstract way, and these measures are often ignored, or implemented in an ad-hoc manner [Scott-Hayward et al. 2016]. Another example is the lack of strong authentication and authorisation in the control plane. Recent reports show that widely used controllers, such as Floodlight and OpenDaylight, employ weak network authentication mechanisms [Scott-Hayward et al. 2016; Wan et al. 2017]. This leads to any forwarding device being able to connect to any controller. However, fake or hostile controllers or forwarding devices should not be allowed to become part of the network, in order to keep the network in healthy operation.

From a security perspective, it is non-controversial that device identification, authentication and authorization should be among the forefront requirements of any network. All data plane devices should be appropriately registered and authenticated within the network domain, with each association request between any two devices (e.g., between a switch and a controller) being strictly authorized by a security policy enforcement point. In addition, control traffic should be secured, since it is the fundamental vehicle for network control programmability. This begs the question: why aren't these mechanisms employed in most deployments?

A strong reason for the current state of affairs is the lack of global guiding and enforcement policies. It is necessary to define and establish global policies, and design, or adopt, the necessary mechanisms to enforce them and meet the essential requirements in order to fill the policy gap. With policies put in place, it becomes easier to manage all network elements, with respect to registration, authentication, authorization, and secure communication.

3.4 Resilient roots-of-trust

A globally recognized, resilient root-of-trust, could dramatically improve the global security of SDN, since current approaches to achieve trust are ad-hoc and partial [Abdullaziz et al. 2016]. Solving that gap would assist in fostering global mechanisms to ensure trustworthy registration and association between devices, as discussed previously, but the benefits would be ampler. For instance, a root-of-trust can be used to provide fundamental mechanisms (e.g., sources of strong entropy or pseudo-random generators), which would serve as building blocks for specific security functions.

As a first example, modern cryptography relies heavily on strong keys and the ability to keep them secret. The core feature that defines a strong key is its randomness. However, the randomness of keys is still a widely neglected issue [Vassilev and Hall 2014], and not surprisingly, weak entropy, and weak random number generation have been the cause of several significant vulnerabilities in software and devices [Albrecht et al. 2015; Hastings et al. 2016; Heninger et al. 2012; Kim et al. 2013]. Recent research has shown that there are still non-negligible problems for hosts and networking devices [Albrecht et al. 2015; Hastings et al. 2016; Heninger et al. 2012]. For instance, a common pattern found in low-resource devices, such as switches, is that the random number generator of the operating system may lack the input of external sources of entropy to generate reliable cryptographic keys. Even long-standing cryptographic libraries such as OpenSSL have been recurrently affected by this problem [Kim et al. 2013; OpenSSL.org 2016].

Similarly, as a second example, sources of accurate time, such as the local clock and the network time protocol, have to be secured to avoid attacks that can compromise network operation, since time manipulation attacks (e.g., NTP attack [Malhotra et al. 2015; Stenn 2015]) can affect the operation of controllers and applications. For instance, a controller can be led to deliberately disconnect forwarding devices if it wrongly perceives the expiration of heartbeat message timeouts.

It is worth emphasizing that the resilient roots-of-trust gap lies exactly in the relative trust that can be put in partial, local, ad-hoc implementations of critical functions by controller developers and manufacturers of forwarding devices, in contrast to a careful, once-and-for-all architectural approach that can be reinstantiated in different SDN deployments. The list not being exhaustive, we claim that strong sources of entropy, resilient, indistinguishable-from-random number generators, and accurate, non-forgeable global time services, are fitting examples of such critical functions to be provided by logically-centralized roots-of-trust, helping close the former gap.

4 LOGICALLY-CENTRALIZED SECURITY

In this section we introduce the specialization of the ANCHOR architecture for logically-centralized security properties enforcement (Figure 2), guided by the conclusions from the previous section. Our main goal is to provide security properties such as authenticity, integrity, and confidentiality for control plane communication. To achieve this goal, the ANCHOR provides mechanisms (e.g., registration, authentication, a source of strong entropy, a resilient pseudo random number generator) required to fulfill some of the major security requirements of SDNs.

As illustrated in Figure 2, we "anchor" the enforcement of security properties on ANCHOR, which provides all the necessary mechanisms and protocols to achieve the goal. It is also a central point for enforcing security policies by means of services such as device registration, device association, controller recommendation, or global time, thereby reducing the burden on controllers and forwarding devices, which just need the local HOOKs, protocol elements that interpret and follow the ANCHOR's instructions.

Next, we review the components and essential security services provided by ANCHOR. We first illustrate, in Section 4.1, how we implement our strategy of improving the robustness of ANCHOR as a single root-of-trust, by hardening ANCHOR in the face of failures. Next, we propose a source of strong entropy (Section 4.2) and a resilient pseudo random generator (PRG) (Section 4.3) for generating security-sensitive materials. These are crucial components, as attested by the impact of vulnerabilities discovered in the recent past, in sub-optimal implementations of the former in several software packages [Bernstein et al. 2016; Mimoso 2016;

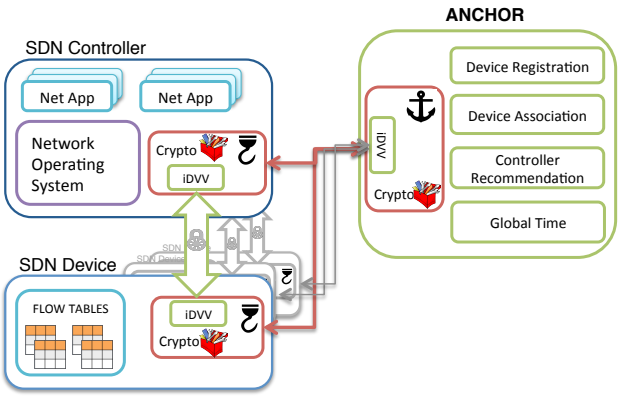

Fig. 2. Logically-centralized Security

Schneier 2012; ZETTER 2015]. We implement and evaluate the robustness of these mechanisms. We also leverage on a recently proposed mechanism, the integrated device verification value (iDVV), to simplify authentication, authorization and key generation amongst SDN components [Kreutz et al. 2017b], which we review and put in the context of ANCHOR (Section 4.4). Namely, the iDVV protocol runs between the ANCHOR, and the HOOKs in controllers and switching devices. We implement and evaluate iDVV generators for OpenFlow-enabled control plane communication. Next, we present three essential services for secure network operation — device registration (Section 4.6) , device association (Section 4.7), and controller recommendation (Section 4.8) — and we describe how the above mechanisms interplay with our secure device-to-device communication approach (Section 4.9).

Concerning the mitigation of possible (though expectedly infrequent) security failures, across the explanation of the algorithms we observe how several robustness measures work, like for example the achievement of PFS, protecting pre-compromise communications in the presence of successful attacks. Finally, in Section 4.10, we see the capstone of these measures, explaining how to re-establish secure communication channels in a semi-automatic way, after ANCHOR has been reinstated in the sequel of compromise.

The roster of services of ANCHOR is not closed, and one can think of other functionalities, not described here, including keeping track of forwarding devices association, generating alerts in case of strange behaviors (e.g., recurrent reconnections, connections with multiple controllers), and so forth. These ancillary management tasks are important to keep track of the network operation status. In what follows, we describe the above components in detail.

4.1 Hardening anchor

The compromise of a root-of-trust is of great concern, since crucial services normally depend on it being secure and dependable. As we stated in the introduction, we have a long-term strategy towards the resilience of ANCHOR, which starts, in the context of this paper, by improving the inherent reliability of its simplex (non-replicated) version, by hardening it in the face of failures, namely, by still providing some security guarantees even when ANCHOR has been compromised. In particular, we propose protocols to achieve two security properties guaranteeing respectively, the security of past (pre-compromise) communications, and

of future (post-recovery) communications. This provides a significant improvement over other existing root-of-trust infrastructures.

The first security property is *perfect forward secrecy (PFS)*, namely, the assurance that the compromise of all secrets in a current session does not compromise the confidentiality of the communications of the past sessions. The enforcement of PFS is systematically approached in the algorithms we present next.

The second property is *post-compromise security (PCS)*. While PFS considers how to protect the past communications, PCS considers how to automatically reinstate and re-establish the secure communication channels, for future communications. This security property has so far been considered only in the specific scenario of secure messaging [Yu and Ryan 2015], and only limited works [Yu et al. 2017a,b] are available. In particular, we consider that when ANCHOR has been compromised by an attacker (e.g., through the exploitation of software vulnerabilities), and has been reinstated by the operator (e.g., by applying software patches and rebuilding servers), the system should have a way to automatically re-establish secure communications between ANCHOR and all other participants, without having to reinstate these components (controllers and forwarding devices in this case, whose shared secrets became compromised).

In summary, even though ANCHOR is a single root-of-trust in our system, we mitigate the associated risks by guaranteeing:

- PFS: the compromise of ANCHOR in the current session does not expose *past communications*;
- PCS: when ANCHOR is compromised and reinstated, ANCHOR can automatically re-establish secure communication channels with all other participants in the system to protect the security of *future communications*.

As a side note, since our system only uses symmetric key cryptography, it will stand up even against an attacker with quantum computers. In other words, our infrastructure will be *post-quantum secure (PQS)*.

4.2 A source of strong entropy

Entropy still represents a challenge for modern computers because they have been designed to behave deterministically [Vassilev and Hall 2014]. Sources of true randomness can be difficult to use because they work differently from a typical computer.

To avoid the pitfalls of weak sources of entropy, in particular in networking devices, ANCHOR provides a source of strong entropy to ensure the randomness required to generate seeds, pseudorandom values, secrets, among other cryptographic material. The strong source of entropy, implemented by Algorithm 1, has the following property:

Strong Entropy - Every value *entropy* returned by the function *entropy_get* is indistinguishable-from-random.

Algorithm 1 shows how the external (from other devices) and internal (from the local operating system) sources of entropy are kept updated and used to generate random bytes per function call (*entropy_get()*). The state of the internal and external entropy is initially set by calling the *entropy_setup(data)*. This function requires an input data, which can be a combination of current system time, process number, bytes from special devices, among other things, and random bytes (*rand_bytes()*) from a local (deterministic) source of entropy (e.g., */dev/urandom*) to initialize the state of the entropy generator. As we cannot assume

Algorithm 1: Source of strong entropy

```
1:  entropy_setup(data)
2:      e_entropy ← rand_bytes() ⊕ H(data)
3:      i_entropy ← rand_bytes() ⊕ e_entropy
4:  entropy_update()
5:      e_entropy ← H(P_i||P_j) ⊕ i_entropy
6:      E_counter ← 0
7:  entropy_get()
8:      if E_counter >= MAX_LONG call entropy_update()
9:      i_entropy ← H(rand_bytes() || E_counter)
10:     entropy ← e_entropy ⊕ i_entropy
```

anything regarding the predictability of the input data, we use it in conjunction with a *rand_bytes()* function call (line 2). A call to *rand_bytes()* is assumed to return (by default) 64 bytes of random data.

Function *entropy_update()* uses as input the statistics of external sources and the ANCHOR's own packet arrival rate to update the external entropy. The noise (events) of the external sources of entropy is stored in 32 pools (P_0, P_1, P_2, P_3, ..., P_{31}), as suggested by previous work [Ferguson et al. 2011]. Each pool has an event counter, which is reset to zero once the pool is used to update the external entropy. At every update, two different pools of noise (P_i and P_j) are used as input of a hashing function H. The two pools of noise can be randomly selected, for instance. The output of this function is XORed with the internal entropy to generate the new state of the external entropy. It is worth emphasizing that *entropy_update()* is automatically called when *E_counter* (the global event counter) reaches its maximum value and whenever needed, i.e., the user can define when to do the function call.

The resulting 64 bytes of entropy, indistinguishable-from-random bytes (*entropy_get()*), are the outcome of an XOR operation between the external and internal entropy. While the external entropy provides the unpredictability required by strong entropy, the internal source provides a good, yet predictable [Vassilev and Hall 2014], continuous source of entropy. At each time the *entropy_get()* function is called, the internal entropy is updated by using a local source of random data, which is typically provided by a library or by the operating system itself, and the global number of events currently in the 32 pools of noise (*E_counter*). These two values are used as input of a hashing function H.

Such sources of strong entropy can be achieved in practice by combining different sources of noise, such as the unpredictability of network traffic [Greenberg et al. 2009], the unpredictability of idleness of links [Benson et al. 2010b], packet arrival rate of network controllers, and sources of entropy provided by operating systems. We provide implementation details in Section 5.1. A discussion about the correctness of Algorithm 1 can be found in appendix A.

4.3 Pseudorandom generator (PRG)

A source of entropy is necessary but not sufficient. Most cryptographic algorithms are highly vulnerable to the weaknesses of random generators [Dodis et al. 2013]. For instance, nonces generated with weak pseudo-random generators can lead to attacks capable of recovering secret keys. Different security properties need to be ensured when building strong pseudo-random number generators (PRG), such as resilience,

forward security, backward security and recovering security. In particular, the latter was recently proposed as a measure to recover the internal state of a PRG [Dodis et al. 2013]. We propose a PRG that uses our source of strong entropy and implements a refresh function to increase its resilience and recovering capability. The pseudo-random number generator, implemented by Algorithm 2, has the following property:

Robust PRG - Every value *nprd* returned by the function *PRG_next* is indistinguishable-from-random.

A robust PRG needs three well-defined constructions, namely *setup()*, *refresh()* (or re-seed), and *next()*, as described in Algorithm 2. The internal state of our PRG is represented by three variables, the *seed*, the *counter* and the next pseudo-random data *nprd*. The setup process generates a new seed, by using our strong source of entropy, which is used to update the internal state. In line 3, we initialize the *counter* by calling the *long_uint* function, which returns a long unsigned int value that will be used to re-seed and to generate the next pseudorandom value. In line 4, we call *entropy_update* to make sure that the external entropy gets updated before calling one more time the *entropy_get* function. The first *nprd* is the outcome of an XOR operation between the newly generated seed and a second call to our source of entropy. It is worth emphasizing that the set up of the initial state of the PRG does not require any intervention or interaction with the end user. We provide strong and reliable entropy to set up the initial values of all three variables. This ensures that our PRG is non-sensitive to the initial state. For instance, in a tradicional PRG the user could provide an initial seed, or other setup values, that could compromise the quality of the generator's output. The *counter*, which is concatenated with the *nprd* (lines 9 and 13), gives the idea of an unbounded state space [Stark 2017]. This is possible because we are using cryptographically strong primitives such as a hash function H and the MAC function HMAC. Thus, in theory, we have unbounded state spaces, i.e., we can keep concatenating values to the input of these primitives.

The *PRG_refresh()* function updates the internal state, i.e., the *seed*, the *counter* and the *nprd*. It uses H to update the state of the *nprd*. Finally, the *PRG_next()* function outputs a new, indistinguishable-from-random stream of bytes, applying HMAC on the internal state. In this function, the *counter* is decremented by one. The idea is for it to start with a very large unsigned 8-bytes value, which is used until it reaches zero. At this point, the *PRG_refresh()* function will be called to update the internal state of the generator. The newly generated *nprd* is the outcome of an HMAC function with a dimension of 128 bits.

Algorithm 2: Pseudo-random number generator

```
1:  PRG_setup()
2:     seed ← entropy_get()
3:     counter ← long_uint(entropy_get())
4:     call entropy_update()
5:     nprd ← seed ⊕ entropy_get()
6:  PRG_refresh()
7:     seed ← entropy_get()
8:     counter ← long_uint(entropy_get())
9:     nprd ← H(seed || nprd || counter)
10: PRG_next()
11:    counter ← counter - 1
12:    if counter <= 0 call PRG_refresh()
13:    nprd ← HMAC(seed, nprd || counter)
```

The main motivation for having a PRG along with a strong source of entropy is speed. Studies have shown that entropy generation for local use can be rather slow, such as 1.5 seconds to 2 minutes for generating 128 bits of entropy [Mahu et al. 2015]. Our source of entropy uses external entropy and random bytes from special devices, whereas the PRG uses an HMAC function, in order to have a fast and reliable generation of pseudo-random values.

In spite of the fact that we could use any good PRG to generate crypto material (e.g. keys, nonce), it is worth emphasizing that we introduce a PRG that works in a seamless way with our strong source of entropy, improving its quality. In Section 5.2, we discuss the specifics of the implementation. We also evaluate the robustness and level of confidence of our algorithms in Section 6.1. A discussion about the correctness of Algorithm 2 can be found in appendix B.

4.4 Integrated device verification value

The design of our logically-centralized security architecture also includes the integrated device verification value (iDVV) component [Kreutz et al. 2017b]. The iDVV idea was inspired by the iCVVs (integrated card verification values) used in credit cards to authenticate and authorize transactions in a secure and inexpensive way. In [Kreutz et al. 2017b] the concept was applied to SDN, proposing a flexible method of generating iDVVs that can be safely used to secure communication between any two devices. As a result, iDVVs can be used to partially address two gaps of non-functional properties, security-performance and complexity-robustness.

An iDVV is a unique value generated by device A (e.g., forwarding device) which can be verified by device B (e.g., controller). An iDVV generator has essentially two interfaces. First, *idvv_setup (seed, secret)*, which is used to set up the generator. It receives as input two secret, random and unique values, the seed and the (higher-level protocol dependent) secret. The source of strong entropy and the robust PRG are, amongst other things, used to bootstrap and keep the iDVV generators fresh. Second, the *idvv_next()* interface returns the next iDVV. This interface can be called as many times as needed.

So, iDVVs are sequentially generated to authenticate and authorize requests between two networking devices, and/or protect communication. Starting with the same seed and secret, the iDVV generator will generate, for example, at both ends of a controller-device association, the exact same sequence of values. In other words, it is a deterministic generator of authentication or authorization codes, or one-time keys, which are, however, indistinguishable from random. The main advantages of iDVVs are their low cost, which makes them even usable on a per-message basis, and the fact that they can be generated off-line, i.e., without having to establish any previous agreement.

Correctness. The randomness and performance of the iDVV algorithm as deterministic generator of authentication or authorization codes, or one-time keys which are however indistinguishable from random, have been analyzed, and its properties proved, in [Kreutz et al. 2017b]. The performance study is complemented in Section 6.2. Overall, these analyses show that iDVVs are robust, achieve a high level of confidence and outperform traditional key generation and derivation functions without compromising the security.

4.5 System roles and setup

Let us assume the roles of *system administrator*, controlling the operation of central services such as ANCHOR, and *network administrator*, controlling the operation of network devices. Each time a new network device (a forwarding device or a controller) is added to the network, it must first be registered, before being able to operate.

In the current practice, the device registration is a manual process triggered by a network administrator through an out-of-band channel. This process would involve manual work from both the system and the network administrators. Given the potentially large number of network devices in SDN, such a manual process is unsatisfactory.

Thus, we propose a protocol, described below, to fulfill the desire of a semi-automated device registration process, which is efficient, secure, and requires the least involvement of ANCHOR. The ANCHOR is first setup by the system admin. Next, each network device is set up by ANCHOR. Devices just need that a key shared with their overseeing network admin is set up initially, at first use. The set up of this key and the registration of devices is described in Section 4.6. Then, devices can be registered automatically.

For simplicity and without loss of generality, in what follows we denote $E_{XY}()$ an encryption using encryption key Ke_{XY}, and we denote $[],HMAC_{XY}$, respectively a message field inside [], followed by an HMAC over the whole material within [], using MAC key Kh_{XY}, where $X, Y \in \{A, D_i, M, C, F\}$. When $X = A$, we omit X for simplicity. For example, we use $E_M(\text{msg})$ to refer $E_{AM}(\text{msg})$, and they both denote the ciphertext of encrypting msg under key Ke_{AM}. In what follows, ANCHOR can generate strong keys using a suitable key derivation function (KDF) based on the high entropy random material described in the previous sections.

Now we present the set up required for ANCHOR, network admin, and device. After that, we describe the device registration and association algorithms, respectively Algorithms 3 and 4.

ANCHOR setup. The ANCHOR needs two master recovery keys, namely the master recovery encryption key Ke_{rec} and master recovery MAC key Kh_{rec}, fundamental for the post-compromise recovery steps described ahead. However, these two master recovery keys, in possession of the authority overseeing ANCHOR (the system administrator), must never appear in the ANCHOR server (if they are to recover from a possible full server compromise), being securely stored and used only in an offline manner [2].

As we will present later, the master recovery keys are only used in two cases, namely (a) when a new network admin is registered with ANCHOR (i.e. the network admin setup process); and (b) when ANCHOR was compromised and is reinstated into a trustworthy state (i.e. the post-compromise recovery process presented in §4.10). When either case occurs, the ANCHOR authority only needs to use the master recovery keys once, to recursively compute the recovery keys of all devices and network admins. The output of the calculation will be imported into the ANCHOR server through an out-of-band channel (e.g. by using a USB).

Network admin setup. Each network administrator (or manager, denoted M) with identity M_ID is registered with ANCHOR manually. This is the *only manual process* to initialize a new network administrator. Afterwards all devices managed by this administrator can be registered with ANCHOR through our device registration protocol.

[2] Just to give a real feel, one possible implementation of this principle is: a pristine ANCHOR server image is created; it boots offline in single user mode; it generates Ke_{rec} and Kh_{rec} through a strong KDF as discussed above; keys are written into a USB device, and then deleted; first online boot proceeds.

During the network admin registration phase, ANCHOR locally generates encryption key Ke_{AM} and MAC key Kh_{AM} to be shared with M, and they are manually imported into M through an out-of-band channel (again, by using a USB, for example).

Further, M recovery keys Kre_{AM} = H(Ke_{rec}||M_ID) and Krh_{AM} = H(Kh_{rec}||M_ID) are also computed by ANCHOR offline. M recovery keys live essentially offline, since M needs to perform only infrequent operations with these keys (e.g. upon device registration). Note that ANCHOR does not store Kre_{AM} or Krh_{AM} as well, but can recompute them offline when the post-compromise recovery process is triggered, as we detail in Section 4.10.

Device setup. A device with identity D_i is either a forwarding device (F) or a controller (C), but we do not differentiate them during the set up and registration processes. The first operation to be made after a device is first brought to the system is the setup, which, in the context of this paper, concerns the establishment of credentials, for secure management access by the network administrator.

Upon request from M, ANCHOR locally generates a pair of keys for each device D_i being set up , Ke_{MD_i} and Kh_{MD_i}, to be respectively the encryption and MAC key to be shared between M and D_i, for management. They are sent to M under the protection of Ke_{AM} and Kh_{AM}. Then, they are manually imported by the network admin into each D_i through an out-of-band channel.

4.6 Device registration

The device registration protocol is presented in Algorithm 3. We assume that Ke_{MD_i} and Kh_{MD_i} described above are in place.

The first part concerns the bootstrap of the registration of a batch of devices with ANCHOR (A), by a network admin M. Let $\{D_i\}_{i=1}^{n}$ be the set of n device identities that the admin wants to register. M requests (line 1) the registration to A, accompanying each D_i with a nonce x_m^i. A computes its own nonce x_a^i, and keys Ke_{AD_i}, Kh_{AD_i}, for each D_i, and returns them encrypted to M (lines 2,3). The random nonces x_m^i and x_a^i are used to prevent replay attacks.

The process then follows for each device D_i. First, the device recovery key is created (line 4), using M's recovery key Kr_{AM}. Then M sends D_i the relevant crypto keys (line 5). Device D_i follows-up confirmation to A, which closes the loop with M, using the original nonce from A (lines 6,7). A then performs a set of operations (lines 8-11) to commit the registration of D_i, namely by inserting it into the controller or forwarding device list, respectively CList or FList, and updating several keys.

Note that in Algorithm 3, the update of several shared keys (i.e., lines 11, 15, 17, 18) at the end of the registration steps at A, M, and D_i, is used to provide PFS. When a key is updated, the old one is destroyed. Continuing, in line 12 M closes the loop with D_i, using the original nonce from A, finally confirming D_i's registration. Upon this step, both M and D_i perform the key update just mentioned.

Note that the generation process of the recovery key Kr_{AD_i} lies with M (line 4), though using its recovery key shared with ANCHOR, Kr_{AM}. This reduces the number of uses of the master recovery key. However, as we will see, albeit not knowing Kr_{AD_i} and Kr_{AM}, ANCHOR can easily compute them offline, if needed. Second, Kr_{AM} possessed by the network admin is only used when new devices need to be registered. So, Kr_{AM} can be usually stored offline. This provides an extra layer of security.

Algorithm 3: Device registration

		{Bootstrap for devices $D_1 - D_n$ }
1.	M $\rightarrow$ A	[Reg, M_ID, $E_M(\{D_i, x_m^i\}_{i=1}^n)$], $HMAC_M$
2.	A	for each D_i, generate $Ke_{AD_i}, Kh_{AD_i}, x_a^i$
3.	A $\rightarrow$ M	[Reg, M_ID, $E_M(\{(D_i, x_m^i, x_a^i, Ke_{AD_i}, Kh_{AD_i})\}_{i=1}^n)$], $HMAC_M$
		{For each device D_i}
4.	M	$Kr_{AD_i} \leftarrow$ H(Kr_{AM}||D_i)
5.	M $\rightarrow D_i$	[Reg, $E_{MD_i}(x_a^i, Ke_{AD_i}, Kh_{AD_i}, Kr_{AD_i})$], $HMAC_{MD_i}$
6.	$D_i \rightarrow$ A	[M_ID, D_i, $E_{D_i}(x_a^i)$], $HMAC_{D_i}$
7.	A $\rightarrow$ M	[M_ID, D_i, $E_M(x_a^i)$], $HMAC_M$
8.	A	tag(D_i) = registered;
9.		for $t \in \{C, F\}$, if Type(D_i)==t, then $tList = tList \cup \{Di\}$
10.		$\forall i \in 1, n$, if tag(D_i) == registered is True
11.		Ke_{AM} = H(Ke_{AM}); Kh_{AM} = H(Kh_{AM}).
12.	M $\rightarrow D_i$	[D_i, $E_{MD_i}(x_a^i)$], $HMAC_{MD_i}$
13.	M	tag(D_i) = registered;
14.		destroys ($Ke_{AD_i}, Kh_{AD_i}, Kr_{AD_i}$);
15.		Ke_{MD_i} = H(Ke_{MD_i}); Kh_{MD_i} = H(Kh_{MD_i});
16.		$\forall i \in 1, n$, if tag(D_i) == registered is True
17.		Ke_{AM} = H(Ke_{AM}); Kh_{AM} = H(Kh_{AM}).
18.	D_i	Ke_{MD_i} = H(Ke_{MD_i}); Kh_{MD_i} = H(Kh_{MD_i}).

4.7 Device association

The association service is required for authorizing control plane channels between any two devices, such as a forwarding device and a controller. A forwarding device has to request an association with a controller it wishes to communicate with. This association is mediated by the ANCHOR.

The association process between two devices is performed by the sequence steps detailed in Algorithm 4. Registered controllers and forwarding devices are inserted in *CList* and *FList*, respectively. *Notation:* As explained above, the registration process set in place shared secret keys between ANCHOR (A) and any controller C or forwarding device F.

The device association implemented by Algorithm 4, has the following properties:

Controller Authorization - Any device F can only associate to a controller C authorized by the ANCHOR.

Device Authorization - Any device F can associate to some controller, only if F is authorized by the ANCHOR.

Association ID Secrecy - After termination of the algorithm, the association ID (AiD) is only known to F and C.

Algorithm 4: Device association

		{Of forwarding device F with controller C}
1.	F $\rightarrow$ A	[x_g, F, GetCList],$HMAC_F$
2.	A $\rightarrow$ F	[x_g, F, E_F(CList(F), x_g)],$HMAC_F$
3.	F $\rightarrow$ C	x_g, GetAiD, F, C, E_F(GetAiD, F, C, x_f, x_g)
4.	C $\rightarrow$ A	[x_g, GetAiD, F, C, E_F(GetAiD, F, C, x_f, x_g), E_C(GetAiD, F, C, x_c, x_g)],$HMAC_C$
5.	A $\rightarrow$ C	[x_g, E_F(x_f, AiD), E_C(x_c, AiD)],$HMAC_C$
6.	A	destroys (AiD)
7.	C $\rightarrow$ F	x_g, E_F(x_f, AiD), E_{AiD}(SEED, x_g)
8.	F $\rightarrow$ C	x_g, E_{AiD}(SEED $\oplus$ x_g)
9.	A, F	Ke_{AF} = H(Ke_{AF}); Kh_{AF} = H(Kh_{AF})
10.	A, C	Ke_{AC} = H(Ke_{AC}); Kh_{AC} = H(Kh_{AC})

Seed Secrecy - After termination of the algorithm, the seed ($SEED$) is only known to F and C.

The algorithm coarse structure follows the line of the Needham-Schroeder (NS) original authentication and key distribution algorithm [Needham and Schroeder 1978], but contemplates anti-replay measures such as including participant IDs, and a global initial nonce as suggested in [Otway and Rees 1987]. Unlike NS, it uses encrypt-then-mac to further prevent impersonation. Furthermore, it is specialized for device association, managing authorization lists, and distributing a double secret in the end (association ID and seed). Secure communication protocols running after association can, as explained below in Section 4.9, use iDVVs on a key-per-message or key-per-session basis, rolling from the initial seed and secret association ID.

The association process starts with a forwarding device (F) sending an association request to the ANCHOR (A) (line 1 in Algorithm 4). This request contains a nonce x_g, the identification of the device and the operation request *GetCList* (get list of controllers). The request also contains an HMAC to avoid device impersonation attacks. The ANCHOR checks if F is in FList (registered devices), and if so, it replies (line 2) with a list of controllers (CList(F)) which F is authorized to associate with. The list of controllers (and the nonce x_g) is encrypted using a key (set up during registration) shared between A and F. This protects the confidentiality of the list of controllers, and x_g ensures that the message is fresh, providing protection against replay attacks. A message authentication code also protects the integrity of the ANCHOR's reply, avoiding impersonation attacks. Next, F sends an association request to the chosen controller C (line 3). The request contains a message that is encrypted using a key shared between F and A. This message contains the get association id (*GetAiD*) request, the identity of the principals involved (F,C), a nonce x_f, and binds to the nonce x_g. The controller forwards this message to A (line 4), adding its own encrypted association request field, similar to F's, but containing C's own noncex_c instead. This prevents the impersonation of the controller since only it would be able to encrypt the freshly generated x_g. In line 5, C trusts that A's reply is fresh because it contains x_g. The controller also trusts that it is genuine (from A) because it contains x_c. As such, C endorses F as an authorized device and AiD as the association key for F. Future compromise of A should not represent any threat to established communication between C and F. To achieve this goal, A immediately destroys the AiD (line 6) and C and F further share a seed not known by A (line 7).

C forwards both the encrypted AiD message and its seed to F (line 7). The forwarding device trusts that this message is fresh and correct because it contains x_g, and x_f under encryption, together with the AiD, only know to F and C, which it endorses then as the association key. F trusts that C is the correct correspondent, otherwise A would not have advanced to step 5. That being true, future interactions will use AiD. F believes that the $SEED$ is genuine, as random entropy for future interactions, because it is encapsulated by AiD, known only to C and F. The forwarding device also trusts that the message is fresh because it contains x_g. Finally (line 8), C trusts it is associated with F (as identified in step 3 and confirmed by A in step 5), when F replies showing it knows both the AiD and the $SEED$, by encrypting the $SEED$ XOR'ed with the current nonce x_g, with AiD. Replay and impersonation attacks are avoided because all encrypted interactions are dependent on nonces, so will become void in the future. At the end of each device association protocol, all keys shared between a device (F or C) and ANCHOR will be updated to the hash value of this key (lines 9, 10). Again, this is used to provide perfect forward secrecy. All nonces are random, i.e., not predictable.

A discussion of the correctness of Algorithm 4 can be found in Appendix C.

4.8 Controller recommendation

Similarly to moving target defense strategies [Wang et al. 2014], devices (e.g., controllers) are hidden by default, i.e., only registered and authenticated devices can get information about other devices. Even if a forwarding device finds out the IP of a controller, it will be able to establish a connection with the controller only after being registered and authorized by the ANCHOR.

Controllers can be recommended to forwarding devices using different parameters, such as latency, load, or trustworthiness. When a forwarding device requests an association with one or more controllers, the ANCHOR sends back a list of authorized controllers to connect with. The forwarding device will be restricted to associate itself with any of the controllers on the list. In other words, forwarding devices will not be allowed to establish connections with other (e.g., hostile or fake) controllers. Similarly, fake forwarding devices will be, by default, forbidden to set up communication channels with non-compromised controllers.

4.9 Device-to-device communication

Communication between any two devices happens only after a successful association. Consider the end of an association establishment, as per Algorithm 4, e.g. between a controller C and a forwarding device F: at this point, both sides, and only them, have the secret and unique material $SEED, AiD$ (as proved in Appendix C). Using them, they can bootstrap the iDVV protocol (see Section 4.4 above), which from now on can be used at will by any secure communication primitives. As explained earlier, iDVV generation is flexible and low cost, to allow the generation: (a) on a per message basis; (b) for a sequence of messages; (c) for a specific interval of time; or (d) for one communication session.

NaCl [Bernstein et al. 2012], as mentioned in previous sections, is a simple, efficient, and provably secure alternative to OpenSSL-like implementations, and is thus our choice for secure communication amongst controllers and devices.

Researchers have shown that NaCL is resistant to side channel attacks [Almeida et al. 2013] and that its implementation is robust [Bernstein et al. 2012]. Different from other crypto libraries, NaCL's API and implementation is kept very simple, justifying its robustness. Through ANCHOR, the SDN communication

channels are securely encrypted using symmetric key ciphers provided by NaCl, with the strong cryptographic material required by the ciphers generated by our mechanisms, allowing secret codes per packet, session, time interval, or pre-defined ranges of packets.

4.10 Post-compromise recovery

As previously mentioned, after ANCHOR has been reinstated in the sequel of a compromise, it is crucial to have a way to automatically re-establish the secure communication channels between ANCHOR and all participants.

Algorithm 5 presents how to re-establish the secure communication channels when ANCHOR is compromised. Intuitively, since ANCHOR's master recovery keys Ke_{rec} and Kh_{rec} are stored securely offline, these keys are unknown to the attacker who has stolen all secrets from the ANCHOR server. As described before, all M and all D_i recovery keys can be recursively computed from the master keys, offline (line 1). Once this done, the operator imports those keys into the ANCHOR server. To continue the recovery process, ANCHOR generates new random keys to be shared with all Ms, and all D_i (line 2).

Now ANCHOR can send to each M (line 3) a recovery message to re-share keys (contained in M_k) both between that manager and the devices controlled by it. The messages are secured by using the according recovery keys. The new shared keys will be used to protect future communications. Each M implements the operation with each of the devices it manages (line 4).

The new keys replace the possibly compromised keys at M and each D_i (lines 5-6, and 9). Likewise, when the recovery process has been completed, the recovery keys will be updated to their hash value (lines 7-8, and 10-11). As mentioned previously, this key update is used to provide perfect forward secrecy (PFS).

Note that at line 3, an additional MAC value on the entire message under the current MAC key Kh_{AM} is created. Since the recovery keys are stored offline, without having this additional MAC value, the manager will have to perform the verification offline manually. This MAC value prevents possible DoS attacks where an attacker creates and sends fake recovery messages to network managers, as this additional MAC value can be verified online efficiently, and it cannot be created without having access to the current MAC key Kh_{AM}.

Algorithm 5: ANCHOR recovery.

		{For each manager M and its associated devices $\{D_i\}_{i=1}^{n}$}
1.	A	computes Kre_{AM}, Krh_{AM}, Kre_{AD_i}, Krh_{AD_i};
2.		generates $M_k = Ke'_{AM}, Kh'_{AM}, \{Ke'_{AD_i}, Kh'_{AD_i}\}_{i=1}^{n}$.
3.	A $\rightarrow$ M	Recovery, A, M_ID, $E_{Kre_{AM}} M_k, HMAC_{Krh_{AM}}, HMAC_M$.
		{For each device D_i}
4.	M $\rightarrow D_i$	Recovery, A, M_ID, $D_i, E_{Kre_{AD_i}} Ke'_{AD_i}, Kh'_{AD_i}, HMAC_{Krh_{AD_i}}$.
5.	M	destroys Ke'_{AD_i}, Kh'_{AD_i};
6.		$Ke_{AM} = Ke'_{AM}$; $Kh_{AM} = Kh'_{AM}$;
7.		$Kre_{AM} = \mathrm{H}(Kre_{AM})$; $Krh_{AM} = HKrh_{AM})$;
8.		$Ke_{MD_i} = \mathrm{H}(Ke_{MD_i})$; $Kh_{MD_i} = \mathrm{H}(Kh_{MD_i})$.
9.	D_i	$Ke_{AD_i} = Ke'_{AD_i}$; $Kh_{AD_i} = Kh'_{AD_i}$;
10.		$Kre_{AD_i} = \mathrm{H}(Kre_{AD_i})$; $Krh_{AD_i} = \mathrm{H}(Krh_{AD_i})$;
11.		$Ke_{MD_i} = \mathrm{H}(Ke_{MD_i})$; $Kh_{MD_i} = \mathrm{H}(Kh_{MD_i})$.

In case of compromise of a manager M, once it has recovered, it can also re-establish its shared secrets with ANCHOR and associated devices in a similar way as described above. A recovery is excluded, and the next steps are made only for a single M instead of all M, and with some differences: M gets the recovery keys (line 1) from ANCHOR through an out-of-band channel, Kre_{AM}, Krh_{AM}, and all Kre_{AD_i}, Krh_{AD_i} from $i = 1ton$. These keys remain the same, but M had lost them, having been rebuilt from scratch. Then, in lines 2-3, M will get (generated by A) the Ke'_{MD_i}, Kh'_{MD_i} keys for managing all devices, instead of Ke'_{AD_i}, Kh'_{AD_i}, which do not need to be changed. In line 4, the former are sent to each D_i, instead of the latter.

5 DESIGN AND IMPLEMENTATION

A prototype of ANCHOR has been implemented as envisioned in Figure 2. Our implementation, using the NOX controller and CBench[3] (OpenFlow switches emulator), has approximately 2k lines of Python code and 700 lines of C code (integration with CBench). It uses Google's protobuf [Google 2017] for defining the communication protocols and efficiently serializing the data. In this section we give an overview of some important system implementation details. The evaluation of the different components of the architecture is presented in Section 6.

5.1 A source of strong entropy

Each external source of noise (e.g., forwarding device, controller) sends heartbeats to the ANCHOR. Each heartbeat carries statistics of the current network traffic, idleness of links, and number of packets received by a controller within a specific time frame.

Recall from Algorithm 1 that for setting up the external entropy, the bytes read from the local source are combined (through an XOR operation) with the output of hashing function H(*data*). We have chosen SHA512 as our strong hashing function H [Dang 2010]. After that, a second read of local random bytes is XORed with the external entropy to setup the internal entropy.

For implementing the *entropy_update()*, one can use the pools of noise in a circular approach (e.g., P_0 and P_1, P_2 and P_3, and so forth), in a combined circular and random way (P_0 and P_7, P_1 and P_{31}, and so forth), or in a completely random fashion, for instance. Ergo, using several pools of events, we create enough data to make it nearly impractical for an attacker to enumerate the possible values for the events used to update the generator's internal state [Ferguson et al. 2011]. In other words, the attacker will arguably be unable to rebuild the internal state of the source of strong entropy.

Even if an attacker is controlling two or more external sources in a timely manner, it will be hard to guess the new state of the external entropy. First, the attacker needs to enumerate the events of the pools being used on each update. This, by itself, is something hard to achieve since the attacker does not know the update sequence of these pools, i.e., which external sources are being used, in which sequence, to update each pool. In other words, he/she would have to know all sources of noise, and the sequence in which they are being used to update the pools. It is also worth emphasizing that the external sources need to have a pre-defined maximum rate for sending the heartbeats, i.e., compromised sources cannot send data at a higher frequency to influence subsequent updates of the external entropy. Second, the attacker would need

[3]CBench is the default and most widely used tool for benchmarking control plane performance [Khattak et al. 2014; Shalimov et al. 2013; Zhao et al. 2015].

to have additional knowledge regarding the internal entropy, which is a result of two combined values, as explained in the following paragraph.

Pools of noise. The 32 pools of events are feed by four different sources, (1) incoming packet rate sent by controllers; (2) incoming packet rate of ANCHOR; (3) network statistics of forwarding devices; and (4) random bytes from local systems. Each of the source feeds the pools in its own way. For instance, sources (1) and (3) use round-robin, while sources (2) and (4) use a random approach to select the next pool to put the new event in. In this way, we have a diversity of approaches for feeding the pools of noise, making the "guessing task" of an attacker even harder. Each pool needs to store only a single value, the digest of a hashing function (e.g., SHA512). The current digest and the newly arrived events are used as input of the hashing function. Lastly, once the pool has been used by the source of strong entropy, it is reset to a new initial state, which consists of the digest of a hash function using as input random bytes of a local entropy source such as */dev/urandom*.

5.2 Pseudorandom generator (PRG)

Our PRG, as was shown in Algorithm 2, combines the strengths of different solutions such as the PRF of SPINS [Perrig et al. 2002] (which is based on an HMAC function), provably secure constructions for building robust PRGs [Dodis et al. 2013; Ferguson et al. 2011], and unbounded state spaces through cryptographic primitives [Stark 2017].

As HASH function we have chosen SHA512. As HMAC function, we have chosen the one time authentication function *crypto_onetimeauth()* from NaCl [Bernstein et al. 2012]. It ensures security and performance while generating outputs of 16 bytes that are indistinguishable from random.

PRG at the controller. As the controller might not have a source of strong entropy, we implemented a slightly modified version of Algorithm 2. Essentially, we replace the *entropy_get()* function by *entropy_remote()*. This function makes an entropy request to the ANCHOR. This means that the recovering security by refreshing, which makes a PRG more resilient, is using our source of strong entropy. With this approach, we are strengthening the controller's PRG.

5.3 iDVV generators

Based on the algorithm proposed in [Kreutz et al. 2017b], we have implemented an iDVV generator that supports seven different cryptographic primitives. In this case, the *idvv_next(primitive_id)* also has an input, which is the id of the primitive to be used. In the implementation, we used the following primitives to generate the iDVVs: *MD5*, *SHA1*, *SHA512*, *SHA256*, *poly1305aes_ authenticate*, *crypto_onetimeauth*, and *crypto_hash*. While the first four functions are provided by OpenSSL, the last three are provided by an independent implementation of Poly1305-AES and NaCl. As MD5 and SHA1 are deprecated, we use them only for performance comparison purposes.

6 EVALUATION

In this section we evaluate the essential security mechanisms and services of our architecture.

For the performance measurements, we used machines with two quad-core Intel Xeon E5620 2.4GHz, with 2x4x256KB L2 / 2x12MB L3 cache, 32GB SDIMM at 1066MHz, with hyper-threading enabled. These machines were interconnected by a Gigabit Ethernet switch and ran Ubuntu Server 14.04 LTS.

6.1 Source of entropy and PRGs

We empirically evaluate both the source of strong entropy and PRGs through statistical methods and tools, following state of the art recommendations [Bassham et al. 2010]. To achieve our goal, we used NIST's test suite [NIST 2017]. We generated one file containing 50MB of random bits per generator. These files were used as input for the test suite tool STS [NIST 2017]. In the end, our generators passed the absolute majority of tests and sub-tests: they failed only 2 sub-tests out of 188 (passed 146 out of 148 non-overlapping template matching), as summarized in Table 1. This gives a very high level of confidence to our generators.

Test	Result
Frequency	✓
Block Frequency	✓
Cumulative Sums (forward)	✓
Cumulative Sums (backward)	✓
Runs	✓
Longest Run of Ones	✓
Binary Matrix Rank	✓
Discrete Fourier Transform	✓
Non-overlapping Template Matching	146/148
Approximate Entropy	✓
Random Excursions	8/8
Random Excursions Variant	18/18
Serial (first)	✓
Serial (second)	✓
Linear Complexity	✓

Table 1. STS: results of the single tests

6.2 iDVV generators

In this section, we analyze the performance of our iDVV generator implementation, which is essential to provide low latency and high throughput control plane communication at a low cost.

Key derivation functions (KDFs) are used to generate secure cryptographic keys, i.e., keys that can resist to different types of attacks such as brute force and exhaustive key search attacks [Yao and Yin 2005]. KDFs have common design characteristics, such as strong hash functions to compute digests for the raw key material.

A secure KDF can be defined as $H^c(p||s||c)$ [Yao and Yin 2005]. H is a strong hash function such as SHA256 or SHA512. The exponent c represents the number of iterations used to make the task of the attackers harder. A common value for c is 2^{16}. This exponent is particularly necessary if the entropy of the input p (e.g., password, seed, key) is unknown. In practice, the input of the KDF is likely to be of low-entropy [Yao and Yin 2005]. While in some use cases a high exponent c might be necessary to increase the cost of an attack trying to recover the key, it also significantly increases the cost of the key derivation function for high performance latency-sensitive applications.

Differently from a traditional key derivation use case, our implementation of the iDVV generator in the context of ANCHOR uses high-entropy values. In other words, we do not need to recur to the exponent c

as a means to compensate a potentially low-entropy p. By using by default two 32 bytes indistinguishable-from-random values in our iDVV generator, we make the task of an attacker very hard. It is also worth mentioning that iDVVs are essentially used in an association basis, i.e., they have a relatively short lifetime.

Figure 3 shows the latency of the seven cryptographic primitives we used with an iDVV generator. We tested each primitive by generating iDVVs of different sizes (16, 32, 64, and 128 bytes). The best performance is achieved by the implementations based on SHA1 and MD5, as expected. However, these two implementations have also the worst serial correlation coefficient, as shown in [Kreutz et al. 2017b]. The iDVV generator using SHA512 or Poly-OTP has good performance, achieving a good security-performance tradeoff.

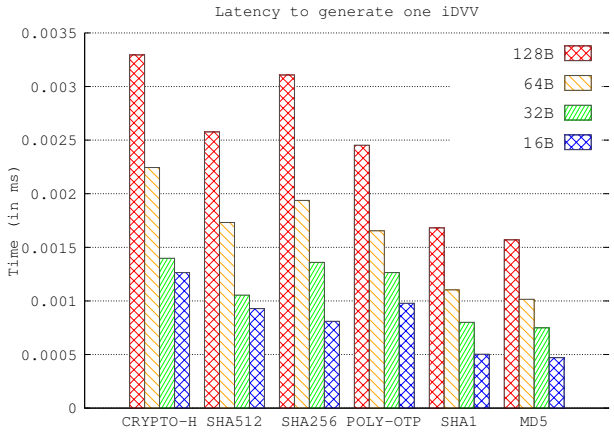

Fig. 3. Latency of different iDVV generators

6.3 Device-to-device communication performance

Connection establishment. While a TLS connection takes around 19 ms to be established, a device association using the ANCHOR takes less than 0.06 ms. In other words, our connection setup process outperforms the TLS handshake because we have only half the number of steps, namely, we don't incur the cost of exchanging data to generate the session keys, and we use NaCl for secure and fast ciphering.

Communications overhead. Figure 4 shows the results of communication between OpenSSL, TCP, and our proposal. For communication of up to 128 forwarding devices, sending 10k control messages each, our solution requires (while offering stronger security guarantees - see below) only half of the resources and time of an OpenSSL-based implementation using AES256-SHA, the most widely available cipher suite — adopted by most IT providers.

In Figure 4, we can also observe the overhead of confidentiality (TCP-iDVV-EMAC). In comparison with providing only authenticity and integrity (TCP-iDVV-MAC), confidentiality incurs in an overhead of 15%. Out-of-band control channels are one example scenario where confidentiality of control plane communications might not be always required.

It is worth emphasizing that we achieved these results by ensuring also much stronger security, as we generated one iDVV (i.e., one secret) *per packet*. On the other hand, the OpenSSL-based implementation used a single key (for the symmetric ciphering) for the entire communication session.

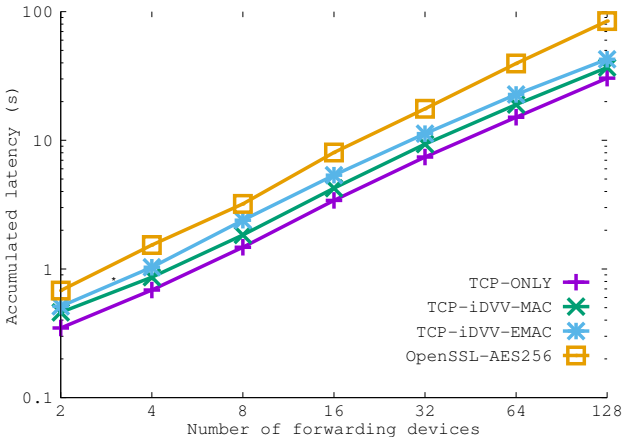

Fig. 4. Control plane communication costs

6.4 Traditional solutions *versus* anchor

In Table 2 we provide a summarised comparison between a traditional solution and our ANCHOR. As traditional solutions we considered the EJBCA (http://www.ejbca.org/) and OpenSSL, two popular implementations of PKI and TLS, respectively. As we have shown before, our bootstrap process (device registration and association) is much faster and our connection latency is also significantly lower. An interesting take away is that our solution has nearly one order of magnitude less LOC and uses four times less external libraries and only four programming languages. This makes a difference from a security and dependability perspective. For instance, to formally prove more than 717k LOC (EJBCA + OpenSSL) is by itself a tremendous challenge. And it gets considerably worse if we take into account eighty external libraries and eleven programming languages.

In conclusion, our proposed architecture offers a functionally equivalent level of security (with respect to security properties such as authenticity, integrity and confidentiality) to traditional alternatives by combining NaCl, our ANCHOR, and the iDVV mechanism. Additionally, our ANCHOR offers a higher level of security by providing post-compromise security (PCS) and post-quantum security (PQS). While the former is ensured through post-compromise recovery (see Section 4.10), the latter is a consequence of using only symmetric cryptography. Further, the lightweight nature of our mechanisms, such as the iDVV, make them amenable to be used on a per message basis to secure communication, increasing cryptographic robustness. Moreover, by having less LOC, we significantly reduce the threat surface.

Finally, it is worth emphasizing that the perfect forward secrecy (*) of traditional solutions, such as those provided by the different implementations of TLS, is not easy or simple to enforce. First, in spite of TLS providing ciphers that offer PFS, in practice, different cipher suites do not feature it [Sheffer et al. 2015].

This means that not all implementations and deployments of TLS offer PFS or provide it with very low encryption grade [DigiCert Inc 2017; Huang et al. 2014; Namecheap.com 2015]. To give an example, widely deployed web servers, such as Apache and Nginx, may suffer from weak PFS configuration [DigiCert Inc 2017]. Second, research results have recurrently shown that most DHE- and ECDHE-enabled servers use weak DH parameters or practices that greatly reduce the protection afforded by PFS, such as private value reuse, TLS session resumption, and TLS session tickets, i.e., provide a false sense of security [Adrian et al. 2015; Huang et al. 2014; Springall et al. 2016].

Table 2. Traditional solutions *versus* ANCHOR

Functionality		**Traditional solutions**	**ANCHOR**
Typical Software		EJBCA (PKI) + OpenSSL (TLS)	ANCHOR + iDVV + NaCl
Device Identification		based on certificates; costs = issue a certificate	based on unique IDs controlled by the ANCHOR; costs = register the device (assign a unique ID)
Device Registration		based on certificates; costs = certificate installation + security control policy/service	registration protocol; costs = register the device + iDVV bootstrap
Device Association & KeyGen		12 step mutual handshake + DH for session keys (incl. certificate validation - any two device can establish an association)	6 step trust establishment with ANCHOR + iDVVs per message, session, interval of time, ... (ANCHOR has to authorize association)
Security Properties	Authenticity	✓	✓
	Integrity	✓	✓
	Confidentiality	✓	✓
	PFS	✓(*)	✓
	PCS	✗	✓
	PQS	✗	✓
Communications		symmetric cryptography (cipher: AES256-SHA)	symmetric cryptography (cipher: Salsa20)
TLS stack		highly configurable and complex (717k LOC)	easy to use, simple (85k LOC), and efficient

7 RELATED WORK IN SDN SECURITY

Most attacks to SDN exploit different vulnerabilities of the control plane, such as the lack of authentication, authorization and other essential security properties (e.g., integrity, confidentiality and data freshness) [Antikainen et al. 2014; Kreutz et al. 2013; Scott-Hayward et al. 2016]. As a consequence, the absolute majority of the works on security of SDN are related to the controller, applications, forwarding devices, or a set of specific attacks (e.g. DDoS, IP and MAC spoofing, eavesdropping on the data plane) [Aseeri et al. 2017; Porras et al. 2012; Scott-Hayward et al. 2013; Shin and Gu 2013; Shin et al. 2013, 2014; Wan et al. 2017]. However, not much attention has been paid to the security requirements of control plane associations and communication between devices (see [Dacier et al. 2017; Kreutz et al. 2015; Scott-Hayward et al. 2016] for broad surveys), one of the aspects we address in this paper.

TLS and IPSec are examples of protocols that can be used to secure the communication between forwarding devices and controllers. While TLS is the one recommended by ONF, recent research discusses the strengths and weaknesses of these protocols as a mean to provide authenticated and encrypted control channels [Samociuk 2015]. While the of use these protocols gives important security properties, they have an impact on control plane performance. Additionally, the complexity of existing software has been recurrently

pointed out as one of the main cause for a high number of reported vulnerabilities, that in many cases have led to security attacks [Hoepman and Jacobs 2007; Markowsky 2013; McGraw 2004; Zhou and Jiang 2012]. By logically-centralizing crucial security mechanisms, our ANCHOR removes complexity from both controllers and switches, enhancing the robustness of the infrastructure, without significant compromise in performance.

Recently, the use of lightweight information hiding based authentication (by means of secrecy through obscurity) has been proposed as one way of protecting SDN controllers from DoS attacks [Abdullaziz et al. 2016]. The idea is to use a specific field in the IP protocol to hide the switch authentication ID. In order for the scheme to be workable, it is assumed that a look-up table and unique IDs are shared among devices through existing key distribution protocols. While such lightweight technique can indeed be used to mitigate DoS attacks, it does not address the security issues of control plane communications – such as authenticity, integrity, confidentiality, and data freshness – we address here.

To our knowledge, an architectural approach as the one we propose here (which ultimately led to following the SDN philosophy of "logical centralization") was lacking. Importantly, this approach allowed us to gain a global perspective of the relevant gaps in SDN and the limitations of existing solutions to the problem. This first step gave insight into one of the most relevant problems of SDN (as noted by the ONF or MEF security groups [MEF 2017; ONF 2017]): the security of the associations and communications between devices—which jointly with the architecture itself, is one of the main contributions of our paper.

8 DISCUSSION

We briefly discuss how we filled the gaps identified in Section 3, with our specialization of the logically centralized ANCHOR architecture for 'security'. Incidentally, we also show, in Appendix D, to which extent these solutions cover ONF's security requirements. We conclude the section with a critique of our choices and results.

8.1 Meeting the challenges

Security vs performance? Control channels need to provide high performance (high throughput and low latency) while keeping the communication secure. However, as it has been shown, security primitives have a non-negligible impact on performance. To mitigate this problem, we selected the most appropriate cryptographic primitives (SHA512) and libraries (NaCl) to ensure the security of control plane communications. Additionally, the proposed integrated device verification values (iDVVs) allow systematic refreshing of crypto material with high performance, while further improving cryptographic robustness. By logically centralizing the fundamental aspects of these mechanisms in the ANCHOR, the performance overhead introduced in forwarding devices and controllers is limited, as they require only minimal functionality to 'hook' to the ANCHOR instructions.

Complexity vs robustness? Traditional implementations of SSL/TLS, such as OpenSSL, have a large, complex code base, that recurrently leads to vulnerabilities been discovered. Similar problems are observed in PKI subsystems. It is well know that an effective means to achieve robustness is by reducing complexity. Hence our choice for the NaCl and iDVV mechanisms to help filling this gap, since they are respectively lightweight (small code base), efficient, yet secure alternatives to OpenSSL-like implementations. As such, they are a robust solution to provide authentication and authorisation material for the secure communications protocols we propose. They are also amenable to verification mechanisms aimed to assure correctness, which

are much harder to employ in very large code bases. Again, the centralization of the nuclear parts of the non-functional mechanisms introduced in our solution is the key to reduce complexity of networking devices, improving their robustness.

Global security policies? We have argued that controllers and network devices often employ suboptimal network authentication and secure communication mechanisms, despite recommendations from ONF and other such organizations for the opposite. This problem is very similar in nature to the state of affairs in networking before SDN. In traditional networks, enforcing relatively "simple" policies such as access control rules [Casado et al. 2007] or traffic engineering mechanisms [Jain et al. 2013] was either very hard or even impossible in practice. Given the current undesirable state of affairs, we believe the same to be true to non-functional properties, with security as a prominent example. Our logically centralized ANCHOR architecture addresses this gap by providing a means for making centralized policy rules (e.g., about registration, authentication and association of network devices) and the necessary mechanisms to enforce them, permeating the SDN architecture in a global and coherent way.

Resilient roots-of-trust? We debated that there is a (probably reduced) number of functions which should not be left to ad-hoc implementations, due to their criticality on system correctness. The list is not closed, but we hope to have shown that strong sources of entropy, resilient indistinguishable-from-random number generators, and accurate, non-forgeable global time services, are clear examples of difficult-to-get-right mechanisms that benefit from such logically centralized approach. ANCHOR addresses this issue, by providing the motivation to design and verify careful and resilient once-and-for-all implementations of such root-of-trust mechanisms, which can then be reinstantiated in different SDN deployments.

8.2 Devil's advocate analysis

Doesn't the logical centralization of non-functional properties create a single point of failure?

As mentioned in the introduction, we have a long-term strategy towards this problem. The results of this paper already go a long way improving robustness of a single root-of-trust, compared to the state of the art: lowering failure probability; mitigating and recovering from the consequences of failure. The logical next step would be to try and prevent failures in the first place. However, the failure of a simplex system of reasonable complexity cannot be prevented. Nevertheless, note that logical centralization is not necessarily physical centralization.

Our plan for future work (and the way we drafted our architecture paved the way) is to leverage state-of-the-art security and dependability mechanisms using replication. For instance, to achieve tolerance of crash and Byzantine faults and attacks, we can readily enhance ANCHOR by replication, taking advantage of state machine replication libraries such as BFT-SMaRt [Bessani et al. 2014], replicating and diversifying components to prevent failure of this logically central point, with the desired confidence. These concepts have been applied to root-of-trust like configurations similar to ANCHOR [Cachin and Samar 2004; Kreutz et al. 2014; Zhou et al. 2002]. Furthermore, systems designed with state machine replication in mind can also handle different types of threats, such as DoS and resource exhaustion, without compromising the operation of the service [Kreutz et al. 2016].

Won't the natural hardware evolution be by itself enough to reduce the penalty imposed by cryptographic primitives? The recent reality seems to contradict this assertion – hardware evolution does not seem enough, for several reasons. First, new hardware architectures can (potentially) benefit different existing

software-based solutions. For instance, both NaCl and OpenSSL take advantage of hardware-based AES accelerators. Second, and as is well known, the fixed price of advancements in hardware seems to be coming to an end [IEEE Spectrum 2015]. Third, most of the major IT companies, such as Google and Microsoft, have been redesigning existing software to make it more usable, efficient, secure, and robust [Livshits et al. 2015]. In short, hardware will not be the panacea.

Aren't traditional PKI and TLS implementations enough? Following what is becoming recurrently advocated by many in the industry and in the security community, we have tried to argue that the simplicity and size of software and IT infrastructure matters [Cisco 2014; Verizon 2015]. Higher complexity has been shown to lead inevitably to an increased likelihood of bugs and security incidents in software. Indeed, different implementations of PKI and TLS have been recently used as powerful "weapons" for cyber-attacks and cyber-espionage [BOCEK 2015; PwC, CSO magazine and CERT/CMU 2014], leading to concerns about their robustness. Contrary to what this argument may suggest, that does not mean PKI and TLS are "broken". We believe they remain fundamental to various IT infrastructures. However, as the main challenges of securing SDN are usually relatively constrained to within a network domain, we have come to understand that simpler, domain-specific solutions seem to be preferable in this environment when compared to complex infrastructures such as the PKI, and large code bases as OpenSSL.

Wouldn't the use of out-of-band control channels solve most problems? Out-of-band channels may be useful in some contexts, but they are not "intrinsically" secure. It is a recurrent mistake to consider physical isolation, *per se*, as a form of security. Several studies have indeed argued the opposite: that out-of-band channels worsen the problem, by making control plane management more complex and less flexible, endangering control plane communications [Edwards 2014; Manousakis and Ellinas 2015]. We do not take a stance in this discussion, but the fact is that real incidents, such as NSA sniffing of Google's cables between data centers [Schneier 2015], seem clear examples that out-of-band channels are not, *per se*, enough.

9 CONCLUDING REMARKS

In this paper, we proposed a solution to the problem of enforcing non-functional properties in SDN, such as security or dependability. Re-iterating the successful philosophy behind the inception of SDN itself, we advocate the concept of logical centralization of SDN non-functional properties provision, which we materialize in terms of the blueprint of an architectural framework, ANCHOR.

Taking 'security' as a proof-of-concept use case, we have shown the effectiveness of our proposal. We made a gap analysis of security in SDN, and populated the ANCHOR middleware with crucial mechanisms and services to fill those gaps and enhance the security of SDN.

We evaluated the architecture, especially focusing on the security-performance analysis tradeoff, giving proofs of the algorithms, cryptographic robustness analyses, and experimental performance evaluations. By resorting to recent primitives, lightweight albeit secure, like NaCl and iDVV, we outperform the most widely used encryption of OpenSSL by 50%, with a higher level of security. Our solution also fulfills eleven of the security requirements recommended by ONF.

The mechanisms we propose are certainly not the final answer to SDN security problems. That is not our claim. We however believe, and hope to have justified in the paper, that an architecture that logically centralizes the non-functional properties of an SDN to have the potential to address some of the most

prement unsolved problems regarding the robustness of the infrastructure. We thus hope our work to trigger an important discussion on these fundamental architectural aspects of SDN.

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A CORRECTNESS OF ALGORITHM 1

Correctness. We argue about the properties of Algorithm 1, as a source of strong entropy.

LEMMA 1. *If the initial values of rand_bytes() and H(data) are indistinguishable from random, then the resulting initial external entropy (e_entropy - line 2) is indistinguishable from random. Then, the initial internal entropy (i_entropy - line 3) will be also indistinguishable from random.*

Proof: Assuming that rand_bytes() uses one of the strongest pools of entropy of an operating system, such as /dev/urandom, the outcome of this function call will be indistinguishable from random. Assuming that H is a cryptographically strong hashing function, the output of H(data) will be indistinguishable from random for every different input data. Consequently, the XOR operation between rand_bytes() and H(data) will result in an indistinguishable-from-random initial e_entropy. Following, the XOR operation between rand_bytes() and e_entropy will result in an indistinguishable-from-random initial i_entropy. In other words, both internal and external entropy are initialized with indistinguishable-from-random values. □

LEMMA 2. *If P_i, P_j, and i_entropy are indistinguishable from random, then the updated external entropy (e_entropy - line 5) will be indistinguishable from random.*

Proof: As discussed before, the pools of entropy P_i and P_j contain unpredictable events of external sources of entropy, such as network traffic and idleness of links. Thus, assuming that H is a cryptographically strong hashing function, then the output of H($P_i||P_j$) will be indistinguishable from random. Lemma 1 shows that the internal entropy (*i_entropy*) is indistinguishable from random. In consequence, the updated external entropy (*e_entropy* - line 5), which is the output of an XOR operation between two indistinguishable-from-random values, will be indistinguishable from random. □

LEMMA 3. *If the initial value of rand_bytes() is indistinguishable from random, then the resulting internal entropy (i_entropy - line 7) is indistinguishable from random.*

Proof: The proof of Lemma 1 establishes that the output of *rand_bytes* is indistinguishable from random. Additionally, *E_counter* is an internal counter not known by external entities. Therefore, assuming that H is a cryptographically strong hashing function, then *i_entropy* output by H(*rand_bytes*||*E_counter*) will be indistinguishable from random. □

THEOREM 1. *If e_entropy and i_entropy are indistinguishable from random, then the resulting entropy returned by entropy_get (line 8) will be indistinguishable from random.*

Proof: Lemmata 1 and 2 show that the initial and updated external entropy are indistinguishable from random. Lemma 3 has shown that the internal entropy generated in line 7 is indeed indistinguishable from random. As a consequence, *entropy*, as the output of an XOR operation between *i_entropy* and *e_entropy* (line 8) will be indistinguishable from random. This proves that Algorithm 1 satisfies property **Strong Entropy**. □

B CORRECTNESS OF ALGORITHM 2

Correctness. We argue about the properties of Algorithm 2, as a source of indistinguishable-from-random pseudo-random values.

Lemma 4. *If entropy_get() returns an indistinguishable-from-random value, then the initial seed (line 2), counter (line 3) and pseudo random value (nprd - line 4) will be indistinguishable from random.*

Proof: Theorem 1 establishes that the output of *entropy_get* is indistinguishable from random. Thus, both the *seed* and the first *nprd* will be indistinguishable from random. Similarly, the function *long_uint* (using as input *entropy_get* - line 3), which, on most architectures, uses 64 bits to represent an unsigned long int, will return the value *counter*, indistinguishable from random. □

Lemma 5. *If entropy_get() returns a value indistinguishable from random, then the refreshed PRG internal state (lines 6-8) will lead to indistinguishable from random values for seed, counter and nprd.*

Proof: The proof follows the same argumentation of the proof of Lemma 4, for *seed* and *counter*. As for *nprd*, assuming that neither the seed or counter are known outside the PRG, and assuming that H is a cryptographically strong hashing function, then the output of H, having as input a concatenation of the new *seed*, current *nprd*, and new *counter*, will be indistinguishable from random. □

Theorem 2. *If seed and nprd are indistinguishable-from-random values, then the next nprd returned by PRG_next (line 12) will be indistinguishable from random.*

Proof: Lemmata 4 and 5 established that both the *seed* and *nprd* are always indistinguishable from random, since the initial state. Assuming that HMAC is a cryptographically strong message authentication code primitive, and that the counter is not known outside of the PRG, then the output of HMAC, keyed by *seed* and having as input a concatenation of *nprd* and *counter*, will be indistinguishable from random. This proves that Algorithm 2 satisfies property **Robust PRG**. □

C CORRECTNESS OF ALGORITHM 4

Correctness. We now formalize and prove the properties of Algorithm 4.

As a result of the registration process, ANCHOR keeps lists of registered devices and controllers, and lists of the controllers each device is authorized to associate with.

Proposition 1. *Any device F can only associate to a controller C authorized by the* anchor.

Proof: Forwarding devices will be able to associate only to controllers listed in the CList(F) provided by A (step 2 of Algorithm 4), since if F tries to associate with a non-authorized controller (for F), A will not proceed past step 4 after being contacted by that controller, aborting the association. On the other hand, a rogue controller posing to F as authorised in reply to step 3, cannot jump to step 6 and invent an association key AiD that convinces F, since it does not know x_f. This proves that Algorithm 4 satisfies property **Controller Authorization**. □

Proposition 2. *Any device F can associate to some controller, only if F is authorized by the* anchor.

Proof: Only if a device F is legitimate, i.e. it is in the list of registered devices, will it be able to associate to some registered controller. A will not proceed past step 1 of Algorithm 4 after being contacted by a rogue device, aborting the association. On the other hand, a rogue device posing to C as legitimate and authorised in step 3, will make C proceed with step 4, indeed, but the request will be rejected by A, since E_F is not recognisable by A, corresponding to no shared key with a legitimate device. The replay of an old

(but legitimate) encrypted E_F request in step 3 will also fail, since it is bound to the (current) nonces. This proves that Algorithm 4 satisfies property **Device Authorization**. □

PROPOSITION 3. *At the end of Algorithm 4 execution, the association ID (AiD) is only known to F and C.*

Proof: A creates AiD in step 5, and forgets about it after sending it to C (see Section 4.7). AiD is sent from A to C, encrypted both by Ke_{AF} and Ke_{AC}, keys shared by A only with F and C respectively. C trusts it came from A, due to the HMAC, so the two encrypted blocks should contain the same AiD value, and sends the AiD under Ke_{AF} encryption to F. So, at the end of the execution of the algorithm, both F and C, and only them, hold AiD. This proves that Algorithm 4 satisfies property **Association ID Secrecy**. □

PROPOSITION 4. *At the end of Algorithm 4 execution, the seed (SEED) is only known to F and C.*

Proof: C creates $SEED$ in step 7. $SEED$ is sent from C to F, encrypted by K_AiD, association key known only to C and F, as per Proposition 3. C trusts that F, and only F, has the same $SEED$ sent, when it receives back from F the XOR of $SEED$ with the current nonce x_g encrypted with AiD, since (as per Proposition 3) only F could have opened the encryption of $SEED$ with AiD in the first place, and encrypt the reply. This proves that Algorithm 4 satisfies property **Seed Secrecy**. □

D ONF'S SECURITY REQUIREMENTS

Several security requirements should be fulfilled in control plane communications. Most of these requirements are enumerated in ONF's best practice recommendations [ONF 2015]. In this appendix we go through the eleven (out of twenty four) such requirements that are addressed by the ANCHOR, iDVV and NaCl.

Both communicating devices should be authenticated (REQ 4.1.1). Using our ANCHOR, all devices have to be properly registered and authenticated before proceeding any other operation.

Operations (e.g., association) of components should be authorized (REQ 4.1.2). The ANCHOR needs to explicitly authorize associations between any two devices. Each association has a unique identification.

Devices should agree upon the security (e.g., key materials) associations (REQ 4.1.3). By using the ANCHOR and its mechanisms, such as the source of strong entropy, we ensure strong key materials. The iDVV mechanism is initialized by the two communicating devices once the association has been authorized by the ANCHOR.

Integrity of packets should be ensured (REQ 4.1.4). We provide integrity and authenticity of packets through message authentication codes. By default, we generate one iDVV per packet, providing stronger security.

Each device should have a unique ID and other devices should be able to verify the identity (REQ 4.2.1). Devices are uniquely identified by the ANCHOR. The unique IDs are associated to the devices as soon as they are registered within the ANCHOR.

Issues related to the lifecycle of IDs should be managed, such as generation, distribution, maintenance, and revocation (REQ 4.2.2). The ANCHOR provides the services required for managing device IDs. IDs are assigned to devices during the registration phase. Revocation can be done by network administrators at any time.

Devices should be able to verify the integrity of each message (REQ 4.4.4). Any two communicating devices are able to verify the integrity of each message through message authentication codes.

Amplification effects should be taken into account, i.e., attackers should not be able to perform reflection attacks (REQ 4.4.5). We use requests and replies of the same size between devices and the ANCHOR, which avoids reflection attacks.

Automated key/credential management should be implemented by default, allowing generation, distribution, and revocation of security credentials (REQ 4.8.3). We have in place automated mechanisms for refreshing credentials, such as refresh the iDVV's seed using the ANCHOR's source of strong entropy.

Data confidentiality, integrity, freshness and authenticity are ensured by the integrated device verification value. iDVVs are used to encrypt data and generate message authentication codes. Additionally, iDVVs can also be used as nonces, ensuring data freshness.

Availability is ensured by recommending multiple controllers to the forwarding devices. This is one of the essential tasks of the ANCHOR.

Lastly, it is also worth mentioning that whilst we do not meet all security requirements of ONF's guidelines, we do meet the fundamental ones with regard to security. For instance, requirements such as REQ 4.4.2, REQ 4.4.3, REQ 4.7.1, REQ 4.7.2, and REQ 4.7.3 [ONF 2015] are not yet covered by our architecture and protocols. However, most of these requirements are related to rate control of messages, additional signaling messages for dealing with future network attack types, and accountability and traceability. Such kind of requirements can be added (in the future) without impairing our conceptual architecture. In fact, some of these requirements, such as rate control of messages, are technical, rather than conceptual, which can be addressed with the right amount of engineering.