Puncturable Encryption – A Fine-Grained Approach to Forward Security and More

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joint work with Sebastian Ramacher & Daniel Slamanig

April 15, 2022

AIT Austrian Institute of Technology

Signatures

Encryption

Key Exchange

Identification

MACs

Security and Trust of Cryptographic Keys

Advanced Primitives

Secure Computation

Zero-Knowledge Proofs

The Heartbleed Bug

The Heartbleed Bug is a serious vulnerability in the popular OpenSSL cryptographic software library. This weakness allows stealing the information protected, under normal conditions, by the SSL/TLS encryption used to secure the Internet. SSL/TLS provides communication security and privacy over the Internet for applications such as web, email, instant messaging (IM) and some virtual private networks (VPNs).

The Heartbleed bug allows anyone on the Internet to read the memory of the systems protected by the vulnerable versions of the OpenSSL software. This compromises the secret keys used to identify the service providers and to encrypt the traffic, the names and passwords of the users and the actual content. This allows attackers to eavesdrop on communications, steal data directly from the services and users and to impersonate services and users.

What leaks in practice?

We have tested some of our own services from attacker's perspective. We attacked ourselves from outside, without leaving a trace. Without using any privileged information or credentials we were able steal from ourselves the secret keys used for our X.509 certificates, user names and passwords, instant messages, emails and business critical documents and communication.

How to stop the leak?

As long as the vulnerable version of OpenSSL is in use it can be abused. Fixed OpenSSL has been released and now it has to be deployed. Operating system vendors and distribution, appliance vendors, independent software vendors have to adopt the fix and notify their users. Service providers and users have to install the fix as it becomes available for the operating systems, networked appliances and software they use.

Q&A

What is the CVE-2014-0160?

CVE-2014-0160 is the official reference to this bug. CVE (Common Vulnerabilities and Exposures) is the Standard for Information Security Vulnerability Names maintained by MITRE. Due to co-incident discovery a duplicate CVE, CVE-2014-0346, which was assigned to us, should not be used, since others independently went public with the CVE-2014-0160 identifier.

Why it is called the Heartbleed Bug?

Bug is in the OpenSSL's implementation of the TLS/DTLS (transport layer security protocols) heartbeat extension (RFC6520). When it is exploited it leads to the leak of memory contents from the server to the client and from the client to the server.

An extended abstract of this article appears in the proceedings of CCS 2021. This is the full version and available in the IACR eprint archive.

On the (in)security of ElGamal in OpenPGP

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ABSTRACT

Roughly four decades ago, Taher ElGamal put forward what is today one of the most widely known and best understood public key encryption schemes. ElGamal encryption has been used in many different contexts, chiefly among them by the OpenPGP standard. Despite its simplicity, or perhaps because of it, in reality there is a large degree of ambiguity on several key aspects of the cipher. Each library in the OpenPGP ecosystem seems to have implemented a slightly different "flavour" of ElGamal encryption. While –taken in isolation– each implementation may be secure, we reveal that in the interoperable world of OpenPGP, unforeseen *cross-configuration attacks* become possible. Concretely, we propose different such attacks and show their practical efficacy by recovering plaintexts and even secret keys.

CCS CONCEPTS

• **Security and privacy → Public key encryption**.

KEYWORDS

OpenPGP, ElGamal encryption, side-channel attacks, key-recovery attacks, modular exponentiation

1 INTRODUCTION

The ElGamal cryptosystem [14] is one of the oldest and best-known public key encryption schemes. In the 80's and 90's it earned wide adoption for being simultaneously efficient and patent-free. Its most prominent use is arguably as part of OpenPGP [12], a standard aimed to promote consumable, interoperable email security, where it has been the default and most popular encryption option for decades [30]. While the change in patent status of RSA encryption slightly reduced its popularity, at the time of writing, still at least 1 in 6 registered OpenPGP keys have an ElGamal subkey [3], with about a 1,000 new registrations per year.

The ElGamal scheme builds on elegant mathematical structures and can be defined very compactly. This simplicity, together with the opportunity to mature for roughly four decades now, suggests that a crisp specification with clear parameter choices, rules, and algorithms would be present in international standards, in particular in OpenPGP. Surprisingly, this turns out *not* to be the case: our research reveals that OpenPGP's understanding of ElGamal encryption is open to interpretation, with several choices subject to the discretion of the implementer.

In this article we consider *cross-configuration attacks* on OpenPGP. Such attacks emerge when different interpretations ('configurations') of the same standard interact insecurely with each other. Towards identifying such conditions for ElGamal encryption, we need to first understand the universe of OpenPGP interpretations that are used in practice. We approach this challenge from various angles: we carefully study RFC4880 [12] which defines OpenPGP, we inspect the source code of three relevant OpenPGP-implementing software libraries (the `Go` standard library, `Crypto++`, and `gcrypt`), and we conduct a large-scale examination of millions of keys registered on OpenPGP key servers.

Our results reveal an insecure posture. For instance, we develop and prototype a plaintext recovery attack that can be mounted on ciphertexts produced by the ubiquitous GNU Privacy Guard (and other implementations, e.g. `Crypto++`) against keys generated following the original ElGamal specification [14]. The attack is effective against 2048 bit keys, which are considered secure at the time of writing. Our OpenPGP key server analysis reveals that more than 2,000 OpenPGP users are currently exposed.[1] We further illustrate how cross-configuration attacks can be combined with known side-channel exploitation techniques like FLUSH+RELOAD [38] or PRIME+PROBE [33]. One of our targets is the ElGamal implementation of `gcrypt`, the cryptographic library used by the GNU Privacy Guard. Interestingly, `gcrypt` has already been fixed twice after seminal work [21, 38] on side-channel attacks identified weaknesses. Concretely, by conducting an end-to-end attack we show that if a 2048 bit ElGamal key generated by `Crypto++` is used by `gcrypt` to decrypt a ciphertext, then an attacker that is OS- or VM-colocated with the decrypter can fully recover the decryption key.

Given that interoperability is the explicit and almost exclusive goal of any standardization effort, and commonplace in the OpenPGP world, we conclude that our attack conditions are as realistic as the attack results awakening. Our research is timely since a new version of the OpenPGP standard is currently being discussed [18]; we hope that our findings will influence that discussion.

This manuscript is organised as follows: In Section 2 we survey (a) the meaningful options available when implementing ElGamal encryption, (b) the options adopted by the `Go`, `Crypto++`, and `gcrypt` libraries, and (c) the options picked by over 800,000 users in practice (as far as reflected on key server databases); we also report on further interesting findings from our key server crawl. In Section 3 we recall various standard algorithms for solving discrete logarithms. In Section 4 we describe "vanilla" cross-configuration attacks, and in Section 5 we describe those combined with side-channel attacks. In Section 6 we conduct end-to-end exploits and describe how we bring in the required side-channel information. We conclude in Section 7.

1.1 Related Work

Since ElGamal encryption was first proposed [14], research efforts were both steered towards formally confirming its security (e.g. via reductions to the DDH problem [34]) and to shed light on its insecurities (e.g. when used in its textbook form [10]). CVE-2018-6829 [2]

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[1] We found that at most a small fraction of ElGamal keys is formed according to the original specification of [14]; otherwise, many OpenPGP users would be affected.

Trust Dies in Darkness: Shedding Light on Samsung's TrustZone Keymaster Design

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Abstract

ARM-based Android smartphones rely on the TrustZone hardware support for a Trusted Execution Environment (TEE) to implement security-sensitive functions. The TEE runs a separate, isolated, TrustZone Operating System (TZOS), in parallel to Android. The implementation of the cryptographic functions within the TZOS is left to the device vendors, who create proprietary undocumented designs.

In this work, we expose the cryptographic design and implementation of Android's Hardware-Backed Keystore in Samsung's Galaxy S8, S9, S10, S20, and S21 flagship devices. We reversed-engineered and provide a detailed description of the cryptographic design and code structure, and we unveil severe design flaws. We present an IV reuse attack on AES-GCM that allows an attacker to extract hardware-protected key material, and a downgrade attack that makes even the latest Samsung devices vulnerable to the IV reuse attack. We demonstrate working key extraction attacks on the latest devices. We also show the implications of our attacks on two higher-level cryptographic protocols between the TrustZone and a remote server: we demonstrate a working FIDO2 WebAuthn login bypass and a compromise of Google's Secure Key Import.

We discuss multiple flaws in the design flow of TrustZone based protocols. Although our specific attacks only apply to the ≈100 million devices made by Samsung, it raises the much more general requirement for open and proven standards for critical cryptographic and security designs.

1 Introduction

Beyond their usage in many and various daily activities, smartphones are increasingly used for many security-critical tasks, such as the protection of sensitive data (messages, images, files), cryptographic key management [26], FIDO2 web authentication [69], Digital Rights Management [68] (DRM),

Simultaneously, smartphones are becoming more and more complex and present an increasingly larger attack surface. The result is that they have become a major target for malware and malicious attackers. There have been many public exploits that allow an attacker to escalate privileges in the Android OS, gaining execution as root or even as the OS kernel [9, 14, 20, 21, 43]. Ideally, such attacks should not be able to compromise the devices' security-critical tasks.

Trusted Execution Environments (TEEs) are largely used in modern mobile devices to provide an isolated environment for execution of Trusted Applications (TAs) that can securely perform security-critical tasks. They have a relatively small codebase and limited APIs.

In contrast, the Rich Execution Environments (REEs), such as Android OS, cannot be fully audited and trusted (due to their complexity). An isolated TEE can be used alongside the REE to implement security-sensitive functions. This makes it harder for an attacker to compromise these functions, as the attack surface is significantly reduced and is limited to communication with the TEE.

In other words, the goal of the TEE is to withstand attacks from a fully compromised REE, including by privileged adversaries with kernel or root capabilities.

ARM is the most widely used processor in the mobile and embedded markets [50], and it provides TEE hardware support with ARM TrustZone [3, 8]. TrustZone separates the device into two execution environments:

1. A non-secure REE where the "Normal World" operating system runs.
2. A secure TEE where the "Secure World" operating system runs.

The REE and TEE use separate resources (e.g., memory, peripherals), and the hardware enforces the protection of Secure World.

In most mobile devices, the Android OS runs the non-

naked security by SOPHOS

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Adobe security team posts public key – together with private key

23 SEP 2017 5

Cryptography

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Previous: Tracking phones without a warrant ruled unc... Next: Monday review – Adobe botches, Apache bleeds a...

by Paul Ducklin

Finnish security researcher Juho Nurminen is a bit of a retweet celebrity right now, for all the wrong reasons.

Not *his* wrong reasons, but the wrong reasons of Adobe's Product Security Incident Response Team (PSIRT).

To explain.

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PRIVACY AND SECURITY

Amazon Engineer Leaked Private Encryption Keys. Outside Analysts Discovered Them in Minutes

By Dell Cameron | 1/22/20 12:24PM | Comments (16)

Photo: Getty

An Amazon Web Services (AWS) engineer last week inadvertently made public almost a gigabyte's worth of sensitive data, including their own personal documents as well as passwords and cryptographic keys to various AWS environments.

While these kinds of leaks are not unusual or special, what is noteworthy here is how quickly the employee's credentials were recovered by a third party, who—to the employee's good fortune, perhaps—immediately warned the company.

On the morning of January 13, an AWS employee, identified as a DevOps Cloud Engineer on LinkedIn, committed nearly a gigabyte's worth of data to a personal GitHub repository bearing their own name. Roughly 30 minutes later, Greg Pollock, vice president of product at UpGuard, a California-based security

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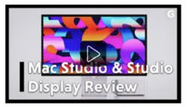

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BEST PRACTICES

Exposing secrets on GitHub: What to do after leaking credentials and API keys

If you have discovered that you have just exposed a sensitive file or secrets to a public git repository, there are some very important steps to follow.

MACKENZIE JACKSON
24 MAR 2020 · 6 MIN READ

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https://blog.gitguardian.com/leaking-secrets-on-github-what-to-do

How to increase the Resilience of Cryptographic Keys?

Resilience after Key Leakage: Forward Security

- Key leakage: severe issue for key establishment – all data immediately in danger
- Mitigation: forward security – old data still safe
- Efficient in interactive key-exchange protocols and mandatory in TLS 1.3 with 1-RTT
- 99% of Internet sites surveyed by Qualys SSL Labs support it
- Highly recognized by industry: Google, Apple, Meta, Microsoft, Cloudflare, ...

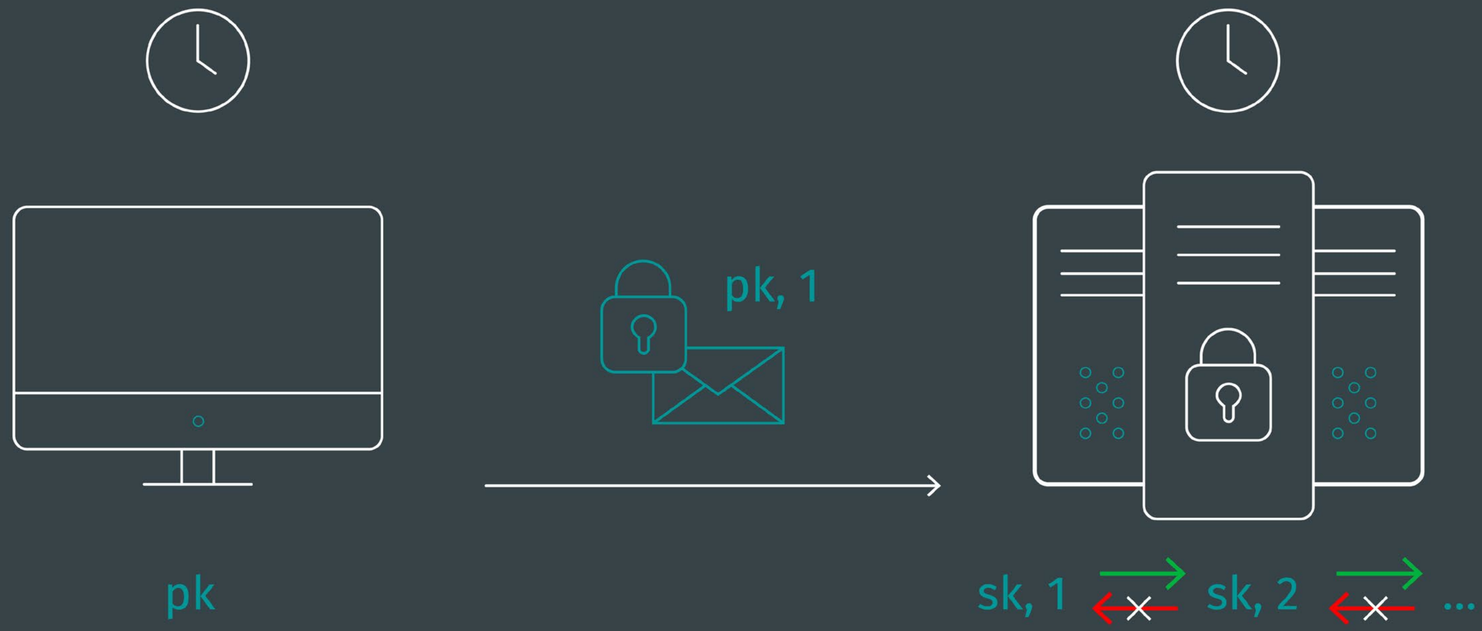
However: much harder in non-interactive settings!

Non-Interactive Forward Security

- Requirements: long-term fixed public key, (minimum to) no state between entities
- Particularly the case in modern distributed settings with many decentralized entities
- Deployed by, e.g., Dfinity in their non-interactive distributed key generation and key resharing protocol

How to even achieve this?

Non-Interactive Forward Security



Epoch-based synchronization [Canetti-Halevi-Katz 2003], compact parameter sizes (independent on # of epochs), coarse-grained

Fine-Grained Forward Security: Puncturable Encryption

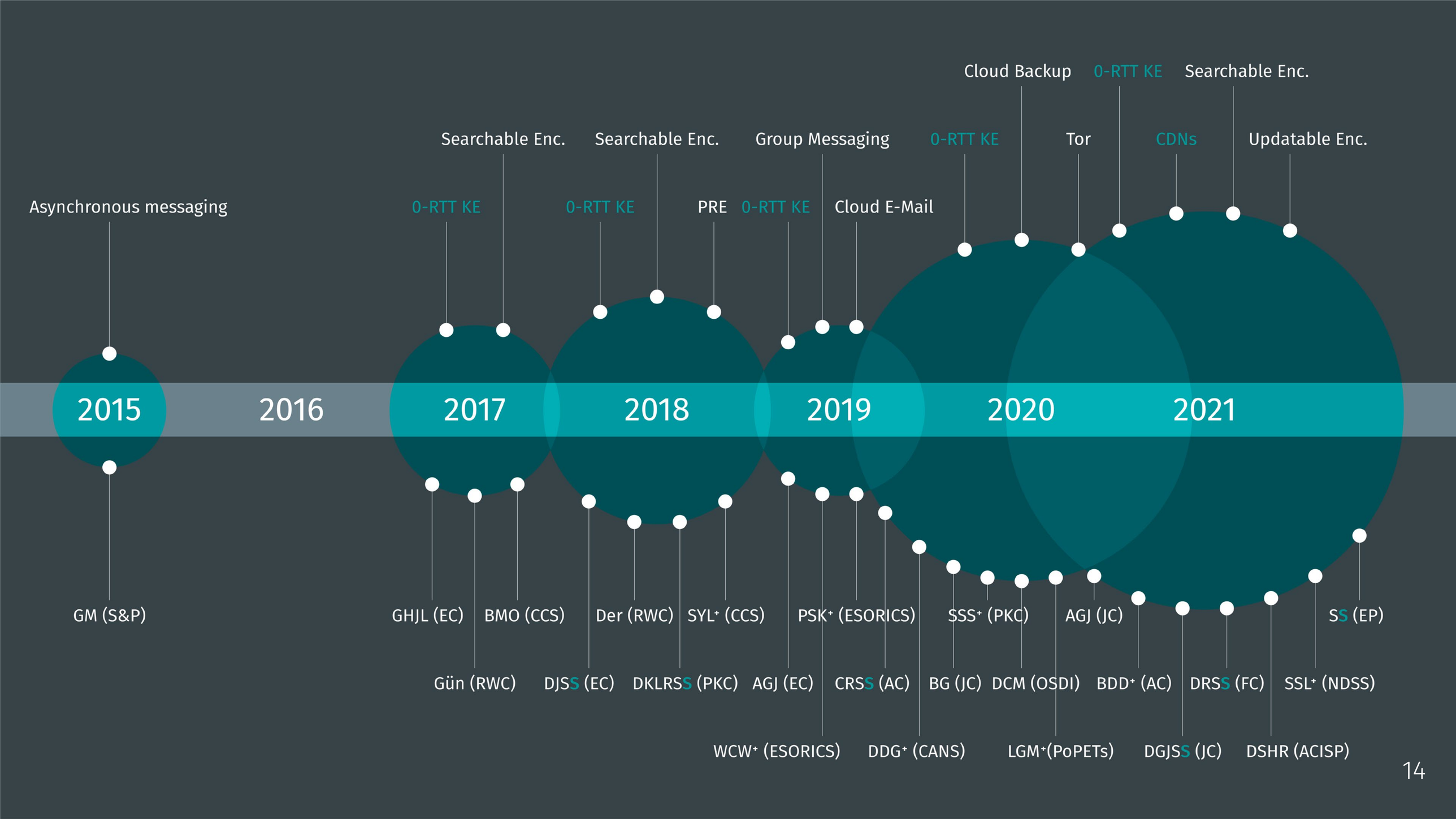
- Problem: loose synchronization required for practicality
- However: no forward-security guarantees for data within epochs
- Solution: Puncturable Encryption (Green & Miers 2015)
- Result: fine-grained forward-security guarantees for *all* data non-interactively

Puncturable Encryption

Tag-based approach (no synchronization required for sufficiently large tag space), fine-grained

Puncturable Encryption

- Common encryption scheme + puncture: $(pk, (sk, \varepsilon)) \leftarrow$ KeyGen, Enc, Dec, Punc
- Encryption: returns $(C, t_1) \leftarrow \mathsf{Enc}(pk, t_1, M)$
- Puncturing: returns $(sk, t_1) \leftarrow \mathsf{Punc}((sk, \varepsilon), t_1)$
- Properties: (sk, t_1) no longer useful to decrypt ciphertexts associated to t_1 (such as (C, t_1)), but still all others with $t_2, \ldots$
- Distinguishing feature: repeated puncturing of secret keys (add more tags to the secret key, exclude more ciphertexts from being decryptable)


Asynchronous messaging
0-RTT KE
Searchable Enc.
0-RTT KE
Searchable Enc.
PRE
0-RTT KE
Group Messaging
Cloud E-Mail
0-RTT KE
Cloud Backup
Tor
0-RTT KE
CDNs
Searchable Enc.
Updatable Enc.
2015
2016
2017
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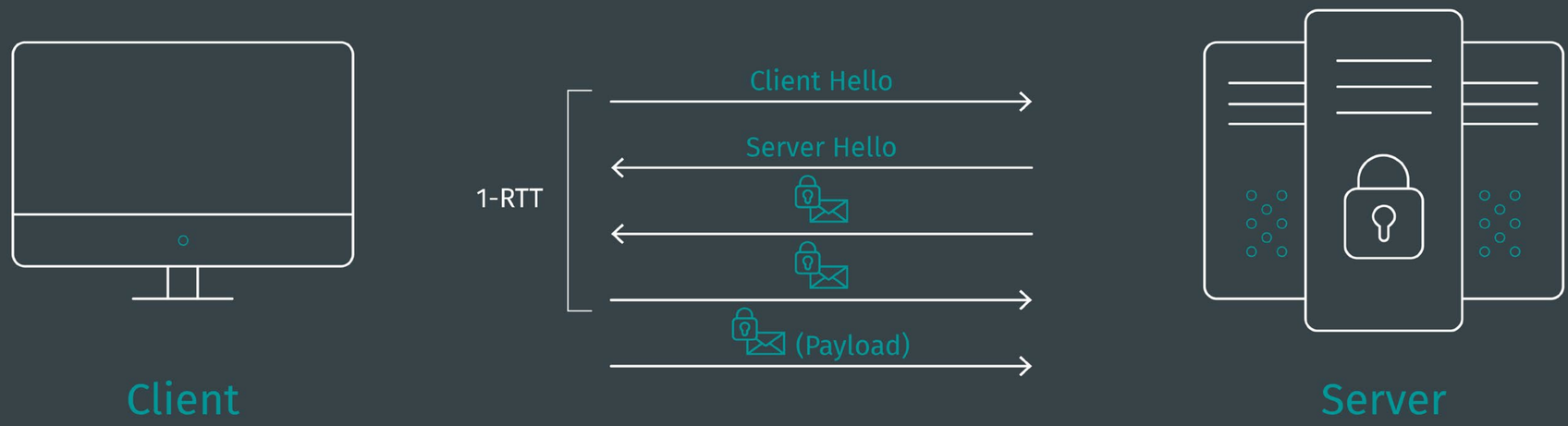
2021
GM (S&P)
GHJL (EC)
Gün (RWC)
BMO (CCS)
DJSS (EC)
Der (RWC)
DKLRSS (PKC)
SYL+ (CCS)
AGJ (EC)
WCW+ (ESORICS)
PSK+ (ESORICS)
CRSS (AC)
DDG+ (CANS)
SSS+ (PKC)
BG (JC)
DCM (OSDI)
LGM+(PoPETs)
AGJ (JC)
BDD+ (AC)
DGJSS (JC)
DRSS (FC)
DSHR (ACISP)
SSL+ (NDSS)
SS (EP)

Appl. I: 0-RTT Key Exchange with Forward Security and Replay Protection

- Goal: send cryptographically protected payload *non-interactively* (i.e., in 0-RTT) with forward security and replay protection
- Incentive: reduce network communication costs

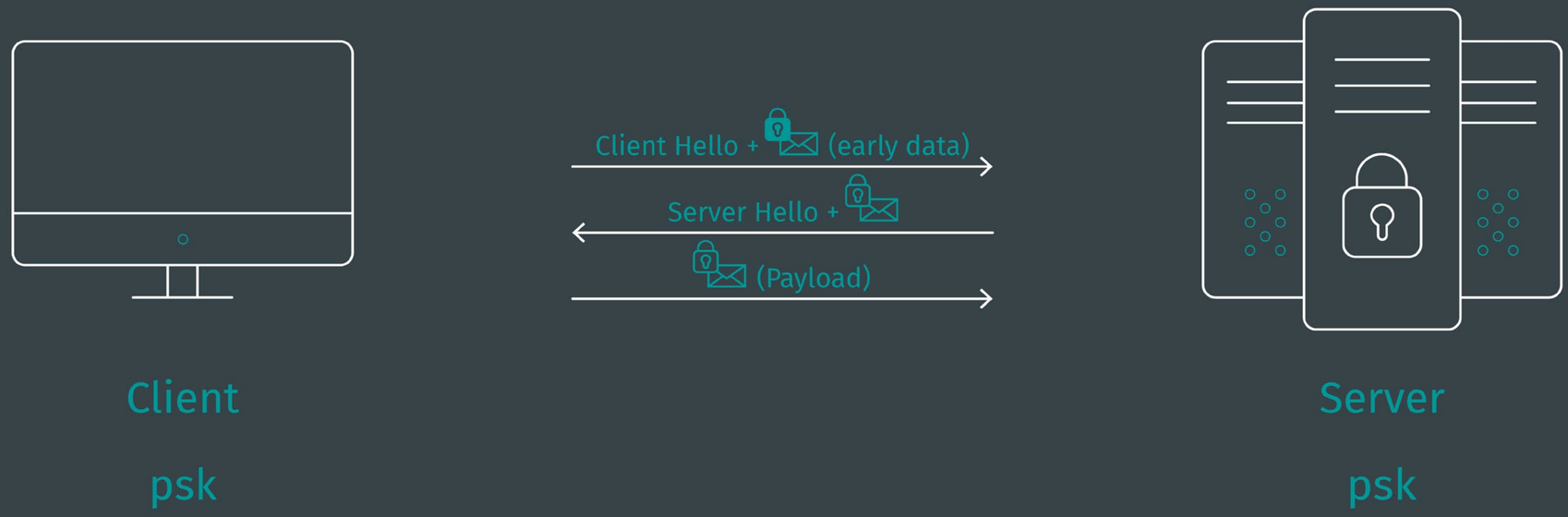
Problem: conventional key establishing modes (e.g., TLS) need at least one round trip (1-RTT) to achieve forward security

Key Establishment with TLS 1.3



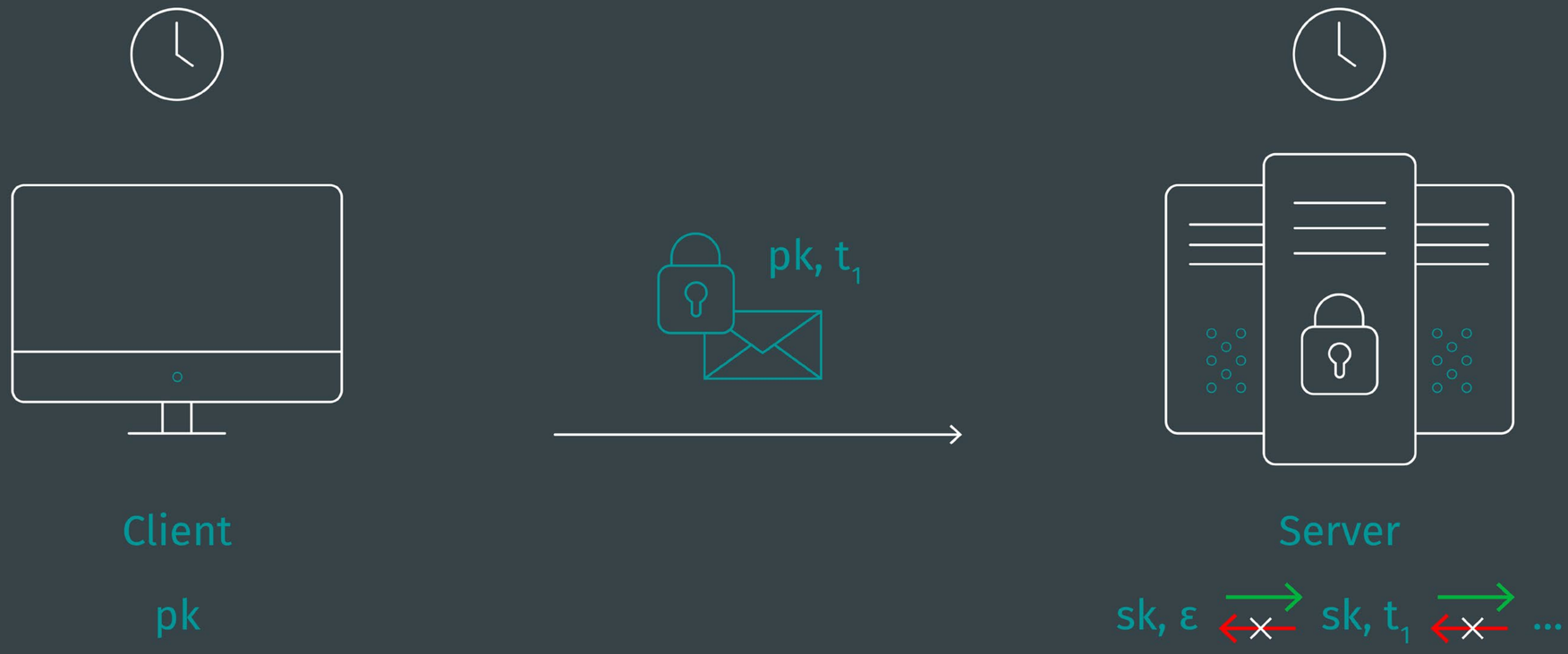
Forward-security guarantees, but 1-RTT before first payload message. Is this necessary?

Key Establishment with TLS 1.3 and Early Data



0-RTT, but no forward-security guarantees for early data.

0-RTT Key Exchange using Puncturable Encryption



Forward security and replay protection in 0-RTT [GHLJ17, DGJSS21],

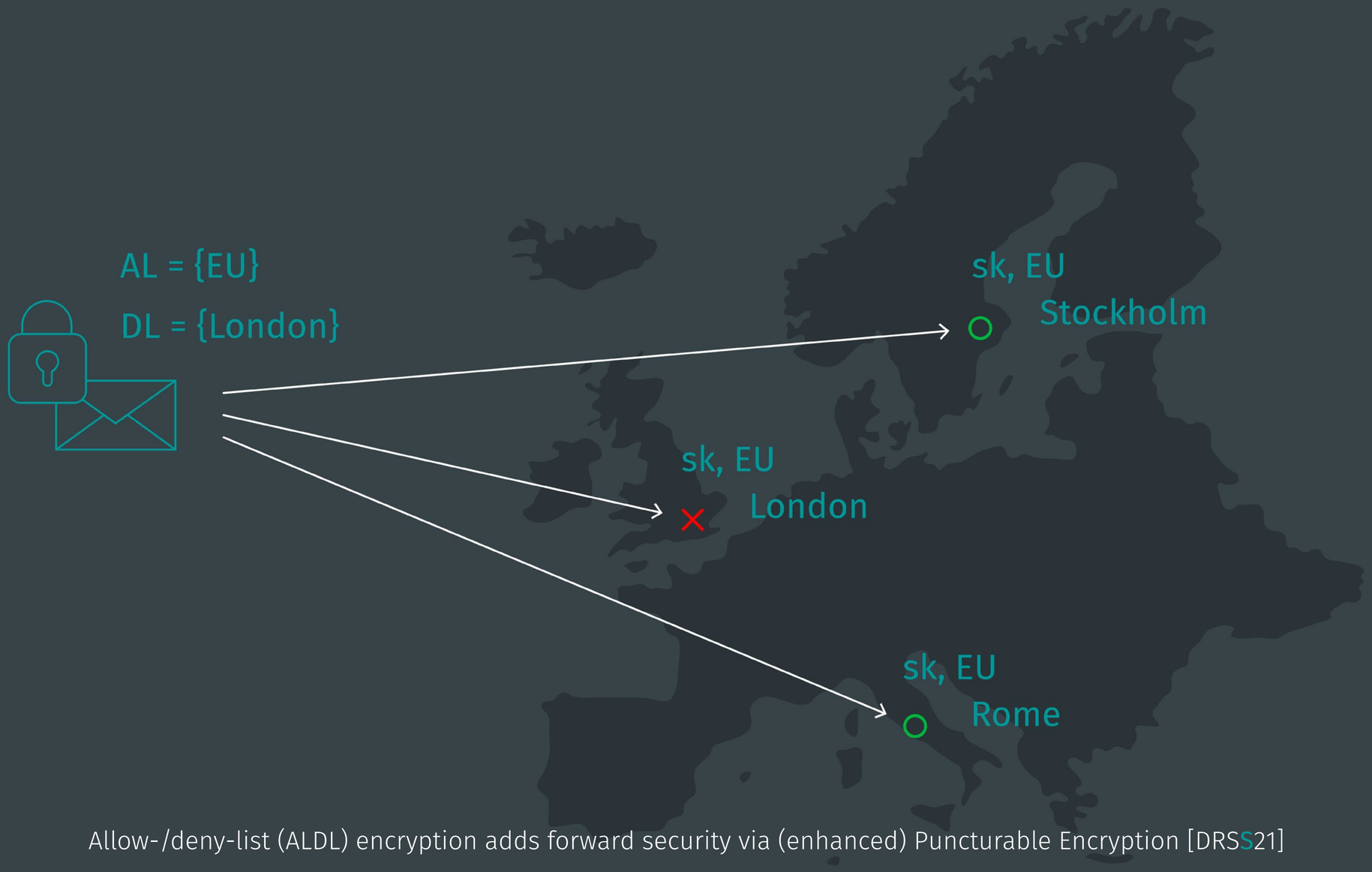
evaluation for QUIC [DDG+20], integration in OpenSSL [Ram21], using time-based puncturable encryption

Appl. II: Forward-Secure Content Distribution Networks

- Goal: Content Distribution Networks distribute TLS secret keys closer to customers
- Incentive: low-latency content distribution
- Solution: restrict access to secret keys – e.g., Cloudflare's Geo Key Manager allows access for certain locations while restricting access for co-locations

Problem: conventional CDNs do not ensure forward security,
i.e., customer keys may leak once a (co-)location key leaks

Forward-Secure CDNs using Puncturable Encryption



Allow-/deny-list (ALDL) encryption adds forward security via (enhanced) Puncturable Encryption [DRSS21]

Takeaways

- High demand in increasing resilience of secret keys
- Puncturable Encryption offers a simple solution on the cryptographic level, particularly for modern distributed and non-interactive scenarios
- Several applications and growing research interest: 0-RTT KE with forward security and replay protection, forward-secure CDNs, Searchable Encryption, mobile Cloud Backup, Tor, Updatable Encryption, ...

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Thank you

Christoph Striecks @cstriecks
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More on the topic: profet.at/blog/pe

SECREDAS Digital Privacy Safety & Security

COMP4DRONES

FWF Der Wissenschaftsfonds.

netidee FÖRDERUNGEN

KRAKEN

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