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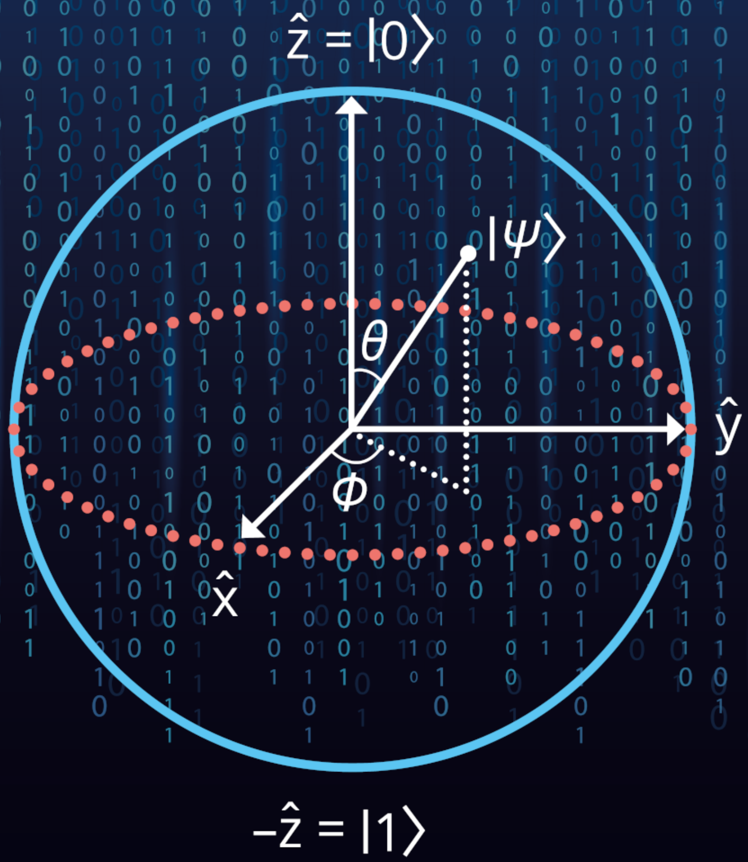

POST-QUANTUM CRYPTOGRAPHY

Current state and quantum mitigation

FEBRUARY 2021

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ISBN: 978-92-9204-468-8, DOI: 10.2824/92307

EXECUTIVE SUMMARY

Quantum Technology is an emerging field of physics and engineering, which exploits the principles of quantum physics, like quantum entanglement, quantum superposition and quantum tunnelling, to provide new paradigms and novel applications. From computing and communications to metrology and imaging, research in the last 2 decades has bear tangible and not so tangible results. It is a critical technology that policy makers believe it will generate a multi-billion euro market in new technological solutions for business and citizens.

Since the beginning the EU has been a key player in this area and with a planned investment of €1 billion over 10 years, the EU Quantum Flagship[1] is mobilising around 2000 scientists and industrialists, in a collaborative initiative on an unprecedented scale to position Europe as leader in the industrial landscape. Of course, Europe is not alone; the US, China, Canada, and Japan have also set this as a top strategic priority.

However, Quantum Technology and in particular Quantum Computing is also a disruptive innovation. In the mid '90s, scientists theorized of quantum computer algorithms that, given the existence of a sufficiently powerful quantum computer, can break widely used public-key cryptography schemes, such as RSA and ECC or weaken standardised symmetric encryption algorithms. And while we do not know when and if such a quantum machine will [ever] become available, researchers and national authorities have been working on solutions. As a result, the US National Institute of Standards and Technology (NIST) launched in 2017 a, still ongoing, process to standardise one or more quantum-resistant public-key cryptographic algorithms, soliciting proposals from cryptographers around the world [2].

It is important to make a distinction between Post-Quantum Cryptography (PQC) and Quantum Cryptography. PQC is about designing cryptographic solutions that can be used by today's [non-quantum] computers and that we believe are resistant to both conventional and quantum cryptanalysis. On the other hand, Quantum Cryptography is about cryptographic solutions that take advantage of quantum physics to provide certain security services. Quantum Key Distribution (QKD) is a good example of the latter.

The EU Cybersecurity Strategy[3], presented by the European Commission and the High Representative of the Union for Foreign Affairs and Security in Policy on December 2020, explicitly singles out quantum computing and encryption as a key technologies (along with AI) for achieving (1) resilience, technological sovereignty and leadership, (2) building operational capacity to prevent, deter and respond, and (3) advancing a global and open cyberspace. The Strategy covers the security of essential services such as hospitals, energy grids and railways and ever-increasing number of connected objects in our homes, offices and factories, building collective capabilities to respond to major cyberattacks and working with partners around the world to ensure international security and stability in cyberspace[4].

[1] https://qt.eu/
[2] https://csrc.nist.gov/projects/post-quantum-cryptography
[3] https://ec.europa.eu/digital-single-market/en/cybersecurity-strategy
[4] https://ec.europa.eu/digital-single-market/en/cybersecurity

Given the recent developments in the Quantum Computing race among industries and nation states, it seems prudent for Europe to start considering mitigation strategies now. The EU Cybersecurity Agency is not alone in this line of though. Other authorities and EU Institutions have also raised concerns; for instance, the European Data Protection Supervisor has highlighted the dangers against data protection[5], national authorities have been investigating and preparing; e.g., the German Federal Office for Information Security has been evaluating Post-Quantum alternatives since before the launch of NIST's standardisation process[6].

This study provides an overview of the current state of play on the standardisation process of Post-Quantum Cryptography (PQC). It introduces a framework to analyse existing proposals, considering five (5) main families of PQC algorithms; viz. code-based, isogeny-based, hash-based, lattice-based and multivariate-based. It then goes on to describe the NIST Round 3 finalists for encryption and signature schemes, as well as the alternative candidate schemes. For which, key information on cryptodesign, implementation considerations, known cryptanalysis efforts, and advantages & disadvantage is provided.

Since the NIST standardisation process is going[7], the report makes no claim on the superiority of one proposal against another. In most cases the safest transition strategy involves waiting for national authorities to standardise PQC algorithms and provide a transition path. There might be cases thought were the quantum risk in not tolerated, in which case the last chapter offers 2 proposals that system owners can implement now in order to protect the confidentiality of their data against a quantum capable attacker; namely hybrid implementations that use a combination of pre-quantum and post-quantum schemes, and the mixing of pre-shared keys into all keys established via public-key cryptography. These solutions come at a cost and as such system designers are well advised to perform a thorough risk and cost-benefit analysis.

[5] EDPS, "TechDispatch #2/2020: Quantum Computing and Cryptography", https://edps.europa.eu/data-protection/our-work/publications/techdispatch/techdispatch-22020-quantum-computing-and_en

[6] https://www.bsi.bund.de/EN/Topics/Crypto/Cryptography/PostQuantumCryptography/post_quantum_cryptography_node.html

[7] tentative deadline 2022/2024, as of 2020, https://csrc.nist.gov/projects/post-quantum-cryptography/workshops-and-timeline

CONTENTS

1 INTRODUCTION

Post-quantum cryptography is an area of cryptography in which systems are studied under the security assumption that the attacker has a quantum computer. This attack model is interesting because Shor has shown a quantum algorithm that breaks RSA, ECC, and finite field discrete logarithms in polynomial time. This means that in this model all commonly used public-key systems are no longer secure.

Symmetric cryptography is also affected, but significantly less. For systems that do not rely on mathematical structures the main effect is that an algorithm due to Grover halves the security level, i.e., breaking AES-128 takes 2^{64} quantum operations while current attacks take 2^{128} steps. While this is a big change, it can be managed quite easily by doubling the key sizes, e.g., by deploying AES-256. The operations needed in Grover's algorithm are inherently sequential which has led some to doubt that even 2^{64} quantum operations are feasible, but since the remedy of changing to larger key sizes is very inexpensive it is generally recommended to do so.

At this moment, the quantum computers that exist are not large enough to pose a threat against current cryptography. However, rolling out new cryptographic systems takes a lot of time and effort, and it is thus important to have replacements in place well before large, powerful quantum computers exist.

What makes matters worse is that any ciphertext intercepted by an attacker today can be decrypted by the attacker as soon as he has access to a large quantum computer (Retrospective decryption). Analysis of Advanced Persistent Threats (APT) and Nation State capabilities, along with whistle-blowers' revelations have shown that threat actors can and are casually recording all Internet traffic in their datacentres and that they select encrypted traffic as interesting and worth storing. This means that any data encrypted using any of the standard public-key systems today will need to be considered compromised once a quantum computer exists and there is no way to protect it retroactively, because a copy of the ciphertext is in the hands of the attacker. This means that data that needs to remain confidential after the arrival of quantum computers need to be encrypted with alternative means.

Signatures can be updated and old keys can be revoked when a signature system is broken; however, not all development in the area of building quantum computers is public and it is fairly likely that the first fully-functional large quantum computer will not be publicly announced, but rather sit in the basement of some government agency. Timing the roll-over of signature keys thus remains guesswork. On top of that, one important use case for signatures is operating-system upgrades. If a post-quantum signature system is not in place by the time an attacker has a quantum computer, then the attacker can take control of the operating system through a fake upgrade and prevent any future upgrades from fixing the problem.

In 2017, the United States National Institute for Standards and Technology solicited submissions for potential public key encryption and signature algorithms that would be secure in a world in which quantum computer existed. Although not officially a 'competition' as the AES and SHA-3 efforts were, it has been treated in much the same way as the AES and SHA-3 efforts. Over the last few years, the number of submissions has been whittled down, and in July 2020 the Round 3 candidates were published.

This report is a much extended update to the ECRYPT-CSA "Whitepaper on Post-Quantum Cryptography" [43]. It provides a short summary of the underlying hardness assumptions in Section 2 and summarizes the Round 3 candidates in Section 3. It also details the so-called 'Alternate Candidates' in Section 4. The Round 3 candidates are algorithms that the National Institute of Standards and Technology (NIST) *"considers to be the most promising to fit the majority of use cases and most likely to be ready for standardisation soon after the end of the third round"*, whilst the Alternate Candidates are ones which NIST regards as *"potential candidates for future standardisation, most likely after another round of evaluation"*. See [87] for more details. Finally, this report covers mitigation strategies in Section 5.

2 FAMILIES OF POST-QUANTUM ALGORITHMS

There would not be much point speaking about post-quantum systems, if there were none able to survive attacks by quantum computers. The usual disclaimers apply as with all of cryptography: It might be possible that more powerful attacks (quantum or not) exist that have not yet been found. Apart from that possibility, research over the last 15–20 years has built confidence in the following four areas that lead to secure systems in a post-quantum world. In this section, we summarize the mathematical basis of post-quantum proposals.

2.1 CODE-BASED

Code-based cryptography uses the theory of error-correcting codes. For some specially constructed codes it is possible to correct many errors, while for random linear codes this is a difficult problem. Code-based encryption systems go back to a proposal by McEliece from 1978 [78] and are among the most studied post-quantum schemes. Some code-based signature systems have been designed to offer short signatures at the expense of very large key sizes. Systems based on binary Goppa codes are generally considered secure; systems based on quasi-cyclic medium-density parity checks have held up to analysis for about a decade and are gaining confidence. For more background on code-based cryptography see [68].

All code-based signature systems submitted to NIST were based on new assumptions and have since been broken. Six code-based encryption systems made it to Round 2, but rank-metric codes (Rollo and RQC), as well as low-density parity-check (LDPC) codes (LEDAkem and LEDAcrypt) had serious cryptanalysis during Round 2 and were thus deselected by NIST.

The remaining code-based candidates are Classic McEliece, which was the finalist selected first for encryption systems, and BIKE and HQC as alternate candidates. The latter two are using special codes in order to reduce the key size of the public key, as that is seen as the main drawback of code-based systems.

2.2 ISOGENY-BASED

An isogeny between elliptic curves is a non-constant map that can be written as a fraction of polynomials and is compatible with addition on both curves, so that the image of the sum of two points on the first curve is equal to the sum of the images, when computed on the second curve. Isogeny-based cryptography uses isogenies between elliptic curves over finite fields. The isogeny problem is to find an isogeny between two elliptic curves that are known to be isogenous. The problem was introduced in 2005 in [27] and is thus the most recent basis for any post-quantum candidates. Usage in protocols differs in whether the degree of the isogeny is known or secret and whether additional information is known. For more background on isogeny-based cryptography see [67].

Only one isogeny-based candidate, SIKE, was submitted to the NIST competition and SIKE is in the third round as an alternate candidate.

2.3 HASH-BASED

Hash functions are functions that map strings of arbitrary length to strings of fixed length. From cryptographic hash-functions we expect that they are one-way (it is hard to find an element in the preimage of a given image) and collision resistant (it is hard to find two inputs that map to the same output). Hash functions are one of the most widely deployed cryptographic tools we got, with applications ranging from password hashing to file checksums, and are used in virtually any cryptographic construction in practice. While hash functions are used in all practical signature schemes to handle arbitrary length messages, it is known, since the beginning of public key cryptography, that they can also be used as the sole building block for this. In the simplest version, a hash-based signature on one bit is as follows. Pick two random strings, hash each of them, and publish the outputs. Reveal the first preimage to sign 0 and the second to sign 1. This signature scheme, due to Lamport from 1979 [66], is a one-time signature scheme – once the secret is revealed it cannot be used a second time. Starting from this basic idea hash-based signatures on longer strings and on multiple messages have been built. The designs fall into stateless and stateful versions. The former work as normal signatures, while for the latter the signer needs to keep track of some information, e.g., the number of signatures generated using a given key. With SPHINCS$^+$ a stateless hash-based signature scheme is in the third round of the competition as runner-up. For the stateful schemes, NIST already published SP 800-208 [29] standardizing LMS [79] and XMSS [53] two stateful hash-based signature schemes. However, it has to be noted that the stateful character limits the applications these schemes are suitable for.

Due to their ubiquity, the security of practical hash functions is well understood. More importantly in the given context, it is known that even quantum computers cannot significantly improve the complexity of generic attacks against cryptographic hash functions. A square-root factor speed-up is the (in practice unreachable) upper limit for improvements.

2.4 LATTICE-BASED

On a high level, the descriptions of lattices look much like those of codes – elements are length-n vectors in some space and get error vectors added to them – but where codes typically have entries 0 or 1, lattices work with much larger numbers in each entry and errors can move away further. The problems underlying the cryptographic constructions are to find the original vector given a disturbed one. Lattices offer more parameters than codes, which means that they might offer solutions better adapted to a given situation, but also offer more attack surface. Lattice-based cryptography goes back to 1996 and the designs of Ajtai [1] and of Hoffstein, Pipher, and Silverman [49]. Both encryption and signature systems exist.

The lattice based schemes submitted to NIST mainly make use of the following two basic hard problems; called Module-Learning-with-Errors (Module-LWE) and Module-Learning-with-Rounding (Module-LWR). In these schemes one selects a polynomial ring $R = \mathbb{Z}[X]/f$, where the degree of f is equal to n, and considers it modulo q (giving R_q). In addition, there is another integer parameter d, called the module degree. For Ring-LWE and Ring-LWR one sets $d = 1$, and for standard LWE and LWR one has $d = n = 1$.

The Module-LWE problem is the problem of finding $s \in R_q^d$ given a number of samples of the form $(a, a \cdot s + e)$ where a is chosen uniformly at random in R_q^d and $e \in R_q$ is chosen to have 'small' coefficients.

The Module-LWR problem is the problem of finding $s \in R_q^d$ given a number of samples of the form $(a, \lfloor a \cdot s \rceil_p)$ where a is chosen uniformly at random in R_q^d, and the function $\lfloor g \rceil_p$ takes the coefficients of the polynomial g and applies the function $x \longmapsto \text{round} - \text{to} - \text{int}(x \cdot p/q) \pmod p$, for some fixed integer p.

A related hard problem is that of the NTRU problem. NTRU-based cryptosystems, also called Quotient NTRU cryptosystems, assume that the NTRU problem is hard and that the n-sample Ring-LWE problem is hard, while Ring-LWE-based cryptosystems assume that the $2n$-sample Ring-LWE problem is hard. The NTRU problem and the $2n$-sample Ring-LWE problem could be weaker than the n-sample Ring-LWE problem. For large parameter sets (not proposed in practice), the NTRU problem is proven to be hard, so NTRU-based cryptosystems are based on the n-sample Ring-LWE problem.

Another related hard problem is the Ring Short Integer Solution (Ring-SIS) problem which asks if there is a short integer solution $x \in \mathbb{Z}^m$ to the equation $A \cdot x = 0 \pmod q$, for a matrix $A \in R_q^{n \times m}$.

2.5 MULTIVARIATE-SYSTEM BASED

Multivariate cryptography goes back to the late eighties and is based on the hardness of finding a solution to a system of multivariate quadratic equations over finite fields. It is possible to build signature schemes from systems of equations with uniformly random coefficients [100], and these are considered to be the most secure multivariate systems. However, the more efficient schemes use trapdoored systems of equations, which appear random to outsiders, but which have some hidden structure that is only known to the person that constructed the system. Thanks to this structures it is possible to find solutions efficiently. These are often called Oil-and-Vinegar schemes.

Currently, the multivariate encryption schemes are not very efficient, often with very large public keys and long decryption times. On the signatures front however, things look a bit better. Out of the nineteen signature schemes submitted to the NIST Post-Quantum Cryptography (PQC) project, seven were multivariate signature schemes. Two of these seven schemes proceeded to the third round of the NIST PQC process. The Rainbow scheme [38] was selected as one of the three finalists, and the GeMMS scheme [26] was selected as an "alternate candidate". These schemes enjoy very short signature sizes (as small as 33 Bytes), but suffer from rather large public keys (160 KB or more).

2.6 THE NIST ROUND 3 CANDIDATES

In the table 2.1, we describe the NIST Round 3 candidates (both the finalists and the alternate candidates) and splitting them into the two groups of encryption and signature scheme, whilst also detailing the hard problems on which they are based.

Table 2.1: NIST Round 3 candidates

Scheme	Enc/Sig	Family	Hard Problem
Round 3 Finalists			
Classic McEliece	Enc	Code-Based	Decoding random binary Goppa codes
Crytals-Kyber	Enc	Lattice-Based	Cyclotomic Module-LWE
NTRU	Enc	Lattice-Based	Cyclotomic NTRU Problem
Saber	Enc	Lattice-Based	Cyclotomic Module-LWR
Crystals-Dilithium	Sig	Lattice-Based	Cyclotomic Module-LWE and Module-SIS
Falcon	Sig	Lattice-Based	Cyclotomic Ring-SIS
Rainbow	Sig	Multivariate-Based	Oil-and-Vinegar Trapdoor
Round 3 Alternate Candidates			
BIKE	Enc	Code-Based	Decoding quasi-cyclic codes
HQC	Enc	Code-Based	Coding variant of Ring-LWE
Frodo-KEM	Enc	Lattice-Based	LWE
NTRU-Prime	Enc	Lattice-Based	Non-cyclotomic NTRU Problem or Ring-LWE
SIKE	Enc	Isogeny-Based	Isogeny problem with extra points
GeMSS	Sig	Multivariate-Based	'Big-Field' trapdoor
Picnic	Sig	Symmetric Crypto	Preimage resistance of a block cipher
SPHINCS+	Sig	Hash-Based	Preimage resistance of a hash function

3 NIST ROUND 3 FINALISTS

3.1 ENCRYPTION SCHEMES

3.1.1 Classic McEliece

Design:

Classic McEliece [3] is a code-based scheme using binary Goppa codes, the same codes that McEliece originally proposed when he introduced code-based cryptography [78] in 1978. Code-based cryptography is the oldest public-key encryption system that is expected to resist attacks by quantum computers and is one of the oldest public-key encryption systems overall. During Round 2 the scheme merged with NTS-KEM, which was using the same codes.

The assumption underlying One-Wayness against Chosen-Plaintext Attacks (OW-CPA) PKE security is that decoding a random binary Goppa code is hard – McEliece encodes messages into code words and encrypts them by adding random errors. The Classic McEliece scheme uses the dual of McEliece's scheme, as proposed by Niederreiter [85], and tightly turns this OW-CPA PKE into an IND-CCA2 KEM using Theorem 8 in Dent [37]. A proof in the QROM (Quantum Random-Oracle Model) is given in [17] which proves a bound ϵ on the probability of a QROM Indistinguishability under adaptive Chosen Ciphertext Attack (IND-CCA2), assuming a bound on the scale of ϵ^2 on the probability of an OW-CPA attack against the underlying deterministic PKE.

Implementation:

A full KEM was specified and implemented in [13] with improvements in [28]. The software is available on the submitters' page, see [3], and includes reference and optimized implementation. All implementations of Classic McEliece are constant time. An implementation for the ARM Cortex-M4 is finished, but not yet publicly available. FPGA implementations are covered in [107] and [108] and are also freely available and constant time.

Classic McEliece has been integrated into the network protocols McTiny [15] and Post-quantum WireGuard [55].

Cryptanalysis:

There are two main avenues of attack against code-based cryptography: information-set decoding (ISD) and structural attacks.

ISD goes back to a general decoding technique from 1962 due to Prange [94]. There is a long history of research on this problem, especially for cryptographic applications, with the most recent papers being [22, 23, 63]. These attacks show their biggest effect for high-rate codes while the binary Goppa codes used in Classic McEliece are only marginally affected. More precisely, achieving 2^λ security against Prange's attack requires keys of size $(0.741186\ldots + o(1))\lambda^2(\log_2 \lambda)^2$ bits as $\lambda \to \infty$. To achieve the same level of security against all the later attacks requires keys of size $(0.741186\ldots + o(1))\lambda^2(\log_2 \lambda)^2$ bits as $\lambda \to \infty$, i.e., the improvements affect only the $o(1)$ term. All these attacks involve huge searches, like attacking AES. The quantum attacks (Grover etc.) leave at least half of the bits of security.

Structural attacks attempt to find a good decoding algorithm for the code in the public key by identifying structures of the private key in the public one. Such attacks have been successful against code-based systems based on other codes, e.g., identifying Reed-Solomon codes as used by Niederreiter [85] or Gabidulin codes used in early rank-metric codes. However, for binary Goppa codes the only attacks known are distinguishing attacks and even those are successful only for very high-rate codes, larger than proposed for any cryptosystems [44].

Advantages and Disadvantages:

The advantages for Classic McEliece are that it has a very long history of analysis with no significant impact on the security and that the ciphertext size is small. The ciphertexts are the smallest of all Round-2 candidates and thus also of all Round-3 candidates. No other public-key encryption system can look back at more than 40 years of cryptanalysis – quantum or not – without taking a hit.

The disadvantage is the size of the public key, which for the highest security level takes more than 1MB. This poses a problem for applications that request fresh public keys for each execution; the McTiny protocol [15] shows how to make this work nevertheless without causing denial-of-service attack on the servers. Post-quantum WireGuard [55] and PGP are applications where the system can be used as a long-term identity key.

3.1.2 Crystals-Kyber

Design:

Kyber is an Indistinguishability under Chosen Plaintext Attack (IND-CCA) secure KEM originally presented in [20]. It has seen some significant changes since then and the latest description can be found in [103]. The security of Kyber can be provably reduced to the Module-Learning-with-Errors problem (Module-LWE), but the parameter set for the lowest security level bases its security estimate on a combination of Module Learning with Errors and Module Learning with Rounding (MLWR). Kyber is based on LPR [73] encryption, but uses vectors of polynomials as elements, performs additional compression on the ciphertext and is designed to accommodate fast multiplications using the Number Theoretic Transform (NTT). IND-CCA security is obtained through a variant of the FO transformation. The public key sizes of Kyber are 800, 1184 and 1568 bytes for security levels 1, 3 and 5 respectively, and the ciphertext sizes are 768, 1088, 1568 bytes.

Implementation:

After an initial implementation on general purpose processors in [20], Kyber has been implemented on Cortex-M4 [24] and a software hardware codesign has been described in [33]. An implementation using an RSA-coprocessor was given in [5]. Moreover, implementations of Kyber can reuse existing designs for Ring-LWE (aka RLWE) encryption schemes that support NTT multiplication, for example implementations of NewHope or early Ring-LWE schemes. No side-channel secure implementation is available for Kyber, but an idea of the challenges and the cost can be gained from a masked Ring-LWE implementation as presented in [88].

Cryptanalysis:

The security of Kyber is provably reducible to the security of the underlying Module-LWE problem (aka Mod-LWE). As there is currently no efficient way to exploit the modular structure security is typically estimated based on the corresponding LWE problem. Such attack typically transforms the LWE problem into a shortest vector lattice problem that can then be solved using lattice reduction techniques. An independent security estimate of Kyber was given in [4].

Kyber has a very small probability of decryption failures in which valid ciphertexts fail to decrypt properly. This paves the road for decryption failure attacks as proposed in [19, 34, 36]. However, when limiting the number of queries to 2^{64} as recommended in the NIST call for proposals [86], these attacks are less efficient than direct lattice attacks. A practical fault injection attack on Kyber was presented in [97].

Advantages and Disadvantages:

Kyber is designed with NTT multiplications in mind, which allows for efficient implementations of Kyber on a variety of platforms. It is notable that some elements are generated and compressed in the NTT domain, which makes it impractical to use other multiplication algorithms for Kyber. Moreover, polynomial multiplications are in the same ring for all security levels, which makes it easy to scale between the security levels. Overall, the support for NTT multiplication makes Kyber efficient to implement. The security of Kyber enjoys strong reductions to underlying hard lattice problems.

3.1.3 NTRU

Design:

Nth Degree Truncated Polynomial Ring Units (NTRU) is one of the oldest encryption schemes that makes use of structured lattices. It was developed by Hoffstein, Pipher, and Silverman in 1998 [49]. The round three submission to NIST [110] is a merger of the initial NTRU submission [109] and the NTRU-HRSS submission [102] implemented after the first round due to large overlaps in the design. The submission specifies a perfectly correct, deterministic public key encryption scheme (dPKE). This dPKE is transformed into a CCA2-secure KEM using the $\mathrm{U}_m^{\not\perp}$ transform of [50]. Assuming the scheme is OW-CPA, i.e., given a public key and a ciphertext, it is hard to learn the encrypted plaintext, a tight proof for CCA2-security in the ROM is given in [50]. A tight proof in the quantum-accessible ROM is known, but makes a less standard assumption [99].

Implementation:

The NTRU-HRSS part of the submission was based on [54] which already contained a high-speed constant-time implementation. NTRU-HRSS was among the fastest first round submissions. NTRU is also known for its speed on constrained devices; implementations go back to at least 2001 [8], but also nowadays NTRU is one of the schemes with the fastest encapsulation and decapsulation routines in the pqm4 project [60].

Also, implementation security of NTRU is well advanced. As mentioned above, for commodity hardware, the optimized implementations provided are constant time [54]. On constrained devices, up-to-date masked implementations are known [101] that protect against side channel attacks like correlation power analysis attacks [70].

NTRU was chosen by Cloudflare and Google for their second PQC experiment [69] and used in connections from users running Chrome Canary to Google and Cloudflare.

Cryptanalysis:

The security of NTRU is supported by a long history of cryptanalysis (see e.g., [30, 48, 52, 75, 76]). Up to parameter changes, NTRU successfully survived the last 20+

years of cryptanalysis. The efforts of the last years suggest that the complexity of the best attacks against NTRU is determined by the complexity of lattice reduction. The complexity of the best algorithms for lattice reduction in turn depends on the complexity of solving the shortest vector problem (SVP). See the specification for an extensive elaboration. An independent evaluation can be found in [4].

Advantages and Disadvantages:

NTRU has several advantages. As mentioned above, it is perfectly correct and the underlying assumption is well studied. It is flexible, meaning that the underlying dPKE can be parameterized for a variety of use cases with different size, security, and efficiency requirements. It is simple: The dPKE has only two parameters, n and q, and can be described entirely in terms of simple integer polynomial arithmetic. It is fast: ntruhrss701 was among the fastest submissions in the first round. It is compact: The ntruhps2048677 parameter set achieves NIST level L1 security with a wide security margin, level L3 security under a reasonable assumption, and has public keys and ciphertexts of only 930 bytes. It is guaranteed patent free as the relevant patents have expired.

On the downside, NTRU is unlikely to be the fastest, most compact, or most secure submission. However, it is competitive on products of these measures. As for all other lattice-based schemes, the choice of optimal parameters for NTRU is currently limited by a poor understanding of the non-asymptotic behaviour of new algorithms for SVP. Finally, there is structure in NTRU that is not strictly necessary, and this may also be seen as a limitation.

3.1.4 Saber

Design:

Saber is a family of cryptographic primitives that includes an IND-CPA secure encryption scheme and an IND-CCA secure KEM, with an initial design as described in [35] and most recent update in [10]. Its security can be reduced to the security of the Module Learning with Rounding (MLWR). As most LWE/LWR based schemes, Saber follows the general structure of LPR [73] encryption. The main differences are power-of-two moduli, the use of vectors of polynomials and the adaptation of learning with rounding. To achieve IND-CCA security Saber relies on a post-quantum variant of the FO transformation. Saber boasts public key sizes of 672, 992 and 1312 bytes; and ciphertext sizes of 736, 1088, 1472 bytes for security level 1, 3 and 5 respectively.

Implementation:

An initial implementation of Saber on high end processors was presented in [35]. Implementation efforts have since then extended to Cortex-M4 and Cortex-M0 in [59, 61, 81, 90], ESP32 in [106], specific coprocessors in [74, 98], large integer coprocessors in [21], a software hardware codesign in [33] and a hardware implementation in [111]. An implementation that batches multiple decapsulations to exploit vector instructions has been proposed in [104]. A first order masked implementation of Saber was given in [11].

Saber has been integrated into the network protocol Post-quantum WireGuard [55] for exchanging ephemeral keys.

Cryptanalysis:

The most straightforward attack on Saber is to break the underlying Mod-LWR problem. Such an attack rewrites the Mod-LWR problem as a shortest vector lattice problem and uses lattice reduction algorithms to retrieve the secret key. The security of this problem is typically estimated as the security of the analogous LWE problem as there is at the moment no efficient attack that exploits the module or rounding structure. An initial security estimate of Saber was given in [4] and was further improved in [10] using the estimation tools of [2, 32].

As Saber is subject to decryption failures with a small probability, there is the possibility of decryption failure attacks. Attacks on the IND-CCA secured KEM were presented in [19, 34, 36] but when limiting the number of queries that can be performed to 2^{64} as proposed in the NIST call for proposals [86], these attacks do not outperform standard lattice attacks.

Advantages and Disadvantages:

The choice for power-of-two moduli avoids the need for explicit modular reductions or rejection sampling that are typically present in prime moduli based schemes. The latter also reduces the number of hash function calls. The drawback of this choice is that the NTT is not naturally supported. However, other multiplication algorithms (e.g., Karatsuba, Toom-Cook, schoolbook, Kronecker) have been shown to be efficient on a range of platforms and the design of Saber does not restrict implementors to a specific multiplication algorithm. Moreover, in multiplications of Saber, one element will always have small coefficients, which could be exploited for optimizing implementations.

Being based on learning with rounding, Saber introduced an error by rounding coefficients. This naturally reduces the communication bandwidth and avoids the generation of the error term. The modular structure of Saber implies that multiplications of polynomials are always in the same ring, and as such the multiplication algorithm of these polynomials is the same for all security levels.

Saber is efficient to mask, due to the power-of-two moduli and the absence of the error term. The first order masked Saber implementation of [11] has an overhead factor 2.5x, which can be compared to an overhead of factor 5.7x previously reported for prime-moduli schemes [88]. Saber also excels at anonymous communication as it is naturally constant time, even over different public keys, due to the avoidance of rejection sampling. Moreover, the power-of-two moduli ensures communication consists of a uniformly random bitstring without apparent structure.

3.2 SIGNATURE SCHEMES

3.2.1 Crystals-Dilithium

Design:

Dilithium is a signature scheme introduced in [41] and with latest version described in [72]. It is based on Fiat-Shamir with aborts, and its security can be reduced to the security of the Module-LWE and Module-SIS problems. It is designed to allow fast multiplications using the NTT transformation and avoids generation of randomness from a discrete Gaussian distribution, instead opting for sampling from a uniform distribution.

Implementation:

The Dilithium team provided an implementation in their initial work [41]. Further work has focused on improving the speed of the signing procedure [96]. An implementation of Dilithium on Cortex-M4 was presented in [47] and a masked implementation was introduced in [83].

Cryptanalysis:

The security of Dilithium is based on that of the underlying Module-LWE and Module-SIS problems. Currently there is no efficient attack exploiting the module structure and as such the security of the equivalent LWE and SIS problems is considered. An independent estimation effort [4] confirmed Dilithium's security estimate. A fault attack on Dilithium was presented in [25].

Advantages and Disadvantages:

In contrast to other signature proposals, Dilitihium samples from a uniform distribution avoiding the complex and inefficient sampling from a discrete Gaussian distribution. The modular structure of Dilithium ensures that polynomial multiplication is always performed in the same ring regardless of security level, which makes it easy to switch between these levels. Multiplication can be performed efficiently due to its NTT friendly parameters. Applying a trick to compress the public key with a factor 2, Dilithium has the smallest public key plus signature size of lattice-based schemes that use uniform sampling.

3.2.2 Falcon

Design:

Falcon [95] is a signature scheme whose design is based on the Gentry–Peikert–Vaikuntanathan (GPV) blueprint [46] for lattice-based signatures. It instantiates this construction with NTRU lattices and an efficient Gaussian sampler [42, 51], which yields a scheme that is provably secure under the assumption that SIS is hard in the particular lattices used. Falcon has been designed so that all of the arithmetic operations can be computed using efficient Fourier-transform techniques.

Implementation:

An efficient constant-time implementation of Falcon is given by [93], using the sampler of [51]. It does not require (but can use) a floating-point unit and runs efficiently on various kinds of microprocessors including Intel x86 and ARM cores. See [89] for a more optimized implementation specific to the latter. The constant-time Gaussian sampler of [62] can be used in Falcon.

Cryptanalysis:

The mathematical security of Falcon relies on the hardness of the SIS problem over NTRU rings, which benefits from the long history of cryptanalysis for the NTRU cryptosystem (cf. Section 3.1.3). The best known attacks are generic lattice techniques: there is no known way to effectively exploit the additional ring structure present in NTRU lattices. To estimate the security against lattice-reduction algorithms, Falcon employs the "Core-SVP" method which was also used by many other lattice-based NIST submissions.

A fault attack on Falcon is demonstrated (and countermeasures proposed) in [77], and the side-channel leakage of Falcon and similar schemes was analysed in [45].

Advantages and Disadvantages:

In a nutshell, Falcon is a very compact (smallest combined size of public key and signature among all NIST candidates) and efficient post-quantum signature scheme whose security reduces to well-established assumptions. The chosen ring structure and error distribution allow for efficient FFT-based implementations, which partially cancels the adverse effects of using a Gaussian error distribution and leads to good performance in practice. Indeed, perhaps the biggest drawback of Falcon appears to be the complexity of understanding all details of the construction and implementing the scheme correctly.

3.2.3 Rainbow

Design:

Rainbow is a multivariate signature scheme, proposed by Ding and Schmidt [38, 39] and based on the Oil and Vinegar (OV) scheme by Patarin [91]. Similar to RSA signatures, Rainbow uses a trapdoor function $\mathcal{P}$, for which only the holder of the secret key can compute preimages. To sign a message M, the signer then publishes a preimage for $\mathcal{H}(M, \mathsf{salt})$, where $\mathcal{H}$ is a cryptographic hash function that outputs elements in the range of $\mathcal{P}$, and where salt is a fixed-length bitstring, chosen uniformly at random for each signature.

The Rainbow trapdoor function is best described as the composition of two or more oil and vinegar trapdoors. The design philosophy is that by iterating the OV trapdoor, it gets more resistant to attacks, which allows for more efficient parameter choices. Unfortunately, the additional complexity also opens up some new attack strategies.

Implementation:

The Rainbow team provided an optimized implementation for general purpose processors and for processors supporting AVX2 instructions. These implementations are claimed to resist timing side-channel attacks. During the second round of the NIST PQC process, the Rainbow team switched to a new key generation algorithm. This does not affect the security of the scheme, but made key-generation more efficient. A fault attack against Rainbow is presented in [65].

Cryptanalysis:

Like most multivariate signature schemes, Rainbow does not have a security proof that reduces a hard computational problem to the security of the scheme. Therefore, we can not rely on widely believed assumptions and it necessary to have a dedicated cryptanalysis of Rainbow. After some initial cryptanalytic results in the first few years after the introduction of Rainbow, the cryptanalysis of Rainbow was relatively stable. However, since Rainbow entered the NIST PQC process, there have been some works that slightly improved existing attacks [9, 105], and during the third round of the NIST PQC process two new attacks were published that broke the security claims. [16] The Rainbow team has announced that a new parameter set will be proposed to address the new attacks.

Advantages and Disadvantages:

Rainbow signatures are small (e.g. ~ 66 Bytes at SL I) and the signing and verification algorithms are fast. Rainbow uses only linear algebra over very small finite fields, which makes it suitable for implementing the scheme on low-cost devices, without the need for a cryptographic coprocessor. On the other hand, the public keys are rather large (e.g. 158 KB at SL I). It is possible to compress the public key size by almost a factor 3 at the expense of slower signing times. The security analysis of Rainbow cannot be considered stable at the moment.

4 ALTERNATE CANDIDATES

4.1 ENCRYPTION SCHEMES

BIKE

BIKE [7], Bit Flipping Key Encapsulation, is a Key Encapsulation Mechanism (KEM) based on quasi-cyclic codes with moderate-density parity-check matrices. The public key specifies an error-correcting code, as in Classic McEliece, but in BIKE the code has a public structure of being quasi-cyclic, allowing the public key to be compressed. The moderate-density parity-check matrices are secret, Bit flipping corrects errors by repeatedly flipping the input bits that, given the secret parity checks, seem most likely to be errors.

HQC

HQC [80], Hamming Quasi-Cyclic, has the same noisy Diffie–Hellman structure as many lattice-based cryptosystems. The public key includes a random G and $A = aG + e$, where a, e are small secrets. The ciphertext includes $B = bG + d$ and $C = M + bA + c$, where b, c, d are small secrets and M is a message encoded using an error-correcting code. The receiver computes $C - aB = M + be + c - ad$, which is close to M since a, b, c, d, e are small, and decodes the error-correcting code to recover M. HQC uses polynomials modulo 2, rather than the larger integer moduli used in lattice-based cryptosystems, but uses polynomial modulus $x^n - 1$ with relatively large n. HQC uses error-correcting codes built from Reed-Muller and Reed-Solomon codes. Public keys are between 2249 and 7245 bytes, and ciphertexts are between 4481 and 14469 bytes, depending on the security level.

Frodo-KEM

FrodoKEM [84] is a key encapsulation mechanism whose security is based on the hardness of the standard Learning With Errors problem. The algorithm is a specific instantiation of the construction of Lindner and Peikert from 2011 [71]. It thus makes no use of so-called structured lattices (such as those based on Ring or Module LWE), this means that the performance is not as good as the lattice based schemes selected to be the main candidates in Round 3. However, for those worried about the structural properties of these latter candidates, Frodo-KEM may be an option.

NTRU-Prime

NTRU Prime [12, 14] is a lattice-based key encapsulation mechanism (KEM) with two options: Streamlined NTRU Prime, which is similar to NTRU, and NTRU LPRime, which is similar to Kyber and SABER. NTRU Prime uses a polynomial $x^p - x - 1$ with a maximum-size Galois group (superexponential in the degree) while NTRU, Kyber, and SABER use cyclotomic polynomials with a minimum-size Galois group (linear in the degree). The original STOC 2009 Gentry FHE system and the original multilinear-map system are broken for cyclotomics but not for $x^p - x - 1$; NTRU Prime predates these attacks and is designed to protect lattice-based cryptosystems against the possibility of cyclotomic attacks. Compared to the performance of NTRU, Kyber, and SABER, the performance of NTRU Prime is sometimes slightly worse and sometimes slightly better, but is generally similar.

SIKE

SIKE [57] is a key encapsulation mechanism based on the hard problem of pseudo-random walks in supersingular isogeny graphs. This is a relatively new problem in the cryptographic arena, but the problem of studying isogenies of supersingular elliptic curves is an old mathematical problem. The main advantage of isogeny based schemes is their small public key and ciphertext size. The key problems associated with SIKE is that the performance is currently not competitive with the other proposals. This may improve however over time.

4.2 SIGNATURE SCHEMES

GeMSS

The GeMMS scheme [26] builds on a line of work that goes back to 1988; schemes in this line of work are called “Big Field” schemes. The public key for GeMMS is a multivariate quadratic system of equations over $\mathbb{F}_2$. The main idea behind “Big Field” schemes is that there is a secret change of variables that turns the public key into a (perturbed version of) a system that models a low-degree univariate polynomial equation over an extension field $\mathbb{F}_{2^n}$. Since it is possible to efficiently find the solutions to a low degree univariate polynomial, this allows someone who knows the secret change of variables to sign messages. The size of GeMMS signatures is exceptionally small, with a size of only 258 bits at NIST security level I. The main drawbacks, however, are that, with 350KB, the public keys are large, and that signing is slow, especially for the more conservative parameter choices.

Picnic

The Picnic signature scheme,[1] currently on its third iteration [58], is unique among the other candidates due to its use of the “MPC-in-the-head” paradigm [56]. In this framework, a proving algorithm simulates a virtual MPC protocol which computes the circuit for an NP relation R, e.g. $x \sim_R y \iff y = \texttt{SHA-256}(x)$. By revealing the views of a random subset of the MPC parties, this forms an interactive zero-knowledge proof of knowledge (ZKPoK) of a witness for R. In Picnic, this ZKPoK is made non-interactive and turned into a signature scheme using the traditional Fiat-Shamir transform; furthermore, the design uses the `LowMC` block cipher for the relation R due to this cipher’s explicit design for efficient computation in MPC.[2] After several iterations in the design, the current specification document for `Picnic3` lists signature sizes of 12.6kB, 27.5kB and 48.7kB for the L1, L3 and L5 NIST security levels, respectively [58].

SPHINCS$^+$

SPHINCS$^+$ is a framework that describes a family of hash-based signature schemes[3]. Using an arbitrary, secure cryptographic hash function, a signature scheme can be obtained using the SPHINCS$^+$ framework. This is in contrast to all other signature

[1] See https://microsoft.github.io/Picnic/ for the project page and a list of design and specification documents. Last accessed December 20, 2020.

[2] While producing efficient and short signatures, the use of the new `LowMC` has been commented on by NIST and other works have explored using more trusted ciphers as replacement.

[3] See https://sphincs.org for the project page with the full submission package and a collection of relevant design documents. Last accessed December 20, 2020

schemes mentioned in this document[4], which require a secure cryptographic hash function and an additional mathematical problem to be computationally hard to solve. The general concept of building signature schemes from cryptographic hash functions goes back to the beginning of public key cryptography [66, 82]. For that reason, SPHINCS$^+$ is widely considered the signature scheme with the most conservative security guarantees in the competition.

The rough concept of SPHINCS$^+$ (as well as its predecessor SPHINCS and the first round scheme Gravity-SPHINCS) is as follows. A key pair defines a huge virtual data structure. Data objects required in a signature operation are generated on the fly from a short secret seed using a pseudorandom generator. This virtual data structure of a key pair contains a massive number of hash-based few-time signature scheme (FTS) key pairs (e.g. 2^{60}). Such FTS become less secure with every signature and after a certain number T of signatures (e.g. $T = 8$) security drops below the targeted security level. To prevent using the same few-time key pair more than T times, for every signature a random FTS key pair is selected for every new message. By using sufficiently many FTS key pairs, the probability of a $T + 1$ times collision can be made about as likely as successfully guessing the secret key. The public keys of all these FTS key pairs are authenticated by a single hash value using certification trees (similar to a PKI) built of hash-based one-time signature schemes and binary hash trees.

The SPHINCS$^+$ submission to the NIST process defines instances using SHA2, SHA3, or Haraka [64]. The SPHINCS$^+$ design remained unchanged since the initial submission. The changes introduced in the last iterations were an additional construction for the internally used functions and parameters that offer better performance trade-offs. SPHINCS$^+$ is a flexible design. For example, at NIST security level L1, the specification contains parameters that lead signature sizes of 7 856 bytes and 17 088, while signing times are 2 721 Mcycles and 138 Mcycles, respectively, using SHA2-256. Verification speed is generally fast with about 3 and 8 Mcycles for above parameters, and keys for both parameter sets are 64 bytes for the secret and 32 bytes for the public keys.

[4] While this is theoretically also true for Picnic, to be competitive, Picnic requires a function with low multiplicative depth, a property common hash functions do not provide.

5 QUANTUM MITIGATION

If you encrypt data that needs to be kept confidential for more than 10 years and an attacker could gain access to the ciphertext you need to take action now to protect your data. Otherwise, security will be compromised as soon as the attacker also gets access to a large quantum computer. Given that the NIST process will still run for a few years, there are essentially two viable options to handle this problem.

The first option is to already migrate to so called hybrid implementations that use a combination of pre-quantum and post-quantum schemes. The second option is to employ the conceptionally easy, but organizationally complicated measure of mixing pre-shared keys into all keys established via public-key cryptography. We will detail these two options below.

If you build devices that will be hard to reach or to upgrade later you should include a post-quantum signature scheme now to ensure secure continuity of service when a quantum computer is available. Otherwise, you should start to prepare for migration by making a catalogue of where you currently use public-key cryptography and for what purpose. Make sure to include software updates and third party products in your overview. Figure out whether you fit into one of the use cases that NIST considers – even better, get involved in the NIST discussions to make sure your use case is covered. Then wait for the outcome of the NIST competition (or quantum computers getting dangerously close, whichever comes first) to update your systems.

5.1 HYBRID SCHEMES

A hybrid scheme in this context describes the combination of a pre-quantum public key cryptographic scheme, such as RSA or (EC)DH, with a post-quantum one in a way that guarantees security as long as at least one of the two schemes is secure. Hence, hybrid solutions might also be interesting for the migration to standardized post-quantum schemes as they can be easier justified in cases where certification and compliance are an issue.

We first look at public-key encryption (PKE) and key exchange (KEX). The most generic way to combine two PKE or KEX schemes is to run both schemes to obtain one shared secret per scheme and to xor the two shared secrets to obtain a combined one. For protocols that derive a session key by means of feeding a premaster secret, obtained via public-key cryptography, into a key derivation function (KDF), it is also possible to establish one pre-master secret per scheme and to feed the concatenation of the two pre-master secrets into the KDF. This would for example be applicable in the context of TLS. An extensive case-study of combining schemes for confidentiality that takes a rather applied angle can be found in [31].

When it comes to signature schemes, the combination of two schemes is generically best handled by using them independently. This means, distributing two public keys (possibly in one certificate) and always sending two signatures, one per scheme. For specific schemes, more efficient combiners might be possible but this is a topic of ongoing research. A more detailed discussion including a discussion of practical implementations of such combiners is presented in [18].

5.2 PROTECTIVE MEASURES FOR PRE-QUANTUM CRYPTOGRAPHY

Users who do not want to embark on deploying post-quantum systems before they are standardised. yet are concerned about the long-term confidentiality of their transmitted data can protect their systems by including retained shared secret data in the key derivation, in addition to the key material obtained by a public key operation. This comes at the expense of keeping pairwise shared data and is thus only an option for systems which keep state and have a limited set of peers.

ZRTP [112] includes such a mechanism called "key continuity" as a measure against man-in-the-middle (MITM) attacks. The protocol – specified in 2006 – does not mention security against quantum adversaries as a motivation but is the first description of this idea that we are aware of. It also goes further than other protocols in updating the shared secret data. The more recent Wireguard [40] protocol uses a pre-shared key (PSK) and includes it in the derivation of session keys but does not update the PSK; Wireguard is based on Noise PSK [92, Chapter 9]. Wireguard explicitly mentions the PSK as a feature to protect against later compromise by quantum attackers. (See also [6] for a small tweak to achieve better protection in that scenario and [55] for a fully post-quantum version.)

The following description follows the approach of ZRTP in that the retained shared secret gets updated with each public-key operation by hashing in new data. Including secret data from public-key operations ensures forward secrecy and post-compromise security against pre-quantum attackers. Updating the retained shared secret during each iteration with a hash function ensures that a later compromise of the system cannot recover previous session keys from the retained shared secret and recorded connection data, even if the attacker has a quantum computer and can thus break the pre-quantum public-key encryption.

Let r denote the retained shared secret. Let s be the fresh shared data, obtained from a public-key operation. The above-mentioned protocols are based on the Diffie-Hellman key exchange, but this approach can also be used for RSA-based protocols. Whenever the original protocol calls a KDF for generating the session key k, the KDF's inputs should be extended to include r:

$$k = \mathrm{KDF}(s, ''\texttt{session key}'', r, *),$$

where $*$ is a placeholder for the context data (handshake messages, public keys, ID strings, etc.). This ensure that an attacker can recover k only if he has obtained r as well as s.

After computing k, the retained secret should be updated to

$$r' = \mathrm{KDF}(k, ''\texttt{retained secret}'')$$

possibly including other context data in the KDF arguments.

The protocol needs to be careful to verify that both parties have obtained s before overwriting r. See ZRTP [112] for an instantiation using two variables for retained secret values in order to avoid desynchronization.

The description above leaves open how the users have received the first PSK value r. Users concerned about long-term security should arrange to share such keys out of band (scanned QR code, password, ...). In scenarios with predefined communication patterns, such as a main server communicating with remote registered devices, the PSK may be provisioned with the devices. Note that each device should get a unique PSK known only to the device and the server.

Users may also start with empty r if they achieve authenticity and protection against MITM attacks in other ways, e.g., comparing fingerprints of the obtained data through a different medium (a phone call etc.), or accept trust-on-first use. Note that this helps against quantum attackers only if the attackers miss the first connection, which is unlikely for an attacker so dedicated that they can get a quantum computer. However, it is worth mentioning that, if an attacker ever misses the communication leading to a key update, so that they do not know s, they also cannot compute later values of r. Hence the system can achieve security at a later state.

Note that the above approach is not suitable for systems that get restored from previously saved images, such as virtual machines. In that case a system with a fixed PSK is more suitable, however it does not protect against attackers that later get access to the system, and thus the PSK, and have recorded all messages exchanged, thus all public-key operations.

6 CONCLUSIONS

It is perhaps inevitable that as the technology sector advances drastically over time, our infrastructures are exposed to new attacking vectors. However, Quantum Technology and in particular Quantum Computing are set to be a major disruptor. We have known for more than 2 decades that the development of a sufficiently large and practical quantum computing machine will render most cryptographic systems insecure, radically transformation the existing threat model and endangering our infrastructure.

Moreover, while current systems do not pose any threat, a working quantum computer (i.e., one having a sufficient number of Qubits that is resistant to quantum noise and other quantum-decoherence, is economically viable and practically operational) is the objective of several ongoing large scale investments from both industry players and nation states. However, not all development in the area is public and it is fairly likely that the first fully functional large quantum computer will not be publicly announced. As such, policy maker and system owner should make preparations.

Rolling out new cryptographic systems takes a lot of time and effort;yew it might even be infeasible for systems with restricted accessibility, like satellites. Moreover, signatures play a significant role in protecting modern operating-system upgrades. If a post-quantum signature system is not in place by the time an attacker has access to a quantum computer, then the attacker can take control of the operating system through a fake upgrade and prevent any future upgrades from fixing the problem.

It is thus important to have replacements in place well in advance. What makes matters worse is that any encrypted communication intercepted today can be decrypted by the attacker as soon as he has access to a large quantum computer, whether in 5, 10 or 20 years from now; an attack known as retrospective decryption.

In this study we have provided a brief background of post quantum cryptography, in section 2 we present the 5 main families of quantum resistant cryptographic algorithms that are proposed as potential candidates to provide post-quantum security resilience; viz. code-based, isogeny-based, hash-based, lattice-based and multivariate-based. Section 3 presents the finalist algorithms that are competing to be considered by NIST ready for standardisation, whereas section 4 refers to the algorithms that NIST considers promising, but still not ready to be applied.

The last section – section 5 – presents and briefly explains two possible mitigation mechanics; namely the so-called *hybrid implementations* that use a combination of pre-quantum and post-quantum schemes, and the conceptionally easy, but organizationally complicated measure of *mixing pre-shared keys* into all keys established via public-key cryptography. Both methods have shortcomings, but for system owners requiring long term confidentiality of transmitted data are worth considering. Given that the NIST PQC standardisation process is scheduled to publish a draft standard somewhere in 2022-2024, system owners with more relaxed security requirements and
or with greater resource constraints might be better served waiting for the process conclusion.

The presented algorithms, on sections 3 and 4, refer to asymmetric key (public-key) cryptographic systems – the area of cryptography that will be mostly affected by the existence of quantum computers due to their high reliance on mathematical structures (e.g., factoring, and discrete logarithm problem). Symmetric key (shared-key) cryptographic systems on the other hand present a higher resilience to the new status-quo. In such systems, the adoption of larger key-sizes is considered an effective mitigation technique that is easy to be adopted.

The apt reader will have noticed the absence of mention of Quantum Key Distribution (QKD)[1] or of Quantum Cryptography in this text. This has been a deliberate choice. QKD is a quantum technology application that has been available for many years. It provides a guaranteed, by the laws of physics, secure way of distributing and sharing secret keys that are necessary for cryptographic protocols. It essentially offers key agreement services, but not authentication or message confidentiality; for these services we need to rely on math-based cryptography. In other words, QKD can complement a traditional cryptographic system and its setup relies on pre-established authenticated communications channels. However, the existence of such an authenticated channel, presupposes that communicating parties either have managed to privately exchanged a symmetric key in the past (e.g., by physically meeting) or are using public key cryptography. In the former case, authentication was achieved by direct interaction, which is not a scalable practice. While, in the latter, we are forced to use the same cryptographic algorithms that, as we established, are insecure against quantum cryptanalysis. It clear that QKD is not a direct solution to the problems of quantum cryptanalysis, but rather a comparatively mature application of quantum technology. The term Quantum Cryptography, on the other hand, is often used to denote QKD or erroneously to signify Post-Quantum algorithms like the ones visited in this report. Nevertheless, it can also refer to more exotic cryptographic applications that exploit quantum properties; like quantum [pseudo]random number generators (QRNG), program obfuscation etc. It is important to note that being a quantum cryptographic application does not equate being immune to quantum or traditional cryptanalysis and for many quantum cryptographic application this remains an open question.

[1] https://qt.eu/discover-quantum/underlying-principles/quantum-key-distribution-qkd/

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ABOUT ENISA

The European Union Agency for Cybersecurity, ENISA, is the Union's agency dedicated to achieving a high common level of cybersecurity across Europe. Established in 2004 and strengthened by the EU Cybersecurity Act, the European Union Agency for Cybersecurity contributes to EU cyber policy, enhances the trustworthiness of ICT products, services and processes with cybersecurity certification schemes, cooperates with Member States and EU bodies, and helps Europe prepare for the cyber challenges of tomorrow. Through knowledge sharing, capacity building and awareness raising, the Agency works together with its key stakeholders to strengthen trust in the connected economy, to boost resilience of the Union's infrastructure, and, ultimately, to keep Europe's society and citizens digitally secure. More information about ENISA and its work can be found here: www.enisa.europa.eu.

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ISBN 978-92-9204-468-8
DOI 10.2824/92307