A Study of PQC Migration Frameworks

Eunisse Nzetchuen, Marc Stöttinger, Alexander Wiesmaier,
Elif Yeşilbek

Faculty of Design Computer Science Media
RheinMain – University of Applied Sciences and Arts
Wiesbaden, Germany

Eunisse.Nzetchuen@hs-rm.de

May 10, 2026

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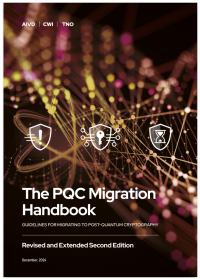
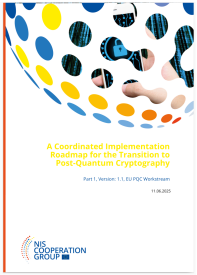
Agenda

Motivation

- Today, cryptography is used everywhere in computer systems
- Current asymmetric algorithms such as RSA and ECC are vulnerable to quantum computers
- Shor's algorithm can break these systems because due to recent advancements in the field of quantum computing it efficiently solves the exact mathematical problems those systems rely on for security.
- So, it is necessary to move to post-quantum cryptography

- NIST is working on standardizing post-quantum algorithms
- Some algorithms have already been standardized
- Current algorithms will be phased out around 2030–2035.
- This leaves little time to migrate because migration es very low and complex.
- There are already exist guideline for how to migrate, but is it enough?





Core Issue with Migration to PQC

- Migration is not only algorithm replacement because, cryptography affects protocols.
- Cryptography is deeply embedded in systems e.g., in TLS.
- Distributed architectures increase complexity because, multiple interconnected components must be updated consistently.
- Hidden dependencies create unexpected risks because, of indirect uses of cryptography.
- Lack of structured methodologies increases failure probability because, without systematic processes, migrations may be incomplete.
- Without a clear methodology, the transition can fail because due partial migration leaving systems insecure.

Paper Objectives

- Analyze and compare existing Post-Quantum Cryptography (PQC) migration frameworks
- Identify how these frameworks address key aspects of migration:
  - Identification of cryptographic components
  - Dependency analysis
  - Risk evaluation and prioritization
  - Cryptographic agility (Crypto agility)
  - Key management
- Evaluate how complete and mature these approaches are
- Highlight the main limitations of current solutions
- Identify open challenges and research gaps for a more reliable PQC migration

- **RQ1 Methodology Maturity**
  - What methods within existing frameworks for PQC migration are used and are they suitable enough for the steps in the migration phases?
- **RQ2 Cryptographic Agility**
  - Do existing frameworks for migration methods take cryptographic agility into account, and if so, to what extent in terms of their properties and a common definition?
- **RQ3 Key Management**
  - What migration stages consider key management and to what extent?

- Survey was done via a systematic literature review following the PRISMA approach
- Search Query: “PQC AND migration AND framework” for academic publications from 2020 to 2026.
- Out of 3760 papers we select 22 relevant papers describing migration frameworks and strategies
- Then we analysed and compared them based on defined criteria.

RESEARCH METHODS AND REPORTING

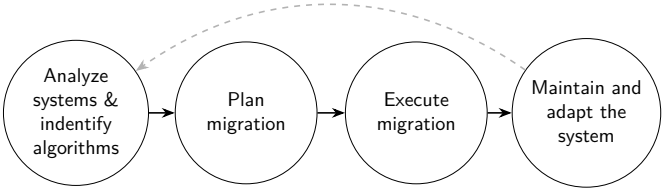
The PRISMA 2020 statement: an updated guideline for reporting systematic reviews

3760 ⟶ 51 ⟶ 22

Initial Filtered Selected

Typical Stages of a Migration Framework

- Most frameworks focus on the identification stage.
- Few frameworks cover the entire migration process [ets24, NHG+24, VNWAH24, WAB+].
- The execution and maintenance phases are often neglected.



Identification of Cryptographic Assets

- Identify all cryptographic assets, e.g., by building an inventory (CBOM):
  - Algorithms
  - Protocols
  - Keys
- Techniques:
  - Manual analysis
  - Automated scanning, cf. [TVSM24] (own tooling *Inventory Generator Tool (IGT)*)
- Challenges:
  - Cryptography hidden in legacy code
  - Third-party libraries are not documented
  - Dynamic usage of cryptographic during runtime
  - Inventory maintenance over time is difficult

Dependency Analysis in PQC Migration

- When we migrate to PQC, we do not change isolated components
- Every system element depends on others (data, crypto, applications)
- These dependencies directly impact:
  - How difficult the migration is
  - In which order components must be updated
  - Whether the migration is even feasible
- All frameworks agree on their importance
- But they differ in how they analyze them:
  - Simple identification vs formal modeling
- Key idea:
  - Complexity comes from the system structure, not just the algorithms [LGH+24]

How Dependencies Are Analyzed

- Some approaches stay at a high level, cf. [GM24]
  - Identify links between systems, data, and organizations
  - Useful to understand global exposure
- Others go deeper and model dependencies explicitly, cf.[HSB+24]
  - Using graphs to represent relationships between assets
  - Helps to reason about security and protection needs
- Some approaches focus on implementation details, cf. [TVSM24]
  - Extract dependencies directly from code (call graphs)
  - Very precise, but harder to scale
- Finally, formal approaches model the system mathematically, cf. [LGH+24, ets24]
  - Identify clusters and constraints
  - Show why migration becomes complex in large systems

Outcomes

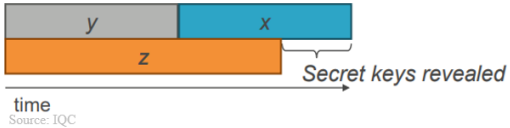
- There is no single “best” approach
- Simpler methods are easier to apply
  - But they miss hidden dependencies
- More formal methods are more powerful
  - But also more complex to implement
- In practice:
  - Small systems $\rightarrow$ simple inventory-based approaches
  - Large infrastructures $\rightarrow$ graph-based models are necessary

Risk Assessment in PQC Migration

- Risk assessment is essential for the planing:
  - What needs to be migrated first
  - What can be delayed
- Risk depends on:
  - Cryptographic vulnerability
  - Value and lifetime of data
  - Migration effort and constraints
- A common approach is based on time:
  - X = data lifetime
  - Y = migration time
  - Z = quantum threat horizon

$$X + Y < Z$$

- If not satisfied $\rightarrow$ high exposure risk, cf. [ets24, TVSM24, GM24]



If the migration is too slow, the risk increases

- Different frameworks assess risk in different ways
- **Temporal and quantitative models**, cf. [TVSM24]
  - Based on time, probability, and exposure
  - Allow prioritization of urgent assets
- **Dependency-based risk**, cf. [HSB+24, LGH+24]
  - Risk appears when sensitive data depends on weak cryptography
  - Influenced by system structure
- **Organizational and strategic risk**, cf. [GM24, NSB+23]
  - Linked to governance and crypto-agility
  - Risk increases if systems cannot evolve quickly

Cryptographic Agility

- The ability to replace or update cryptographic algorithms quickly and safely. (No uniform definition)
- Key requirement for long-term resilience
- Allows hybrid cryptographic deployments

Approach of Cryptographic Agility

- Cryptographic agility is not just technical, it involves design, processes, and organization
- Common approaches:
  - **Architecture and design**
    - Avoid hard-coded cryptography
    - Separate cryptography from application logic
  - **Policies and governance**
    - Integrate cryptographic agility into system design and procurement
- Challenges:
  - Increased complexity and attack surface
  - Performance and storage constraints
  - legacy systems

Key Management in PQC Migration

- Key management is a core part of any cryptographic system
- In PQC migration, it becomes even more critical:
  - New algorithms → new keys
  - Larger key sizes
  - New constraints on storage and performance
- However, most frameworks treat it only at a high level
  - Mainly as part of inventory or asset identification
- Few approaches consider the full lifecycle:
  - Generation
  - Storage
  - Rotation
  - Deprecation

Approach for Key Management

- Inventory-level approaches, cf. [AAB+24, NSB+23, MCD+21]
  - Keys treated as assets
  - Little detail on lifecycle management
- Integrated but implicit approaches, cf. [ets24]
  - Key management appears across all migration phases
  - No dedicated process, but consistent consideration
- Operational and lifecycle-oriented approaches, cf. [WAB+, Rob25]
  - Focus on key rotation, storage, and deployment
  - Consider real-world constraints and tooling

- **RQ1 Methodology Maturity**
  - Frameworks differ in structure and level of detail
  - No unified methodology covering all migration stages
- **RQ2 RQ2 Cryptographic Agility**
  - Widely recognized as essential
  - But no common definition or consistent implementation
- **RQ3 Key Management**
  - Often limited to asset identification
  - Rarely addressed as a full lifecycle process

Conclusion & Future Work

- PQC migration is not optional anymore it is a complex but necessary transition for future security.
- Existing PQC migration frameworks remain fragmented and do not provide a complete solution.
- A unified and systematic methodology is essential to enable a reliable and scalable PQC migration.
- Future work must integrate following dimensions:
  - Develop a unified methodology
  - Better integrate key management
  - Improve dependency analysis
  - Clarify crypto-agility

Thank you!

Let us start to create a sufficient migration framework!

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Back to start

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