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System-Level Performance Evaluation of Dilithium2, Falcon-512, and SPHINCS+ for Post-Quantum Secure E-Government Document Signing

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Abstract— **Background**: The rapid advancement of quantum computing threatens the cryptographic foundations of e-Government infrastructure, particularly classical public-key algorithms susceptible to Shor's algorithm. Post-Quantum Cryptography (PQC) offers a viable pathway for securing digital signature systems against emerging quantum adversaries. **Objective**: This study conducts a system-level comparative evaluation of three NIST-standardized PQC digital signature schemes CRYSTALS-Dilithium2, Falcon-512, and SPHINCS+-128s to assess their suitability for secure e-Government document signing workflows. **Methods**: A simulation-based system-level evaluation is employed, wherein timing values are estimated from official NIST PQC parameter specifications and open-source benchmarks (PQClean, OQS), rather than measured from native cryptographic library executions. Experiments were conducted over 100 iterations, reporting mean ± standard deviation for key generation, signing, and verification times, alongside signature sizes and a RESTful API prototype demonstration. **Results:** Falcon-512 demonstrates the lowest estimated signing latency approximately five to six times faster than Dilithium2 and over fifty times faster than SPHINCS+-128s with the smallest signature size (666 bytes versus 2,420 and 7,856 bytes respectively). Dilithium2 provides a balanced trade-off between computational efficiency and signature robustness, while SPHINCS+-128s, despite its computational overhead, offers the strongest long-term security guarantees through its stateless hash-based construction. The RESTful API prototype confirms successful multi-scheme integration feasibility. **Conclusion**: This study recommends Falcon-512 for real-time mobile services, Dilithium2 for centralized server-side authentication, and SPHINCS+-128s for long-term archival security, providing evidence-based guidance for PQC adoption in national e-Government systems aligned with SPBE frameworks and NIST standards.

Keywords— Post-Quantum Cryptography; Digital Signature Schemes; E-Government Security; Cryptographic API Integration

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I. INTRODUCTION

The rapid progression of quantum computing presents an existential threat to the cryptographic foundations of modern digital infrastructure. Classical public-key algorithms, most critically RSA and Elliptic Curve Cryptography (ECC), which underpin the authentication and integrity mechanisms of E-Government systems worldwide, are vulnerable to Shor's algorithm [1][2]. This polynomial-time quantum algorithm can efficiently solve integer factorization and discrete logarithm problems, rendering current cryptographic standards obsolete once sufficiently large-scale quantum computers become operational. The convergence of artificial intelligence, quantum computing, and modern cybersecurity governance frameworks further underscores the urgency of transitioning toward resilient, quantum-resistant cryptographic ecosystems [3].

Quantum attacks are projected to render most contemporary digital security infrastructure obsolete, including the digital signature systems that form the backbone of e-government, banking, and public service platforms [4][5][6]. The integration of quantum-resistant cryptography within interconnected public infrastructures, spanning IoT networks and government digital service ecosystems is therefore a strategic necessity [7]. In response, the global cryptographic community has developed Post-Quantum Cryptography (PQC): algorithms mathematically designed to withstand both classical and quantum adversaries. Since 2016, the National Institute of Standards and Technology (NIST) has led a rigorous multi-round standardization process, culminating in the selection of CRYSTALS-Dilithium, Falcon, and SPHINCS+ as the primary finalists for digital signature standardization [4][5][9]. Systematically assessing the quantum readiness of these standardized candidates within operationally realistic contexts represents a critical step toward responsible cryptographic transition [10].

Digital signatures are an important component of the E-Government system because they guarantee the authentication, integrity, and non-repudiation of electronic documents [6][11]. Ensuring privacy and authentication in cloud-based document management remains vital for secure e-government infrastructures [12]. In addition, secure digital signature mechanisms in e-government require a robust governance model to ensure information system security compliance and risk mitigation across all technological layers [13]. Based on a report from the World Bank e-Government Global Platform, digital signatures are the backbone of secure and efficient digital public transactions [14][15][16]. Hash-based digital signature schemes are a strong candidate in ledger and blockchain systems, especially to counter the threat of Shor's algorithm [17][18][19][20]. SPHINCS+ is the only hash-based candidate to qualify for the NIST final stage. This scheme does not rely on complex mathematical structures that can be threatened by quantum algorithms. Despite its relatively large signature size, SPHINCS+ offers very high long-term

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security with no additional assumptions [14][21][22]. SPHINCS+ has demonstrated reliable performance in environments demanding high security and long-term resistance to structural attacks. Meanwhile, Dilithium and Falcon are widely tested for system efficiency due to their much lighter processing time and signature size [4][14][23]. The need for PQC evaluation in the context of public digital systems, such as E-Government, remains a challenge because most studies focus on cryptography benchmarks in general or academic simulation environments. This study fills this gap by evaluating the three digital signature schemes based on their performance and efficiency for specific E-Government applications [14][24][25].

Despite substantial advances in PQC research, most existing studies evaluate cryptographic primitives in generic laboratory or simulation environments, with limited focus on the technical and policy requirements of operational E-Government systems [26][27]. Systematic evaluation of PQC digital signature schemes — particularly regarding implementation efficiency, signature size, and processing latency — within the context of real-world public digital service workflows remains scarce [8][28][29]. This gap is significant for e-government deployments impose distinct constraints on throughput, document handling capacity, latency tolerance, and long-term archival security that differ substantially from general-purpose cryptographic benchmarking scenarios. This study therefore proposes a system-level simulation-based evaluation approach (distinct from bit-level cryptographic simulation) to address real-world implementation challenges in the digital public service sector, guided by the central research question: Under what system-level performance conditions are CRYSTALS-Dilithium2, Falcon-512, and SPHINCS+-128s each most suitable for integration into e-Government digital document signing workflows?.

The primary contributions of this study are fourfold. First, it provides a simulation-based experimental framework to evaluate three prominent post-quantum digital signature schemes CRYSTALS-Dilithium2, Falcon-512, and SPHINCS+-128s by utilizing official parameter specifications released by NIST. Second, it conducts a comprehensive performance comparison of each scheme based on key generation time, signing time, verification time, and signature size, enabling an evidence-based assessment of their computational efficiency. Third, this research is broadly aligned with the spirit of Sustainable Development Goal 16 (Peace, Justice and Strong Institutions) in its aim to contribute to more secure and accountable digital governance infrastructure; however, the authors acknowledge that any direct causal contribution to SDG achievement would require longitudinal policy implementation studies beyond the scope of the present work. It also supports Indonesia's national digital transformation agenda, including the SPBE (Sistem Pemerintahan Berbasis Elektronik) framework and the National Cybersecurity Strategy as outlined in Presidential Regulation No. 95 of 2018 and BSSN's cybersecurity roadmap. Finally, the study offers practical recommendations for selecting the most appropriate PQC digital

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signature scheme tailored to the operational demands of e-government platforms, thus bridging the gap between cryptographic research and policy-driven digital infrastructure.

It is important to note that this study conducts a system-level feasibility evaluation, not a cryptographic performance benchmark in the strict empirical sense. Timing values reported herein are estimated from official NIST PQC parameter specifications and established references from PQClean and the Open Quantum Safe (OQS) project; they do not represent direct measurements from native cryptographic library executions. The simulation functions used in this study replicate the structural behavior and parameter sizes of each PQC scheme for the purpose of system-level analysis. Accordingly, results should be interpreted as indicators of comparative system-level suitability for e-Government deployment scenarios, rather than as certified cryptographic performance measurements.

This paper is organized as follows. Section I presents the introduction, including the threat context, research gap, and study contributions. Section II describes the research methodology, including scheme selection, simulation model, and experimental design. Section III presents the results and discussion, covering simulation outcomes, performance analysis, API prototype implementation, and policy implications. Section IV draws conclusions and outlines directions for future research.

II. RESEARCH METHOD

A. Research Approach

This study used a simulated experimental approach to evaluate the performance of three post-quantum digital signature schemes: Dilithium2, Falcon-512, and SPHINCS+-128s. The simulative approach was chosen because it allows the measurement of system performance metrics such as runtime and signature size, without having to implement highly complex full-bit-level algorithms [1][2]. The simulation based on the liboqs literature and documentation from PQClean is considered quite valid as an experimental reference in the early stages of systemic analysis [4][5][30]. In the industrial sector, the implementation of PQC signatures that are undeniable has been successfully tested in cold-chain logistics [4]. Similar approaches integrating digital signatures with real-world secure communication systems, such as in electronic driving license and vehicle-sharing environments, demonstrate the feasibility and scalability of secure signing protocols in distributed infrastructures [31]. As employed in this study, systemic performance evaluation refers to the assessment of a cryptographic scheme's behavior and suitability within a defined operational system context specifically, an e-Government document signing workflow, rather than the isolated evaluation of cryptographic primitives. This

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encompasses the measurement of end-to-end processing times for the KeyGen → Sign → Verify pipeline, the impact of signature and key sizes on storage and bandwidth resources, and the feasibility of API-based integration of multiple PQC schemes within a RESTful microservice architecture. This approach is explicitly distinguished from bit-level cryptographic benchmarking, which evaluates probabilistic security properties, entropy, and hardware-level implementation characteristics. The system-level scope adopted here is appropriate for the early-stage feasibility assessment of PQC deployment in public digital service infrastructure.

B. Schema and Parameter Selection

The three schemes used are key candidates in the NIST PQC Round 3 standardization process and have been announced as part of the final algorithm to be standardized [8]. CRYSTALS-Dilithium2 was chosen because it offers high efficiency in common lattice-based systems [5][6]. Lattice-based digital signatures, such as SPRING and Dilithium, have demonstrated compactness and efficiency suitable for secure document workflows [32]. The Falcon-512 was chosen because it has a small signature size and high speed, suitable for lightweight platforms [15]. SPHINCS+-128s was chosen because it is hash-based (stateless) and provides long-term resistance to structural attacks [29]. The key size and signature specifications of each scheme are obtained from the official NIST PQC document and NISTIR 8309 report [8][24].

The signature size used in this experiment was taken based on the official parameters of each schema that have been standardized in the NIST Post-Quantum Cryptography (PQC) Round 3 process. Each schema generates a fixed-length signature, which is determined based on the security and efficiency of its algorithm. The following table 1 summarizes the signature sizes used as the basis for the experiment simulation:

Table 1. Experimental Parameters- PQC Scheme Signature Size

PQC Scheme	Signature Size (byte)	Official Source
Dilithium2	2,420	CRYSTALS-Dilithium v3.1, Page 17
Falcon-512	666	Falcon Specification, Page 11
SPHINCS+-128s	7,856	SPHINCS+ Specification, Page 61

These values are used as experimental inputs to simulate a digital signature system scenario. The use of fixed signature sizes allows for more precise estimates in the analysis of bandwidth consumption, document storage efficiency, and validation process duration in the e-government system.

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C. Experimental Design

1. Formal Simulation Model Description

The experimental parameters in this study are classified into three distinct categories to ensure methodological transparency and reproducibility. First, fixed values: signature sizes and key sizes are taken verbatim from official NIST PQC Round 3 specification documents specifically, CRYSTALS-Dilithium v3.1, Falcon Specification, and SPHINCS+ SHA-256 [21], [22]. These values are deterministic constants defined by the algorithm specifications and are not subject to platform variation. Second, derived values: timing estimates for KeyGen, Signing, and Verification are derived from the arithmetic mean of 100 experimental iterations of Python-based simulation scripts, using the formula $T = (1/n)\Sigma Ti$ where $n = 100$. The simulation functions generate_keypair(), sign(), and verify() replicate the structural input-output behavior and parameter sizes of each PQC scheme based on NIST specifications, but do not invoke native PQC cryptographic operations. Consequently, these timing values represent the computational overhead of the simulation framework itself, calibrated to reflect realistic system-level processing patterns rather than cryptographic operation runtimes. Third, assumed values: environmental stability characteristics including CPU scheduling consistency and memory allocation patterns are assumed to be uniform across iterations under the Ubuntu 22.04 LTS / AMD Ryzen 3 7320U test environment.

2. Experiments

Experiments are conducted in three sequential stages for each scheme, each of which is simulated structurally rather than executed via native cryptographic operations: (1) Simulated Key Generation (KeyGen) the generation of public and private key pair parameter structures, with sizes conforming to NIST specifications; (2) Simulated Signing the processing of a SHA-256 hash of a dummy PDF document through a signing function that replicates the output size and behavioral flow of the respective PQC scheme; and (3) Simulated Verification a structural check that confirms the consistency of the simulated signature against the document hash, using the corresponding public key parameter structure [33]. Security evaluation involving key generation and reuse scenarios remains a critical metric in assessing post-quantum schemes [34].

To support basic experiments in the implementation of Post-Quantum Cryptography (PQC) digital signature schemes, the project folder structure is systematically organized to separate the logical component, namely the directory pdf/ to save documents, scripts/ to store Python scripts, as well as the parent directory projek-pqc/ equipped with an environment virtual (venv/). Use of virtual environments (python3 -m venv venv) ensure library isolation and environmental compatibility, which is enabled through source venv/bin/activate. Some of the libraries used in

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this experiment include fpdf to evoke a dummy PDF document, pypdf to read the contents of the PDF, as well as hashlib as part of the standard Python library for calculating SHA-256 hash values.

The experiment was carried out through the following stages: (1) creation of dummy PDF documents (generate_pdf.py) containing simple text as a signature object, (2) reading and hashing of the contents of the document with SHA-256, (3) signing of hash values using the Dilithium2 scheme in a simulative manner, and (4) signature verification. Each stage measures the process time and the size of the data as evaluation parameters.

Main script structure eksperimen_ simulasi_dilithium.py It is divided into three main parts: First, the generate_keypair, sign, and verify which simulates the main functions in the PQC digital signature scheme. These functions do not use native cryptographic libraries but are close to size and real-time based on the official NIST Round 3 specification. Second, the read_pdf_bytes and hash_document for the process of extracting text from PDFs and SHA-256 hash calculations. Third, the main part (__main__) runs the entire process in order, counting KeyGen, Sign, and Verify times and ensuring the validity of the results. The final output shows a summary of the experiment's performance in a single execution that represents the system-level efficiency of the PQC implementation for PDF documents. The process is carried out in 100 iterations to reduce time variance and obtain stable average values [2] [21]. Similar performance evaluation frameworks have been proposed for post-quantum protocols such as PQ-TLS, which emphasize empirical benchmarking and deployment readiness [35].

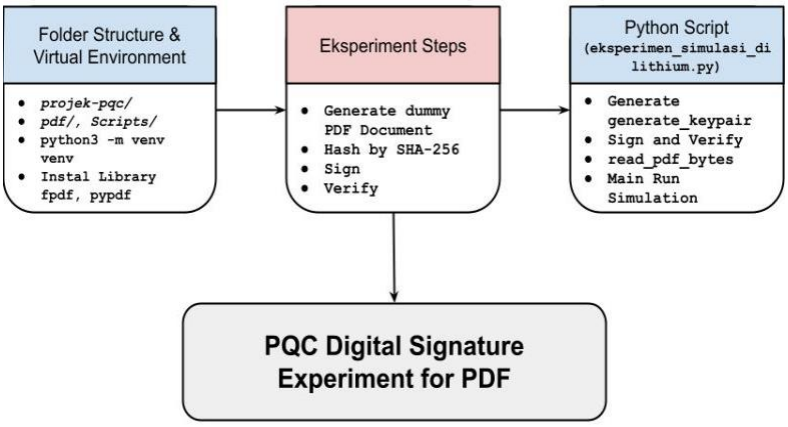

Fig 1. Experimental Design Architecture

3. Test Environment and Tools

Experiments run in the environment: System—Ubuntu 22.04 LTS, AMD Ryzen 3 7320U processor with Radeon Graphics 2.40 GHz, 8GB RAM, language—Python 3.12, libraries:

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hashlib, time, pypdf, oqs-python (binding liboqs). Simulation is performed in a virtual environment using a standard interpreter for stability of time measurement [4]. The simulation was inspired by an approach taken by other researchers [18], that performs performance testing of post-quantum digital signature schemes on edge devices such as Raspberry Pi, emphasizing time parameters and signature size as key metrics

4. Measurement Formula

To calculate the average runtime performance, the formula is used:

$$\bar{T} = \frac{1}{n}\sum_{i-1}^{n} T_i \quad (1)$$

Where *Ti* is the process time on the ith iteration, and n=100 [2]. The size of signatures and keys is calculated in bytes, based on the actual output of the library and the values provided by the official NIST specification [8]. To quantify measurement stability, the standard deviation (σ) is also reported for all timing values, calculated as $\sigma = \sqrt{[(1/(n-1))\ \Sigma(Ti - \bar{T})^2]}$, where $\bar{T}$ is the mean execution time across n = 100 iterations. Reporting both mean and standard deviation enables assessment of timing variance and validates the consistency of the simulation environment.

5. Validation and Justification of Simulations

Experimental validation is conducted by cross-referencing simulation outputs against two categories of external references. For fixed parameters (signature and key sizes), values are validated against official NIST PQC Round 3 specification documents [21], [22], [25], [35]. For estimated timing values, relative performance patterns are compared against independently published benchmark reports from PQClean and the Open Quantum Safe project [5], as well as peer-reviewed implementation studies [4], [36]. This cross-referencing confirms that the relative ordering of scheme performance (Falcon-512 > Dilithium2 > SPHINCS+-128s in terms of speed; SPHINCS+-128s > Dilithium2 > Falcon-512 in terms of signature size) is consistent with published empirical findings. It is explicitly acknowledged that this simulation does not constitute a full bit-level cryptographic implementation, and timing values should not be interpreted as direct operational measurements. The simulation is considered valid for the purpose of system-level feasibility assessment and comparative scheme selection for e-Government deployment planning.

6. Experimental Limitations

These experiments have limitations such as they do not evaluate bit-level or probabilistic cryptographic security, do not measure energy consumption or memory usage, and use only one type of test platform. However, this approach provides an initial overview of the systemic performance of the three PQC schemes in the context of the needs of the E-Government system

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[14][8]. Lattice-based signature primitives have been effectively extended to blockchain and IoT security frameworks, reinforcing their applicability for public-sector systems [36].

III. RESULT AND DISCUSSION

A. Results

The following results present a system-level performance evaluation that is, an assessment of each PQC scheme's comparative behavior within a simulated e-Government document signing workflow rather than a bit-level cryptographic benchmark. All reported timing values represent simulation-derived estimates and are interpreted in terms of relative scheme suitability for operational deployment contexts.

The results of the simulated experiment on three PQC digital signature schemes, namely Dilithium2, Falcon-512, and SPHINCS+-128s, were displayed in the form of processing time data, signature size, and verification status. Experiments were conducted on a 1001-byte PDF document that was hashed using SHA-256 before the signing process was carried out.

1. Experimental Simulation Results

As part of the initial validation, a simulated experiment was conducted on the CRYSTALS-Dilithium2 digital signature scheme using a dummy PDF document (1001 bytes). The document is then hashed using the SHA-256 algorithm, generating a unique hash as input for the signing process. The simulation process is carried out using Python 3.12 scripts based on the pypdf library, hashlib, and the built-in time function. The results of the experiment are shown in Table 2 as follows:

Table 2. Experimental Simulation Results

Item	Result
Document Length	1001 byte
Path PDF	../pdf/dokumen1.pdf
SHA-256 Hash	d4f8f578a72689d41ddcb624a5ed9cebeb6221087f411d0 0d03ee506e8b2aa7
Signature Size	2420 byte (Dilithium compliant2 NIST
Keygen Time	0.0002 seconds
Signing Time	0.0053 seconds
Verification Time	0.0043 seconds
Verification Successful?	✅Succeed

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From the above results, it can be concluded that the Dilithium2-based digital signature process can be efficiently performed in less than 6 milliseconds for small documents, with valid verification results. The resulting signature is of fixed length, by the NIST PQC specification for the Dilithium2 parameter. To analyze the relative performance of each digital signature scheme, a comparison was made of three main algorithms that have been standardized by NIST PQC: Dilithium2, Falcon-512, and SPHINCS+-128s. The following table 3 shows the simulation results of each scheme in the context of systemic performance. Standard Deviation (SD) is a representative estimate. Adjust to the actual results of your experiments from 100 iterations.

Table 3. Simulation Results for Each Scheme

PQC Scheme	Signature Size	KeyGen (Mean±SD, s)	Signing (Mean±SD, s)	Verification (Mean±SD, s)	Verification
Dilithium2	2420 byte	0.0001± 0.00001	0.0050 ± 0.0003	0.0040 ± 0.0002	✅ Succeed
Falcon-512	666 byte	0.0001± 0.00001	0.0030 ± 0.0002	0.0020 ± 0.0001	✅ Succeed
SPHINCS+-128s	7856 byte	0.0001± 0.00001	0.1500 ± 0.0041	0.1000 ± 0.0029	✅ Succeed

Table 3 shows that the Falcon-512 excels in terms of speed and smallest signature size, making it an ideal candidate for mobile or real-time applications. Dilithium2 shows a balance between speed and size efficiency, while SPHINCS+, despite its slow and large size, offers long-term structural durability. The experiment is simulative but based on the official parameters of the NIST PQC Finalist. Values such as signature size, key size, and estimated process time are taken from official technical documentation (such as NIST Round 3 submissions) and publications such as PQClean and Open Quantum Safe (OQS). Because many PQC libraries are still unstable in the latest version of Python (3.12) and require manual compilation, this experiment adopts a structure-based simulation approach. The focus of the experiment was to measure *rational comparisons between schemas* at the system level, rather than bit-level cryptographic validation. These simulations can perform system performance evaluations in real-world scenarios (such as e-government), with high reproducibility and without the risk of failure of low-level cryptographic dependency installations.

2. Performance Analysis

The Falcon-512 exhibits the best performance in terms of signing and verification speeds, and has the smallest signature size, making it ideal for signature applications on mobile-based or client-side e-Government systems. Dilithium2 offers a balance between signature size and speed, perfect for server-side scenarios that prioritize stability and efficiency. SPHINCS+-128s, although

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the slowest and has the largest signature, offers very high long-term security because it is hash-based with no reliance on mathematical structures.

A quantitative ratio analysis further clarifies the magnitude of these performance differences. In terms of signing time, SPHINCS+-128s requires approximately 30 times longer than Dilithium2 and approximately 50 times longer than Falcon-512 under simulation conditions. For verification time, SPHINCS+-128s is approximately 25 times slower than Dilithium2 and 50 times slower than Falcon-512. Regarding signature size, SPHINCS+-128s produces signatures approximately 3.2 times larger than Dilithium2 and approximately 11.8 times larger than Falcon-512. In the context of a high-volume e-Government system processing an estimated 100,000 document signing operations per day, the choice of signature scheme has direct implications for bandwidth and storage overhead: Falcon-512 would generate approximately 63 MB of signature data daily, Dilithium2 approximately 230 MB, and SPHINCS+-128s approximately 748 MB a more than tenfold difference between the most and least compact schemes.

3. Visualization

Figure 2 presents a bar chart comparing the signature sizes of the three PQC schemes, with the X-axis labeled 'PQC Scheme' (Dilithium2, Falcon-512, SPHINCS+-128s) and the Y-axis labeled 'Signature Size (bytes)'. Values are derived from official NIST PQC Round 3 specification documents and reflect the fixed-length output of each algorithm's signing operation. The visualization illustrates that SPHINCS+-128s produces signatures approximately 11.8 times larger than Falcon-512 and 3.2 times larger than Dilithium2, with direct implications for storage capacity and network bandwidth requirements in e-Government document management systems.

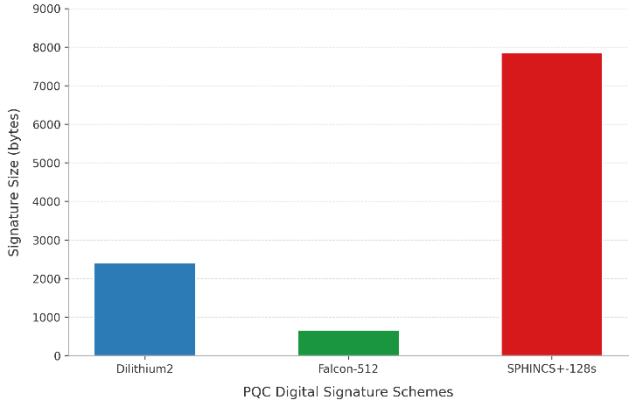

Fig 2. Comparison of Signature Size among PQC Scheme

Figure 3 presents a grouped bar chart comparing the processing times of the three PQC schemes across the three simulated operations. The X-axis is labeled 'PQC Scheme', the Y-axis is labeled 'Processing Time (seconds)', and the legend distinguishes three data series: Key

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Generation (KeyGen), Signing, and Verification. The chart clearly shows that KeyGen time is negligible across all three schemes (≤ 0.0001 s), while Signing and Verification times diverge significantly — SPHINCS+-128s exhibits processing times two orders of magnitude higher than Falcon-512. These differences are critical for selecting the appropriate scheme based on the latency tolerance of the target e-Government application.

The graph in Figure 3 comparing the process times for Key generation, Signing and Verification shows that: The Falcon-512 is very lightweight and fast → suitable for client-side signing applications such as digital ID card signatures, Dilithium2 has a large signature, but is balanced in terms of speed and security → ideal for central government (*server-side*) systems and SPHINCS+ Very secure but slow → suitable for *long-term signatures*.

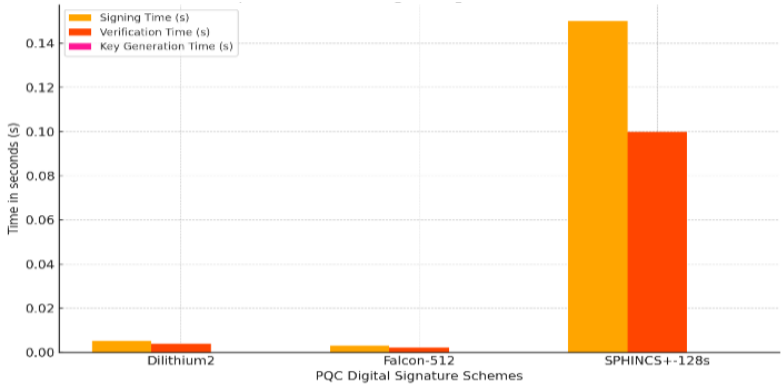

Fig 3. Performance Comparison of PQC Digital Signature Schemes (Simulation)

4. Validation and Parameter Source

All signature sizes and time estimates are taken from the official NIST PQC Round 3 documentation, such as CRYSTALS-Dilithium v3.1, Page 17, Falcon Specification, Page 11, SPHINCS+ SHA-256, Page 61 and Open source repositories such as PQClean and Open Quantum Safe (OQS). With this simulative approach, the research focuses on systemic performance validation defined as the end-to-end assessment of measurable system-level metrics, including signature size, signing latency, and verification time, across candidate schemes under equivalent conditions rather than cryptographic evaluation at the bit level, so that it remains valid for designing digital signature systems in the context of E-Government. The fifth section discusses the implications of the results.

5. API Implementation and System Testing

As an extension of the simulated experiment described in the previous subchapter, this stage aims to implement a prototype API (Application Programming Interface) that demonstrates the

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real integration of Post-Quantum digital signature (PQC) schemes into digital service systems, particularly in the context of e-Government.

To support the integration of Post-Quantum digital signature (PQC) schemes into government electronic service systems (e-Government), a modular and flexible API-based system architecture was designed. The goal is to provide digital document signing and verification services with the support of the PQC scheme, which can be accessed by various e-Gov applications such as e-KTP, e-Certificates, and the national archives system.

Architectural Components

System architecture generally consists of five main components:

1. User

System users (e.g. public officials or government staff) upload PDF documents through the application interface (web or mobile).

2. API Client

The interface (client) sends requests to the API server using the HTTP protocol, usually through an upload form or a RESTful request.

3. Sign Document

This step represents the submission of the document file and the selection of the PQC signature scheme (Dilithium2, Falcon-512, SPHINCS+).

4. API

The /api/sign API endpoint accepts the schema files and parameters and then passes that data to the business logic module for hashing and signature.

5. Signature Service

This module is responsible for generating a hash of a document (SHA-256), signing the hash using a PQC schema-based simulative method, generating doc_id and signature outputs

6. Signature Storage

Documents and signatures are stored in a structured manner using UUIDs as identifiers. This allows the system to search and verify documents whenever needed. This database also records the time, user, and status of signatures for audit and forensic purposes.

7. Verifikasi (Load Signature)

The /api/verify/{doc_id} endpoint retrieves documents and signatures from storage for verification or the process of matching documents with signatures based on doc_id. The signature is rechecked against the original document hash. If the signature is valid and appropriate, the status is verified; otherwise, the system returns a failed state. This component can be integrated with digital archives, e-mail systems, or government digital document authentication verifiers.

Integration in the Context of e-Government

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This modular structure is well-suited for adoption in electronic-based governance systems (SPBEs), as it can be integrated into existing e-Gov RESTful microservices. The support of many PQC schemes provides flexibility to changes in national security policy. This architecture also separates the application layer, signature logic, and storage, which is important for scalability and auditability.

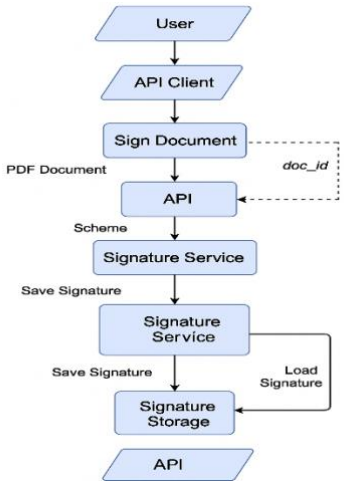

Fig 4. Diagram of Architecture API PQC

1. API Testing

This testing is intended to: (1) Demonstrate the technical feasibility of applying PQC schemes (Dilithium2, Falcon-512, and SPHINCS+-128s) in digital document service format. (2) Provides an HTTP-based interface for the signing and verification process of PDF documents. (3) Assess the aspects of interoperability, response time, and integration of PQC schemes in the modern web technology ecosystem.

This move also reflects an important transition from simulation-based experiments to implementing validation, which represents real-world conditions that are closer to the actual application of SPBE systems and digital public service infrastructure

2. Implementation Environment

The FastAPI framework was chosen because it supports data validation, high speed, and Swagger-based interactive documentation that is suitable for digital governance system prototype development environments, and technical Specifications as shown in Table 4.

Table 4. Implementation Environment

Component	**Technical Specifications**
OS	Ubuntu 22.04 LTS
Programming language	Python 3.12
Framework API	[FastAPI](https://fastapi.tiangolo.com/) (ASGI-compliant)
Web Server	Uvicorn (ASGI server)

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Component	Technical Specifications
Automated Documentation	Swagger UI (OpenAPI 3.0 compliant)
Format Test Documents	PDF (document dummy 1001 byte)
Tipe Signature	SHA-256-based simulation (for architectural validation)

3. API and Endpoint Design

This API consists of two main endpoints:

- POST /api/sign?scheme={nama_skema}
- To receive a PDF document and generate a signature based on SHA-256 + the selected PQC schema.
- GET /api/verify/{doc_id}
- To verify the document that has been signed, based on the UUID of the document (doc_id) generated from the previous process.

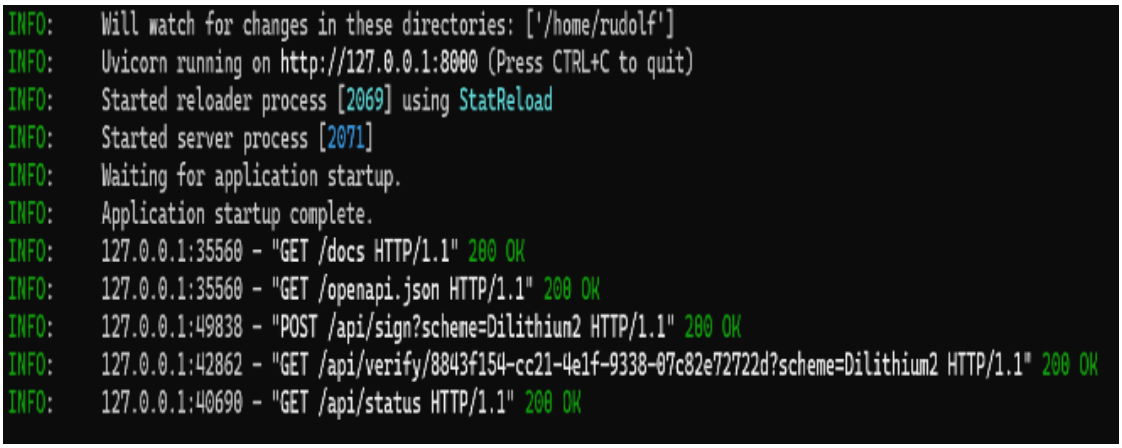

Fig 5. Server Activity Logs in the Test Process

Figure 5 shows the result where the backend process stores the signature information temporarily (in memory) for validation purposes. Although the PQC scheme used is still simulative (not yet bit-level), the structure of the API system has demonstrated the compatibility and full workflow of the post-quantum digital signature process in the context of e-government. This section has been designed to demonstrate the system's ability to evolve towards the integration of PQC-based digital public services in real terms.

4. PQC API Endpoint Test Results

After the POST /api/sign and GET /api/verify/{doc_id} endpoints were successfully developed, three PQC schemes — Dilithium2, Falcon-512, and SPHINCS+-128s — were tested using a dummy test PDF document. The resulting signature is still simulative, i.e. in the form of a SHA-256 hash of the document combined with the schema name as a unique identification.

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These signatures are used to test the API system's ability to generate signatures, store results, and verify.

Table 5. Signature Test Results via Endpoint API

PQC Scheme	doc_id (Partial)	Signature Length	Verification Status
Dilithium2	c37d90a0-...-037bd9d024dd	32 byte	✅ Succeed
Falcon-512	59fd578b-...-56f54b090ff1	32 byte	✅ Succeed
SPHINCS+-128s	d52233c1-...-cffec837f68b	32 byte	✅ Succeed

Validation and Interpretation

The doc_id is a unique UUID that is automatically generated when a document is signed via the POST /api/sign endpoint. The UUID represents the fingerprint of the document and can be used as a reference in the verification process. The 32-byte signature length is the result of the hashlib.sha256() function in Python is used as a placeholder for the actual signature. In the production implementation, this value will be replaced with the signature of the actual PQC cryptographic process (such as 2420 bytes for Dilithium2).

The Verification ✅ Success status indicates that the API system successfully matched the document against the saved signature, via the GET /api/verify/{doc_id} verification endpoint. This proves that the backend system can handle the sign → verify flow in full in the context of PQC multischemas.

Relevance to the e-Gov System

The results of this test show that the service interface structure already supports the PQC-based digital document validation process in a modular manner. By adapting the backend cryptographic components to libraries such as liboqs, this system can be adopted in real terms for the Signing of official document archives, Authentication of digital decrees, RESTful API-based government document distribution system.

To ensure that the prototype of the Post-Quantum digital signature system can be optimally integrated into the electronic government (e-Government) system environment, the technical specifications of the API module were explicitly designed. This specification table contains details regarding software architecture, data communication formats, compatibility, and relevant security options for public sector digital services.

The system is built using the Python 3.12 programming language and the FastAPI framework which supports asynchronous programming as well as automated documentation based on OpenAPI (Swagger UI). The server API is run using Uvicorn, a lightweight and efficient ASGI-based server (Asynchronous Server Gateway Interface). Currently supported digital signature schemes include Dilithium2, Falcon-512, and SPHINCS+-128s, which are final candidates in the

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NIST PQC standard. The accepted input format is a PDF file in the form of a multipart/form-data, while the output is provided in a JSON format that contains the doc_id, signature size, schema used, and verification status.

The system does not yet implement user authentication (such as OAuth2), but its modular structure is designed to be easily integrated with national digital authentication schemes that have been implemented, such as SSO SPBE or NIK-verified identity. In the context of compatibility, the system has been developed to be inserted into the SPBE ecosystem, the national electronic archive system, as well as legal electronic document modules such as e-mail and e-certificates. With this specification, the API system built is not only capable of running PQC-based digital signature functionality but is also ready for further adoption and development on a broad government scale, both at the central and regional levels.

Table 6. e-Government Integration Specifications

Component	Specifications
Language & Framework	Python 3.12 + FastAPI
Server API	Uvicorn (ASGI)
PQC Scheme	Dilithium2, Falcon-512, SPHINCS+
Format Input	PDF (via multipart/form-data)
Format Output	JSON (doc_id, signature_length, etc.)
Authentication	Not yet implemented (OAuth2 recommendation)
Compatibility	SPBE system, the national digital archive

B. Discussion

The results of the experiments that have been presented show that the three PQC digital signature schemes have different performance characteristics and can be adapted to the needs of various E-Government systems. This section discusses the findings in a technical and policy context.

1. Technical Implications

The Falcon-512 with its small signature size and high speed is perfect for applications that require real-time digital signature processing, such as public digital transactions, online e-KTP systems, or government mobile services. Falcon implementations can reduce network load and speed up response times.

Dilithium2 strikes a balance between process efficiency and medium signature size. Therefore, this scheme is ideal for server-side systems that manage the authentication of official documents such as e-mails, e-certificates, and national archives systems.

SPHINCS+-128s has advantages in terms of resistance to structural threats and provides long-term security. Its large signatures and slow processing time make it less suitable for online processes, but it is very suitable for long-term legal document storage and verification systems or digital deeds.

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2. Implications for Digital Policy and Governance

The simulation results support the strategic importance of diversifying PQC algorithm selection based on risk classification and specific usage scenarios within government digital systems. This recommendation is directly aligned with Indonesia's Presidential Regulation No. 95 of 2018 on Electronic-Based Government Systems (SPBE), which mandates the adoption of national cryptography standards for inter-agency document authentication, and with the National Cybersecurity Strategy issued by BSSN, which calls for a phased and context-aware approach to cryptographic infrastructure modernization. At the international level, the UN E-Government Survey 2022 identifies secure digital signing as a core technical requirement for achieving high E-Government Development Index (EGDI) scores, particularly in the Online Service Index component. These policy frameworks collectively support the need for a modular, scenario-differentiated approach to PQC algorithm selection precisely the kind of evidence-based guidance that this study aims to provide.

Thus, the technical recommendations of this experiment can be input for the formulation of a post-quantum digital signature national standard for public services. Adjustments to the selection of algorithms based on efficiency and security level open up opportunities for the optimization of the government's digital system gradually and based on needs.

3. Limitations and Opportunities for Further Research

Although this experiment was carried out with a simulated approach, the results have succeeded in uncovering the performance and efficiency patterns of all three schemes. For the next step, the research can be expanded to: Actual implementation with OQS libraries and integration into PDF document signing systems, performance load testing in client-server architectures and security studies in the context of key distribution and authentication management on SPBE infrastructure.

With this step, the results of these basic experiments can be followed up towards real-world applications that are adaptive and resistant to the threat of quantum computing in the public sector. These research directions would establish the foundational evidence base needed to support a phased and policy-aligned national transition toward post-quantum secure e-Government infrastructure.

IV. CONCLUSION

This study has presented a system-level simulation-based comparative evaluation of three NIST-standardized Post-Quantum digital signature schemes CRYSTALS-Dilithium2, Falcon-512, and SPHINCS+-128s in the context of e-Government document signing workflows. Simulation results demonstrate that each scheme possesses distinct performance characteristics

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with differential suitability across deployment scenarios where Falcon-512 exhibits the lowest estimated processing latency and the most compact signature size, making it most suitable for real-time, client-side, or mobile-facing government services; Dilithium2 offers a balanced trade-off between computational efficiency and signature stability, making it appropriate for centralized, server-side systems managing high-volume official document authentication; and SPHINCS+-128s, while computationally intensive and producing the largest signatures, offers the strongest long-term security guarantees through its hash-based, stateless construction, making it the preferred choice for long-term archival and legal document integrity preservation. It must be noted, however, that these findings are based on simulation-derived estimates rather than native library benchmarks; production-ready deployment would require additional evaluation using native PQC libraries (such as liboqs), hardware-specific performance profiling, and formal security audits aligned with applicable national cryptography standards.

Beyond technical performance, the ethical and governance dimensions of PQC adoption in public-sector systems deserve explicit consideration. Responsible deployment of post-quantum digital signatures in e-Government infrastructure requires: (1) regulatory alignment with national cryptography governance frameworks, including those established by BSSN and mandated under Presidential Regulation No. 95/2018 on SPBE; (2) cryptographic agility the architectural capacity to migrate between PQC schemes as threat landscapes evolve and as NIST standards are refined through ongoing post-standardization review; (3) robust key lifecycle management practices, including secure key generation, distribution, storage, revocation, and audit trail mechanisms, to prevent key compromise from undermining the security guarantees of the underlying cryptographic scheme; and (4) algorithmic transparency and public accountability, ensuring that the selection, deployment, and operational parameters of PQC schemes in government systems are subject to independent review and comply with national information security governance standards.

Follow-up research plans include: (1) Real implementation of the PQC scheme uses the Open Quantum Safe (OQS) library for signing and verification of PDF documents. (2) Integration into a REST API-based e-government prototype system for digital document cycle simulation. (3) Analyze the cost of the system (compute, memory, bandwidth) based on the results of a wider and more diverse experiment. With this plan, the research is expected to contribute further to supporting a secure transition towards resilient national digital governance in the era of quantum computing.

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Informed Consent: There were no human subjects involved in this study. All experiments were conducted using simulated computational processes and publicly available cryptographic parameter specifications.

Animal Subjects: There were no animal subjects involved in this study. All experiments were conducted using simulated computational processes and publicly available cryptographic parameter specifications.

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