

Quantum-Resistant Domain Name System: A Comprehensive System-Level Study

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The Domain Name System (DNS) plays a foundational role in Internet infrastructure, yet its core protocols remain vulnerable to compromise by quantum adversaries. As cryptographically relevant quantum computers become a realistic threat, ensuring DNS confidentiality, authenticity, and integrity in the post-quantum era is imperative. In this paper, we present a comprehensive system-level study of post-quantum DNS security across three widely deployed mechanisms: DNSSEC, DNS-over-TLS (DoT), and DNS-over-HTTPS (DoH). We propose *Post-Quantum Cryptographic (PQC)-DNS*, a unified framework for benchmarking DNS security under legacy, post-quantum, and hybrid cryptographic configurations. Our implementation leverages the Open Quantum Safe (OQS) libraries and integrates lattice- and hash-based primitives into BIND9 and TLS 1.3 stacks. We formalize performance and threat models and analyze the impact of post-quantum key encapsulation and digital signatures on end-to-end DNS resolution. Experimental results on a containerized testbed reveal that lattice-based primitives such as Module-Lattice-Based Key-Encapsulation Mechanism (MLKEM) and Falcon offer practical latency and resource profiles, while hash-based schemes like SPHINCS+ significantly increase message sizes and processing overhead. We also examine security implications including downgrade risks, fragmentation vulnerabilities, and susceptibility to denial-of-service amplification. Our findings inform practical guidance for deploying quantum-resilient DNS and contribute to the broader effort of securing core Internet protocols for the post-quantum future.

Additional Key Words and Phrases: PQC, DNS, DoT, DoH

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1 INTRODUCTION

The **Domain Name System (DNS)** is a fundamental basis of the Internet that translates human-readable domain names into **Internet Protocol (IP)** addresses and facilitates all modern network communication. However, the original DNS protocol was not designed with security in mind, leaving it vulnerable to a number of attacks. Common threats include **DNS spoofing** (or cache poisoning), where attackers inject false DNS records into a resolver's cache, **DNS amplification attacks**, a form of **Distributed Denial of Service (DDoS)**, where DNS servers are exploited to flood a target with traffic, and **DNS hijacking**, where queries are redirected to malicious servers [18]. Over the past two decades, a number of **DNS**

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security extensions and enhancements, [Domain Name System Security Extensions \(DNSSEC\)](#), [DNS over TLS \(DoT\)](#), and [DNS over HTTPS \(DoH\)](#), have been developed to mitigate threats such as spoofing, tampering and surveillance [1] [35]. DNSSEC provides data integrity and origin authentication through digital signatures and thus protects against cache poisoning and similar attacks. DoT, and DoH, provide encrypted transport mechanisms to protect DNS requests and responses from eavesdropping and data manipulation in transit. Together, these protocols form the backbone of secure DNS resolution in the current Internet ecosystem.

However, the security of all three protocols depends on classical public key cryptographic primitives, most commonly RSA, ECDSA, and X25519, which are known to be vulnerable to quantum attacks. Once quantum computers can be deployed on a large scale, algorithms like Shor’s will render these cryptosystems obsolete and make DNS vulnerable to privacy and integrity issues [4].

To counter this new threat, there is growing interest in [Post-Quantum Cryptography \(PQC\)](#) - cryptographic algorithms designed to resist attacks from quantum computers. Although standardization efforts are underway, most notably by [National Institute of Standards and Technology \(NIST\)](#), adapting these new primitives to the DNS infrastructure is a major challenge. The DNS is a performance-critical system with strict constraints on message size, latency, and compatibility. Post-quantum signature schemes such as MLDSA, Falcon, and SPHINCS+, while secure against quantum adversaries, may introduce larger keys and signatures or increased computational overhead, which can impact DNSSEC’s ability to remain efficient and interoperable. Similarly, post-quantum key exchange mechanisms must be evaluated in the context of DoT and DoH, where low-latency TLS handshakes are essential for practical use.

While progress has been made in incorporating post-quantum cryptographic primitives into particular components of DNS security, such as DNSSEC with PQ-signatures [22] or TLS with PQ key exchanges [6], most current research endeavors focus on these protocols alone. This disjointed picture leads to an inadequate comprehension of the performance of post-quantum measures across the whole DNS security stack, especially when deployed in combination within real-world operational constraints. In particular, encrypted DNS protocols such as DoT and DoH, which form the privacy-enhancing basis of current DNS resolution, have received little attention in the post-quantum discourse compared to DNSSEC. Furthermore, the impact of the introduction of post-quantum cryptography on the interoperability, latency and scalability of DNS systems has hardly been comprehensively investigated when all three protocols are analysed together. This narrow focus creates a notable gap in the literature: the lack of a thorough, comparative, and system-level examination of DNSSEC, DoT, and DoH within post-quantum cryptography frameworks. Without this, it is difficult to assess the practical feasibility and trade-offs of transitioning DNS infrastructure to a post-quantum-resilient architecture.

To address this gap, our research presents a comprehensive analysis of post-quantum security concerning the three primary DNS protection mechanisms: DNSSEC, DoT, and DoH. We specifically present the following key contributions:

- **Post-Quantum DNS Implementation and Evaluation Framework:** We present a unified implementation of DNSSEC, DoT, and DoH protocols secured with NIST-recommended post-quantum cryptographic primitives. Our framework enables protocol-level benchmarking across classical, hybrid, and PQC-only modes, and includes a formal model of DNS resolution performance under varying cryptographic configurations. Experimental results quantify latency, bandwidth, and resource trade-offs, providing practical insights into DNS migration feasibility.
- **Security Threat Taxonomy and Mitigation Strategies:** We identify critical vulnerabilities introduced by PQC adoption-such as downgrade attacks, timing leaks, and fragmentation exploits-and propose mitigation strategies ranked by severity. Our analysis informs secure-by-design integration of PQC into DNS systems.

- **Deployment Challenges and Design Recommendations:** We uncover practical constraints-including compatibility gaps, resource consumption at the edge, and hybrid mode fragility-that limit immediate deployment. Based on our findings, we offer actionable guidance for transitioning DNS infrastructure toward quantum resilience.

The remainder of the paper is structured as follows. Section 2 surveys related work on DNS security extensions and post-quantum cryptography in networked protocols. Section 3 presents the system architecture and formalizes the performance model, protocol sequence, and associated cost equations for PQC-DNS. Section 3 also analyzes emerging security threats introduced by PQC adoption, and presents corresponding mitigation strategies. Section 4 reports empirical findings for DNSSEC, DoT, and DoH under classical, hybrid, and post-quantum cryptographic configurations. Section 5 discusses deployment challenges, sustainability, and directions for future work. Finally, Section 6 concludes the paper.

2 RELATED WORK

DNS, a foundational component of the Internet, has long been recognized as a target of privacy and integrity attacks. In response, several privacy enhancements such as DoT [17], DoH [16], and DNSSEC [3] have been standardised to enable encryption and authentication. However, these protocols are based on classical cryptographic primitives that are vulnerable to future quantum adversaries. With the standardisation of PQC underway [23], recent research has begun exploring how DNS security protocols can be adapted for post-quantum resilience. Early work on PQ-TLS, e.g. by Stebila et al. [37] and Hülising et al. [19], demonstrated hybrid key exchange techniques that combine classical and post-quantum algorithms (e.g. X25519+MLKEM) within the TLS 1.3 framework. These hybrid approaches have been piloted in real-world deployments, including Google Chrome [39] and Cloudflare [9], and showed acceptable latency and bandwidth overheads. However, these evaluations primarily focused on performance metrics rather than broader integration into DNS infrastructures.

Work on incorporating post-quantum cryptography for DNS has been comparatively limited. Titan-DoH by Ali and Chen [2] introduces a trust-aware, adaptive architecture for PQC-secure DoH. Their solution integrates trust algebra, graph signal processing, Bayesian contextual inference, and FrodoKEM-based TLS handshakes, supported by verifiable delay functions to identify encrypted malicious requests. The system demonstrates high accuracy and low latency under simulated adversarial loads, pushing the boundaries of secure PQC-ready DoH infrastructures.

Other existing work focuses primarily on DNSSEC. The IETF DNSOP working group has explored considerations for integrating post-quantum signatures into DNSSEC, addressing issues like key size, algorithm agility, and protocol compatibility [14]. Zhang et al. [42] evaluated SPHINCS+ in a DNSSEC setting, noting its suitability for quantum-resilient authentication but also highlighting challenges due to its large signature sizes and the risk of IP-layer fragmentation. These concerns underscore the importance of experimentally validating PQ signatures within real DNS server and resolver implementations. Pan et al. [25] present a double signature DNSSEC method that integrates classical and post-quantum techniques to provide transitional security against quantum and classical attacks. Through the use of application layer fragmentation, their dual-signed records provide resolution over UDP while adhering to packet size limitations. Raavi et al. [27] tackle fragmentation-based attacks using a commit-and-reveal method with a blockchain-based public key offloading strategy. Their approach guarantees fragment authenticity and lowers DNSSEC packet size, especially for substantial signatures such as Falcon-512. The solution, though unique, addresses fragmentation mis-association issues inside DNSSEC and does not integrate with wider DNS security protocols like DoT and DoH.

Goertzen and Stebila [13] propose ARRF (Application-layer Request-based Resource Fragmentation), which moves fragmentation logic to the application layer. Unlike prior fragmentation methods, ARRF sends an initial truncated response and requires the client to request additional fragments explicitly, improving both reliability and backward compatibility. Their experiments show ARRF significantly reduces resolution time and data overhead compared to traditional DNS-over-UDP with TCP fallback when using PQC algorithms such as Falcon-512, Dilithium2 (aka MLDSA44), and SPHINCS+. Expanding upon ARRF, McGowan et al. [22] identify a memory exhaustion vulnerability that can be exploited by altered RRSIZE fields. They address this using a dynamic memory allocation approach that maintains ARRF’s efficiency while protecting against amplification threats. Rawat and Jhanwar have contributed several complementary protocols aimed at minimizing the overhead of PQC integration. They present QNAME-Based Fragmentation (QBF) [31], a DNS-layer fragmentation scheme that avoids IP fragmentation and TCP fallback altogether. QBF fragments DNSSEC responses using standard DNS records, enabling reconstruction in a single round trip without altering the DNS protocol stack. Their experimental results demonstrate significant performance gains: QBF outperforms both standard DNS and parallel ARRF in post-quantum resolution scenarios, particularly with Falcon-512, Dilithium2 (aka MLDSA44), and SPHINCS+. By remaining fully backward compatible and avoiding changes to zone files or DNS stacks, QBF represents a promising middle ground for immediate PQC deployment. Rawat and Jhanwar further extend this line of work with the SL-DNSSEC protocol [33], which replaces digital signatures with post-quantum **Key Encapsulation Mechanisms (KEMs)** and MACs, significantly decreasing message size and resolution delay. TurboDNS [32] enhances PQC DNSSEC over TCP by including authentication data into the first UDP query, using cryptographic cookies to provide one-round-trip resolution. While these protocols offer substantial performance gains, they depart from traditional signature-based validation chains, posing challenges for universal adoption. In parallel, Schutjijser et al. [34] introduce PATAD, a containerized platform for PQC and DNSSEC experimentation. PATAD employs PowerDNS and modular topologies to assess Falcon and other signature methods inside realistic zone hierarchies. While PATAD enables empirical benchmarking of Falcon and other candidates, it remains focused on DNSSEC and does not extend to encrypted DNS protocols such as DNS-over-TLS (DoT) or DNS-over-HTTPS (DoH).

Several theses offer foundational empirical studies supporting the integration of post-quantum signatures in DNSSEC. Jafarli [20] presents a Merkle Tree-based framework using XMSS for the signing of grouped records. This framework optimizes payload dimensions and signing efficacy by adjusting tree size according to record update frequency, but at the expense of heightened memory consumption and update intricacy. Beernink [5] assesses the viability of many post-quantum cryptography algorithms using actual DNS traffic and signer logs. His research demonstrates that Falcon-512 complies with current DNS packet limitations while exerting little computing burden. Beernink further presents an out-of-band key exchange architecture to bypass signature size constraints for more substantial post-quantum cryptography systems such as Rainbow. Projects like *PQDNS* [26] and industry recommendations from NLnet Labs [21] and NIST [7] have emphasized the importance of prototyping and testing post-quantum secure DNS under realistic operational conditions. However, most existing works focus on isolated components (e.g., PQ-TLS or PQ-DNSSEC) rather than a holistic evaluation across all major DNS security channels.

3 PROPOSED PQC-DNS METHOD

In this section, we first give a short background on the DNS infrastructure and how the DNS protocol works. Later, we describe the problem that we aim to solve. Then, we define our proposed PQC-DNS sequences, and finally we discuss security threats and potential mitigation techniques.

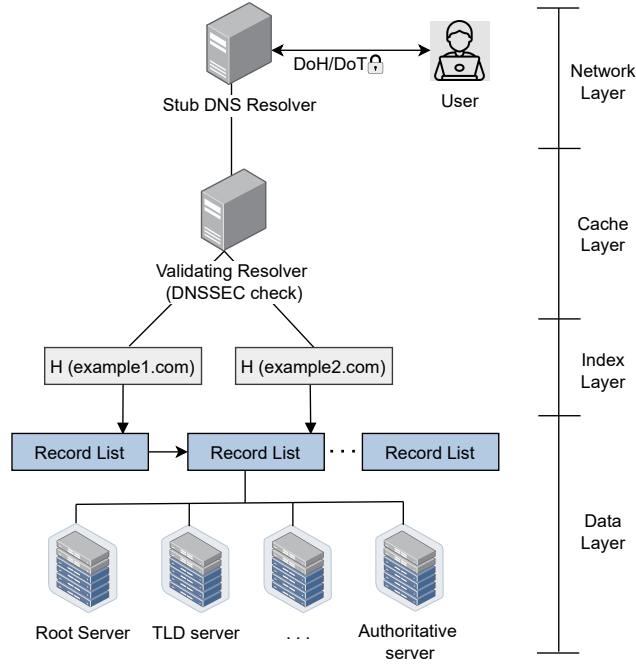


Fig. 1. Layered Architecture of Secure DNS

3.1 DNS Infrastructure

Fig. 1 presents a vertically layered architecture of secure DNS resolution that integrates DoH, DoT, and DNSSEC into a coherent workflow. It is structured across four key layers: Network, Cache, Index, and Data, each representing a distinct phase in the resolution and security pipeline. At the Network Layer, a user initiates a DNS query that is transmitted securely to a DNS resolver using encrypted transport protocols (DoH or DoT), ensuring confidentiality and protection against man-in-the-middle attacks. The resolver forwards the query to a Validating Resolver in the Cache Layer, which checks whether the result is cached and performs DNSSEC validation by verifying digital signatures (RRSIG) against trusted keys (DNSKEY and DS). If the answer is not locally available, the resolver consults the Index Layer, where the queried domain (e.g., example.com) is hashed and mapped to a pointer that locates the relevant DNS records. Finally, the Data Layer contains the actual signed DNS records retrieved from external authoritative DNS servers, such as the Root, TLD (.com), and domain-specific authoritative name servers. These servers return the required resource records (A, AAAA, DNSKEY, RRSIG), which are then validated recursively up to the DNS root using DNSSEC. The validated result is passed back up through the layers and ultimately returned to the user. This layered model demonstrates how privacy (via DoH/DoT) and integrity (via DNSSEC) are simultaneously enforced in modern DNS infrastructure.

3.2 Problem Formulation

While the security properties of PQC algorithms have been rigorously analyzed in isolation, their systematic integration into DNS protocols remains underexplored, especially for encrypted transport mechanisms such as DoT and DoH. Modern transition frameworks, such as those proposed by NIST and the IETF, include both PQC-only and hybrid

classical+PQC configurations to accommodate backward compatibility. However, their real-world impact on latency, resource consumption, and protocol compatibility requires a unified system-level evaluation. To address this, we propose a unified post-quantum DNS security architecture (PQC-DNS) that evaluates three deployment classes:

- (1) **Legacy-only:** DNS configurations using classical **KEM** and signature algorithms.
- (2) **PQC-only:** DNS configurations using post-quantum **KEMs** and signatures.
- (3) **Hybrid:** Mixed deployments combining classical and **PQC** schemes in KEM or digital signatures.

We define a DNS resolution performance profile $\mathcal{P}_{\text{DNS}}^{(k,s)}$ as a function of cryptographic configurations, as described in Equation 1. Notations used throughout the paper are listed in Table 1.

$$\mathcal{P}_{\text{DNS}}^{(k,s)} = \delta_{\text{DNSSEC}} \cdot \mathcal{S}_{\text{DNSSEC}}(k, s) + \mathcal{S}_{\text{Transport}}(k, s) \quad (1)$$

Each $\mathcal{S}_i(k, s)$ is defined as:

$$\mathcal{S}_i(k, s) = \left(T_{\text{latency}}, B_{\text{bandwidth}}, C_{\text{client}}, C_{\text{server}}, M_{\text{client}} \right) \quad (2)$$

Table 1. Notation Summary for PQC-DNS Performance Modeling

Symbol	Meaning
$\mathcal{P}_{\text{DNS}}^{(k,s)}$	DNS resolution performance profile under KEM k and signature s scheme
k	Selected post-quantum Key Encapsulation Mechanism (e.g., MLKEM)
s	Selected post-quantum Signature Scheme (e.g., MLDSA, Falcon, SPHINCS+)
δ_{DNSSEC}	Indicator variable for whether DNSSEC is enabled (1) or disabled (0)
$\mathcal{S}_i(k, s)$	Measured performance metrics under (k, s) for component i
T_{latency}	End-to-end resolution latency
$B_{\text{bandwidth}}$	Total bandwidth consumed for DNS transaction
$C_{\text{client}}, C_{\text{server}}$	CPU usage on client and server during resolution
M_{client}	Memory overhead on the client
T_{Phase1}	Time to establish a PQC-secure TLS 1.3 session
$T_{\text{CH}}, T_{\text{SH}}$	Time to send/receive ClientHello / ServerHello
$T_{\text{KEM}}, T_{\text{SIG}}$	Time for key encapsulation and signature verification
T_{KDF}	Time for TLS key derivation function
T_{FIN}	Time to exchange TLS Finished messages
$T_{\text{TLS_termination}}$	Time for TLS session termination or reset
n	Number of DNS resolution steps (root, TLD, authoritative)
$T_{\text{query},i}, T_{\text{response},i}$	Time to send query and receive response from DNS server i
$T_{\text{DNSSEC},i}$	Time to validate DNSSEC signature at server i
T_{return}	Time to return final validated DNS response to client

This formulation allows systematic comparison across cryptographic configurations and quantifies trade-offs in latency, computational effort, bandwidth, and memory.

Security Model: We consider an adversary \mathcal{A} with quantum computational capabilities, capable of executing Shor’s and Grover’s algorithms. The attacker may (i) Eavesdrop and perform MITM attacks on TLS handshakes. (ii) Perform DNS spoofing and cache poisoning. (iii) Attempt to break digital signatures or key exchanges via quantum means. We assume PQC primitives satisfy the following: (i) KEMs are IND-CCA2 (Indistinguishability of Ciphertexts under Chosen-Ciphertext Attack) secure under quantum adversaries [8]. (ii) Signatures are EUF-CMA (Existential Unforgeability under

Chosen Message Attack) secure in the quantum random oracle model [41]. The system seeks to provide post-quantum confidentiality, authenticity, and integrity for DNS queries and responses against such adversaries.

3.3 PQC-DNS Protocol Sequence

Fig. 2 illustrates the architecture of PQC-DNS. The protocol consists of two stages: a TLS 1.3 handshake with PQC primitives and the subsequent DNS resolution.

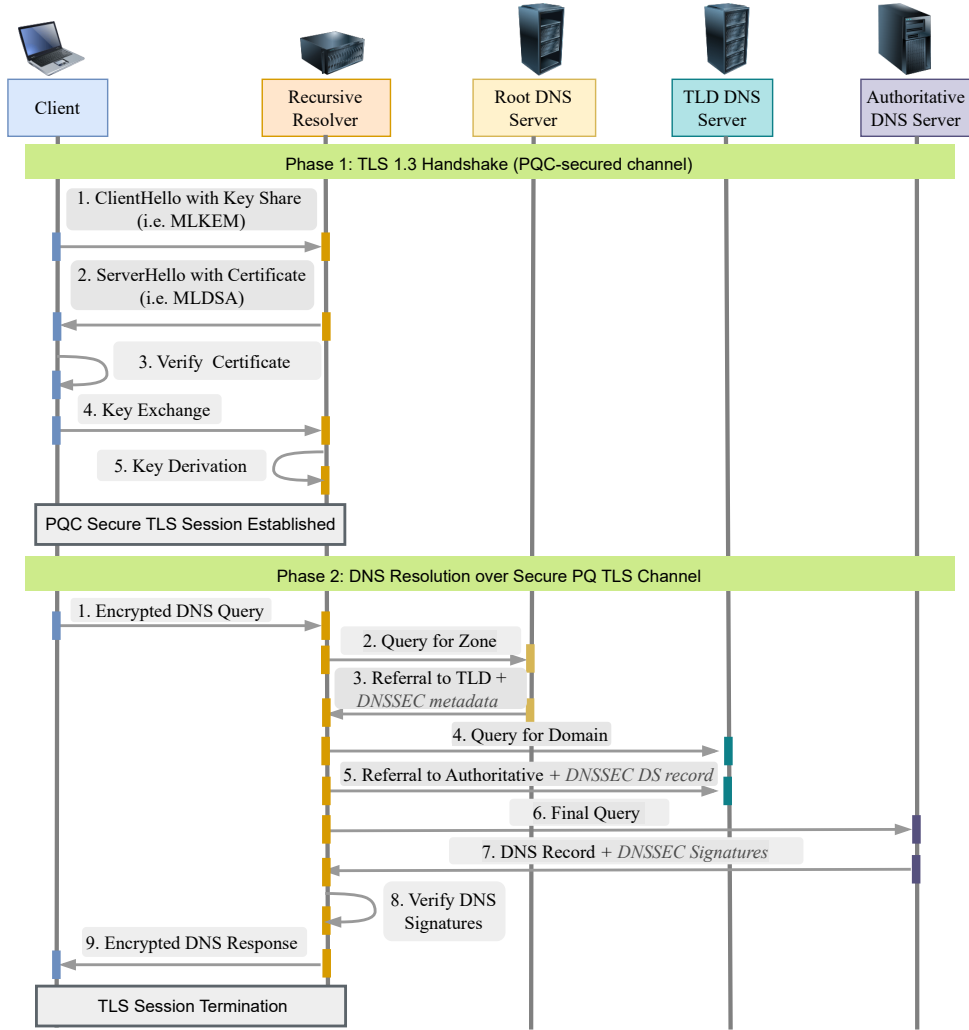


Fig. 2. Layered Protocol Sequence for PQC-DNS with DNSSEC Option

Phase 1: Establishing PQC-Secure TLS 1.3 Session

Let T_{Phase1} be the total time to establish a post-quantum secure TLS session. We define:

$$T_{\text{Phase1}} = T_{\text{CH}} + T_{\text{SH}} + T_{\text{KEM}} + T_{\text{SIG}} + T_{\text{KDF}} + T_{\text{FIN}} + T_{\text{TERM}} \quad (3)$$

This handshake ensures post-quantum confidentiality and mutual authentication prior to DNS exchange.

Phase 2: Encrypted Recursive DNS Resolution

Once TLS is established, DNS queries traverse the traditional recursive path under encryption. The total time for DNS query resolution is:

$$T_{\text{Phase2}} = \sum_{i=1}^n (T_{\text{query},i} + T_{\text{response},i}) + \delta_{\text{DNSSEC}} \cdot \sum_{i=1}^n T_{\text{DNSSEC},i} + T_{\text{return}} \quad (4)$$

The variables appearing in these equations are defined in Table 1.

3.4 Security Considerations

PQC-DNS resists quantum attacks due to the use of NIST-standardized algorithms. However, there are further threats to be considered as follows: (i) *Timing Attacks*: Constant-time implementations of post-quantum KEM and signature algorithms are essential to prevent side-channel leakage during TLS handshakes. Recent work has shown that even lattice-based schemes like Kyber and Dilithium may be susceptible if implemented without strict timing controls [15]. (ii) *DDoS Attacks*: The increased bandwidth and CPU overhead introduced by PQC operations, especially during handshake and validation phases, can be exploited for denial-of-service attacks. Mitigation strategies include client puzzles and rate-limiting mechanisms tailored for PQC-induced latency [36]. (iii) *Downgrade Attacks*: Hybrid configurations combining classical and post-quantum algorithms must rigorously enforce cipher suite negotiation policies to prevent fallback to classical-only modes. Improper negotiation can expose sessions to downgrade attacks, negating the intended quantum resistance [38]. (iv) *Fragmentation Vulnerabilities*: Large PQC signatures (e.g., SPHINCS+) may trigger IP-layer fragmentation, particularly in DNSSEC responses. Techniques such as *Application-layer Request-based Resource Fragmentation (ARRF)* [11] mitigate this by moving fragmentation logic to the application layer. *QNAME-Based Fragmentation (QBF)* [28] avoids IP-layer fragmentation entirely by using standard DNS record fields. While protocols like *TurboDNS* [30] and *SL-DNSSEC* [29] improve post-quantum DNSSEC performance, they do not directly address fragmentation and may pose compatibility trade-offs. (v) *Key/Signature Reuse*: Reusing nonces or ephemeral keys in PQC schemes (e.g., Dilithium, Falcon) can lead to private key recovery via algebraic attacks. This risk is amplified in multithreaded resolver environments with shared randomness. Mitigation includes using hardened libraries (e.g., liboqs) that enforce one-time key usage and thread-safe randomness [10]. (vi) *Interoperability Failures*: PQC deployment may fail across clients, resolvers, or middleboxes lacking support for hybrid or PQC-only cipher suites. Misconfigured fallback behavior can result in silent downgrades or dropped connections. Operators should test compatibility using hybrid-aware configurations and monitor failure modes [40]. Finally, the summary of these threats and potential mitigation strategies are listed in Table 2.

4 EXPERIMENTAL EVALUATIONS

In this section, we describe our experimental setup, metrics, numerical findings, and provide our analysis on the results.

Table 2. Summary of Threats and Mitigations in PQC-DNS Deployment

Threat	Description and Exploit Vector	Mitigation Strategy	Severity
Timing Attacks	Variation in handshake duration reveals secret-dependent operations in KEM or signatures.	Use constant-time implementations of all cryptographic primitives; avoid branching on secret values [15].	High
DDoS Amplification	PQC handshakes consume more CPU/memory, making resolvers vulnerable to resource exhaustion via spoofed requests.	Deploy client puzzles, adaptive rate-limiting, and TLS session resumption to mitigate load [36].	High
Downgrade Attacks	Adversary forces fallback to classical-only modes in hybrid configurations by interfering with cipher negotiation.	Enforce hybrid binding and strict cipher suite policies; validate negotiated modes [38].	High
Fragmentation Attacks	Large PQC signatures cause IP-layer fragmentation, which can be exploited for DNS poisoning or evasion.	Use application-layer fragmentation techniques (e.g., ARRF [11]) or QNAME-based approaches [28]; avoid UDP-only transport.	Medium
Key/Signature Reuse	Incorrect implementation may reuse nonces or keys, weakening PQC scheme guarantees.	Use verified libraries (e.g., liboqs), follow NIST-compliant API usage, and enforce nonce uniqueness [10].	Medium
Interoperability Failures	Mixed deployments may fail due to unsupported PQC or hybrid modes in client or middleboxes.	Conduct fallback testing, negotiate cipher suite compatibility, and monitor DNS path transparency [40].	Medium

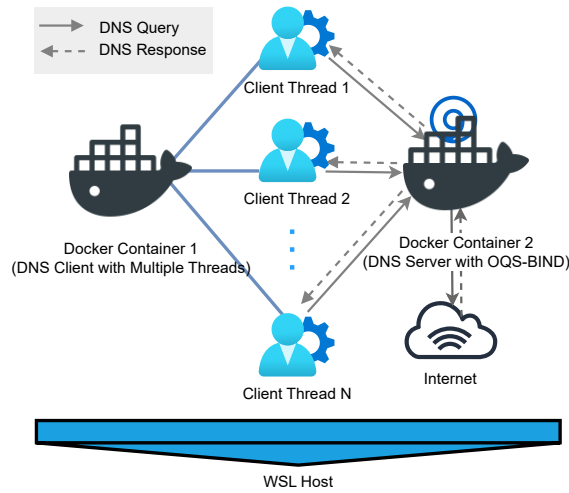


Fig. 3. Experimental setup used in our evaluations.

4.1 Experimental Setup

The experimental testbed consisted of two Docker containers running on Ubuntu 22.04, deployed within a Windows Subsystem for Linux 2 (WSL2) as presented in Fig. 3 to isolate resource usage from host system activities and obtain accurate performance benchmarks. One container operated as a PQC-enabled local DNS resolver, while the other functioned as a client issuing DNS queries. The resolver was built using a forked version of BIND9 (OQS-BIND) [12], compiled with OpenSSL integrated with the Open Quantum Safe (OQS) library and oqsprovider. This configuration enabled support for post-quantum key exchange and digital signature algorithms. The resolver acted as a local DNS server capable of handling DNS-over-TLS (DoT), DNS-over-HTTPS (DoH), and DNSSEC queries. The client container generated DNS queries over both DoT and DoH protocols using the dig tool with the +tls and +https options, respectively. Each test run issued 100 queries to a test domain hosted on the resolver.

The benchmark tests were conducted on a system running Windows 11 Home, equipped with an Intel(R) Core(TM) i7-10700 CPU operating at 2.90 GHz. The processor consists of 8 physical cores and 16 threads. The machine has 16.0 GB

of installed RAM, of which 15.7 GB is usable. The experimental environment was set up using Windows Subsystem for Linux 2 (WSL2), with Ubuntu 22.04 running as the guest operating system. WSL2 dynamically allocated approximately 7.6 GiB of RAM for the guest system, and provided access to all 16 logical CPUs (8 cores with 2 threads per core). The software stack consisted of Docker version 26.1.3 as the container engine, OpenSSL 3.4.0 with integrated support for post-quantum cryptography, and liboqs version 0.12.0. The OQS OpenSSL provider used was oqsprovider version 0.8.0. The DNS resolver used in the experiments was a customized build of BIND, based on a forked version of BIND 9.19.17 (referred to as OQS-BIND), compiled to support PQC-DNS with liboqs and oqsprovider.

4.2 Evaluation Framework and Benchmarking Metrics

To evaluate the impact of different cryptographic configurations on DNS performance, we analyze the components of the performance vector $\mathcal{S}_i(k, s)$, previously introduced in Section 3.2. This vector represents the empirical behavior of the system under each KEM-signature pair (k, s) . We develop Python-based benchmarking scripts that automates DNS query execution, monitors system resources, captures network traffic, and aggregates performance data across repeated trials. It uses tools such as psutil, /usr/bin/time, and tshark to gather reproducible system-level measurements. The full benchmarking suite and some sample packet captures are available on GitHub¹. The step-by-step execution of the evaluation framework is formally defined in Algorithm 1 and a high-level summary is presented in Fig. 4. The individual components of $\mathcal{S}_i(k, s)$ are defined as follows:

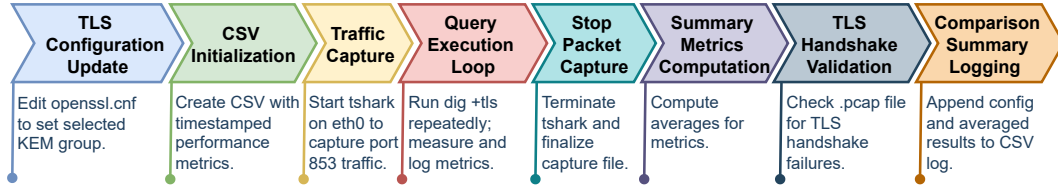


Fig. 4. Process Steps of Benchmarking

- *Latency* (T_{latency}): This value is calculated based on the time (in milliseconds) it takes between the first packet for a DNS request from the client to the last packet received for that request. This metric measures the responsiveness of the protocol and the ease of use.
- *Bandwidth Usage* ($B_{\text{bandwidth}}$): The total network traffic generated by each DNS query, measured in kilobytes, taking into account both transmitted and received data. This reflects protocol efficiency and cryptographic overhead.
- *CPU Usage* : The percentage of CPU time consumed during the DNS query was measured independently for the client and the server to assess the cryptographic workload on both sides:
 - (i) *Client CPU Usage* (C_{client}): This metric reflects the CPU utilisation of the dig process that initiates the DNS query. The /usr/bin/time -v utility was used to run dig and provides detailed statistics. The field “Percent of CPU this job got” was extracted using regular expressions. This raw percentage represents the ratio of CPU time to real (wall clock) time and is calculated internally as follows:

$$\text{Raw CPU \%} = \left(\frac{\text{User Time} + \text{System Time}}{\text{Elapsed Time}} \right) \times 100$$

¹<https://github.com/ljy4499/pqc-dns>

Algorithm 1 Post-Quantum Secure DNS Evaluation

```

1: procedure EVALUATESECUREDNS(KEM, DS, Domain,  $N$ )
2:   // Step 1: TLS Configuration
3:   Open openssl.cnf
4:   Locate section [system_default_sect]
5:   Update Groups parameter to KEM
6:   // Step 2: Metrics CSV Initialization
7:   Create CSV with columns:
      { $t, l, b, c, r$ }, where:
       $t$  = timestamp,  $l$  = latency (ms)
       $b$  = bandwidth (KB),  $c$  = CPU (%),  $r$  = RAM (%)
8:   // Step 3: Start Traffic Capture
9:   Launch tshark on interface eth0
10:  Apply filter: tcp port 853
11:  Save output to file dot_{KEM}_{DS}.pcapng
12:  // Step 4: Execute DNS Queries
13:  for  $i \leftarrow 1$  to  $N$  do
14:     $B_{pre} \leftarrow$  Network I/O snapshot
15:     $T_{start} \leftarrow$  System time
16:    Execute dig + tls @DS Domain
17:     $T_{end} \leftarrow$  System time
18:     $B_{post} \leftarrow$  Network I/O snapshot
19:     $l \leftarrow (T_{end} - T_{start}) \times 1000$ 
20:     $b \leftarrow (B_{post} - B_{pre})/1024$ 
21:     $c \leftarrow$  CPU usage from /usr/bin/time
22:     $r \leftarrow$  Peak RSS divided by container memory
23:    Append { $t, l, b, c, r$ } to CSV
24:  end for
25:  // Step 5: Stop Traffic Capture
26:  Terminate tshark process
27:  // Step 6: Summary Metric Computation
28:  Read all records from CSV
29:  Compute:  $\bar{l}, \bar{b}, \bar{c}, \bar{r}$ 
30:  Display summary statistics
31:  // Step 7: TLS Handshake Validation
32:  Run tshark -r < pcap_file >
33:  if "failure" in output then
34:    Report TLS handshake error
35:  else
36:    Report handshake success
37:  end if
38:  // Step 8: Log Final Results
39:  Append {KEM, DS,  $\bar{l}, \bar{b}, \bar{c}, \bar{r}$ } to:
      dot_comparison_results.csv
40: end procedure

```

"User Time" accounts for execution of user-level instructions (e.g., cryptographic operations), while "System Time" includes time spent in kernel-level operations such as I/O. "Elapsed Time" refers to the total real-world (wall-clock) duration from the start to the end of the operation. To present this on a normalized 0–100% scale, the raw value was

divided by the number of virtual CPUs allocated to the container (**16 vCPUs**):

$$\text{Normalized CPU \%} = \frac{\text{Raw CPU \%}}{n_{\text{vCPU}}}$$

This normalization ensures that a value of 100% represents full utilization of all assigned cores.

(ii) *Server CPU Usage* (C_{server}): This metric was derived from periodic snapshots using `docker stats`, which provides live CPU utilization for containers. All other background processes were terminated to ensure the accuracy of the measurement.

A monitoring script continuously sampled the container's CPU usage, and the highest observed percentage over the entire duration of client requests was recorded as the server's CPU usage. Internally, `docker stats` computes CPU usage as:

$$\text{Raw CPU} = \left(\frac{\Delta \text{Container CPU \%}}{\Delta \text{System CPU \%}} \right) \times \text{vCPUs} \times 100$$

- $\Delta \text{Container CPU usage}$: The total amount of CPU time consumed by the container during the measurement period.
- $\Delta \text{System CPU usage}$: The total CPU time in the system for the same period.
- vCPUs : The number of virtual CPUs allocated to the container. In this case, the container was allocated **16 vCPUs**.

This formula calculates the proportion of CPU time consumed by the container relative to the host system's total CPU time, scaled by the number of virtual CPUs allocated to the container. To present this on a normalized 0–100% scale, the raw value was divided by the number of virtual CPUs allocated to the container (**16 vCPUs**):

$$\text{Normalized CPU \%} = \frac{\text{Raw CPU \%}}{n_{\text{vCPU}}}$$

This adjustment ensures comparability with the normalized client CPU usage and expresses container CPU consumption as a proportion of its full computational capacity.

- *Memory Usage* (M_{client}): The peak physical memory used by the `dig` process, relative to the total available memory in the container. The maximum resident set size (RSS) in kilobytes was obtained from `/usr/bin/time -v`. It was converted to mebibytes (MiB):

$$\text{RAM Peak (MiB)} = \frac{\text{RSS (KB)}}{1024}$$

RAM usage was computed as a percentage of total memory (i.e., 7810.3 MiB):

$$\text{RAM Usage (\%)} = \left(\frac{\text{RAM Peak (MiB)}}{7810.3} \right) \times 100$$

To evaluate the **scalability** and impact of PQC on resources with concurrent DNS workloads, a multi-threaded test configuration was used. In contrast to the single-threaded tests described above, this benchmark included 100 parallel workers (i.e., DNS clients), each sending one query per session, resulting in a total number of 10,000 queries in 100 sessions. The Docker built-in utility `docker stats` was used to capture CPU and memory usage metrics. Resource utilisation was recorded by taking snapshots at regular intervals and extracting the peak values from the client and server during the test period. All reported CPU usage values were normalised on a scale from 0 to 100%, which corresponds to the normalisation approach used in the single-thread evaluation. This ensures fair comparisons between different cryptographic methods and system configurations. This benchmark specifically aims to evaluate the behaviour of PQC algorithms under load compared to traditional cryptographic methods, with a focus on throughput scaling and system resource evolution under high query volume. Network usage and latency are measured as shown in Algorithm 2.

Algorithm 2 Execute Multi-client DNS Test Session

```

1: function RUNSESSION(session_id)
2:    $B_{\text{start}} \leftarrow \text{GETTOTALNETWORKBYTES}$ 
3:    $T_{\text{start}} \leftarrow \text{GETCURRENTTIME}$ 
4:   Initialize thread pool with 100 workers
5:   for all worker  $\in$  thread pool do
6:     Submit RUNDNSQUERY
7:   end for
8:   Wait for all queries to complete
9:    $T_{\text{end}} \leftarrow \text{GETCURRENTTIME}$ 
10:   $B_{\text{end}} \leftarrow \text{GETTOTALNETWORKBYTES}$ 
11:   $\Delta T \leftarrow (T_{\text{end}} - T_{\text{start}}) \times 1000$  ▷ Latency in ms
12:   $\Delta B \leftarrow (B_{\text{end}} - B_{\text{start}})/1024$  ▷ Bandwidth in KB
13:  WRITETOCsv(session_id,  $\Delta T$ ,  $\Delta B$ )
14: end function

```

4.3 Experimental Results: Legacy vs. PQC Algorithms

This section presents the benchmark results of DNS using various combinations of classical and post-quantum **KEM** and **Digital Signatures (DSs)** at different NIST security levels [24]. For each evaluated cryptographic configuration (k, s) , we compute the corresponding performance vector $\mathcal{S}_i(k, s)$ as defined in Section 3.2. The performance data are organized by protocol category, with separate tables for DoT, DoH, DNSSEC-enabled configurations and security levels. All tables present results across the three cryptographic profiles: (i) Legacy-only, (ii) PQC-only and (iii) Hybrid. Each table includes measurements for latency, bandwidth usage, CPU utilization by the client/server, and memory consumption, whose notations and definitions are introduced earlier in the notation summary (Table 1) and Section 4.2. We **bolded** the lowest numerical values in each subcategory for each metric in each table provided. Each combination (k, s) is categorized based on the cryptographic primitives used to facilitate comparison across hybrid and fully post-quantum configurations.

In Table 3, the benchmark evaluates **DoT** performance using a range of **PQC** and legacy algorithms at NIST security level 1, which corresponds to the legacy 128-bit security level. Despite initial expectations that PQC algorithms would incur significant performance penalties relative to legacy counterparts, certain combinations-particularly MLKEM512 paired with either MLDSA44 or Falcon512-demonstrated latency metrics that closely matched or even outperformed legacy configurations. These combinations achieved latencies around 9 ms, which is comparable to commonly used Elliptic Curve and RSA-based solutions. However, a consistent trend was observed in bandwidth usage: PQC-based configurations generally incurred a higher data overhead. This is attributable to the larger key and signature sizes characteristic of quantum-resistant primitives. Among PQC candidates, SPHINCS+-SHA2-128f and HQC-128 exhibited significantly higher latency and bandwidth usage. These results highlight a trade-off between post-quantum robustness and operational efficiency, making these algorithms less practical for latency-sensitive applications.

The benchmark in Table 4 represents the performance of **DoH** at NIST security level 1 and is directly comparable to the previously presented DoT benchmark results. For all analysed combinations of key exchange and digital signature, the metrics for latency, CPU usage and memory consumption show negligible differences between DoH and DoT. The main deviation lies in the bandwidth utilisation: DoH configurations consistently caused a slight overhead of 0.3 to 0.4 kilobytes on average compared to their DoT counterparts. This increase is due to the HTTP-based encapsulation and the additional protocol headers inherent to DoH.

Table 3. DNS over TLS Benchmark Results by Algorithms (Security Level 1)

KEM	DS	Latency(ms)	Bandwidth(kB)	Client / Server CPU(%)	Memory(%)
<i>[Legacy(KEM) + Legacy(DS) Algorithms]</i>					
ffdhe2048	rsa2048	10.08	4.14	5.00 / 0.95	0.151
ffdhe2048	ecdsa-p256	9.67	3.58	5.39 / 0.71	0.154
ffdhe2048	ed25519	9.61	3.50	5.38 / 0.71	0.153
secp256r1	rsa2048	9.36	3.78	5.33 / 0.78	0.155
x25519	rsa2048	9.17	3.71	5.27 / 0.76	0.153
<i>[PQC(KEM) + PQC(DS) Algorithms]</i>					
mlkem512	mldsa44	9.10	10.54	5.80 / 0.50	0.165
mlkem512	falcon512	9.11	6.54	5.47 / 0.57	0.164
mlkem512	sphincsha2128f	16.36	38.24	3.14 / 2.76	0.165
hqc128	mldsa44	19.07	15.54	4.41 / 1.62	0.166
hqc128	falcon512	19.13	11.67	4.39 / 1.64	0.164
<i>[Legacy(KEM) + PQC(DS) Algorithms]</i>					
ffdhe2048	mldsa44	9.61	9.51	5.37 / 0.75	0.161
ffdhe2048	falcon512	9.73	5.51	5.35 / 0.81	0.159
ffdhe2048	sphincsha2128f	17.16	37.19	3.15 / 2.81	0.158
secp256r1	mldsa44	8.91	9.14	5.71 / 0.55	0.163
x25519	falcon512	8.97	5.08	5.61 / 0.61	0.158
<i>[PQC(KEM) + Legacy(DS) Algorithms]</i>					
mlkem512	rsa2048	9.37	5.17	5.42 / 0.74	0.161
mlkem512	ecdsa-p256	8.96	4.60	5.77 / 0.47	0.163
mlkem512	ed25519	8.91	4.54	5.90 / 0.47	0.161
hqc128	rsa2048	19.67	10.17	4.37 / 1.71	0.160
hqc128	ecdsa-p256	19.08	9.60	4.46 / 1.61	0.162

Table 4. DNS over HTTPS Benchmark Results by Algorithms (Security Level 1)

KEM	DS	Latency(ms)	Bandwidth(kB)	Client / Server CPU(%)	Memory(%)
<i>[Legacy(KEM) + Legacy(DS) Algorithms]</i>					
ffdhe2048	rsa2048	9.97	4.54	5.00 / 0.97	0.152
ffdhe2048	ecdsa-p256	9.67	3.96	5.41 / 0.74	0.155
ffdhe2048	ed25519	9.63	3.90	5.40 / 0.74	0.154
secp256r1	rsa2048	9.43	4.13	5.37 / 0.80	0.156
x25519	rsa2048	9.19	4.13	5.39 / 0.80	0.154
<i>[PQC(KEM) + PQC(DS) Algorithms]</i>					
mlkem512	mldsa44	8.93	10.95	5.76 / 0.52	0.166
mlkem512	falcon512	9.07	6.89	5.53 / 0.60	0.166
mlkem512	sphincsha2128f	16.44	38.67	3.19 / 2.83	0.166
hqc128	mldsa44	19.23	15.96	4.46 / 1.66	0.167
hqc128	falcon512	19.11	12.10	4.41 / 1.67	0.165
<i>[Legacy(KEM) + PQC(DS) Algorithms]</i>					
ffdhe2048	mldsa44	9.96	9.88	5.35 / 0.77	0.162
ffdhe2048	falcon512	9.93	5.89	5.22 / 0.83	0.160
ffdhe2048	sphincsha2128f	17.11	37.64	3.16 / 2.91	0.159
secp256r1	mldsa44	8.93	9.48	5.72 / 0.57	0.164
x25519	falcon512	9.16	5.47	5.58 / 0.66	0.159
<i>[PQC(KEM) + Legacy(DS) Algorithms]</i>					
mlkem512	rsa2048	9.41	5.60	5.36 / 0.77	0.162
mlkem512	ecdsa-p256	8.87	5.00	5.84 / 0.51	0.163
mlkem512	ed25519	8.84	4.88	5.93 / 0.49	0.161
hqc128	rsa2048	19.49	10.57	4.41 / 1.74	0.161
hqc128	ecdsa-p256	19.06	10.04	4.48 / 1.64	0.163

The results in the Table 5 show the DoT performance results at NIST security level 3, which corresponds to 192 bits of security. One notable observation is the superior performance of MLKEM768 paired with MLDSA65, which outperforms all tested legacy combinations in terms of latency, achieving the lowest measured value (9.24 ms). Compared to traditional key exchange mechanisms like FFDHE3072 or SECP384R1 paired with RSA3072 or ECDSA-P384, this PQC combination delivers faster DoT performance. However, PQC algorithms exhibit a significantly higher bandwidth cost, consuming between $2\times$ to $23\times$ more bandwidth than legacy counterparts. For example, the HQC192 with SPHINCS+ signatures combination notably increases total bandwidth usage, with values exceeding 87 kB compared to sub-5 kB values in legacy configurations. This illustrates the tradeoff between post-quantum security and communication overhead, which must be considered when evaluating PQC deployment in bandwidth-sensitive environments.

Table 5. DNS over TLS Benchmark Results by Algorithms (Security Level 3)

KEM	DS	Latency (ms)	Bandwidth (kB)	Client / Server CPU (%)	Memory (%)
<i>[Legacy(KEM) + Legacy(DS) Algorithms]</i>					
ffdhe3072	rsa3072	12.51	4.77	4.45 / 1.58	0.152
ffdhe3072	ecdsa-p384	12.29	3.92	4.62 / 1.25	0.152
secp384r1	rsa3072	13.20	4.21	4.28 / 1.66	0.152
secp384r1	ecdsa-p384	13.01	3.36	4.73 / 1.33	0.153
<i>[PQC(KEM) + PQC(DS) Algorithms]</i>					
mlkem768	mldsa65	9.24	13.58	5.63 / 0.55	0.161
mlkem768	sphincsha2192f	21.69	75.63	2.50 / 3.49	0.162
hqc192	mldsa65	39.64	24.68	3.95 / 2.19	0.166
hqc192	sphincsha2192f	51.95	86.63	3.11 / 3.01	0.164
<i>[Legacy(KEM) + PQC(DS) Algorithms]</i>					
ffdhe3072	mldsa65	11.22	12.12	5.02 / 1.06	0.161
ffdhe3072	sphincsha2192f	23.47	74.16	2.47 / 3.46	0.158
secp384r1	mldsa65	11.79	11.57	4.92 / 1.15	0.162
secp384r1	sphincsha2192f	24.17	73.61	2.45 / 3.46	0.159
<i>[PQC(KEM) + Legacy(DS) Algorithms]</i>					
mlkem768	rsa3072	10.81	6.23	4.74 / 1.24	0.160
mlkem768	ecdsa-p384	10.19	5.38	4.96 / 0.85	0.161
hqc192	rsa3072	41.43	17.33	3.82 / 2.28	0.160
hqc192	ecdsa-p384	41.05	16.48	3.92 / 2.20	0.161

The benchmark in Table 6 shows the DoH performance results at NIST security level 3. The results show no significant difference compared to the previous DoT benchmark results.

The benchmark in Table 7 shows the DoT performance results at NIST security level 5, which corresponds to a 256-bit security level of the legacy algorithms. One noticeable observation is the consistently low latency achieved by the PQC algorithms MLKEM1024 with MLDSA87, achieving sub-10 ms latency. These results outperform several legacy combinations-such as FFDHE4096 with RSA4096-which exhibited latencies ranging from 12 to 18 ms. However, not all PQC configurations demonstrated such efficiency. The HQC256 key encapsulation mechanism, when paired with either PQC or legacy digital signature schemes, significantly increased the latency, reaching values over 65 ms. This degradation in performance is primarily due to HQC's large key and ciphertext sizes, which impose higher computational and transmission overhead during the TLS handshake process.

Fig. 5 shows a comparison of DoT performance at NIST security levels 1, 3 and 5. It is noteworthy that the **KEM** of MLKEM in conjunction with the **DS** algorithms of MLDSA or Falcon has a consistently low latency regardless of the security level, indicating good scalability of performance. In contrast, algorithms such as HQC and SPHINCS+ showed a proportional increase in latency with increasing security level, reflecting their greater computational and structural

Table 6. DNS over HTTPS Benchmark Results by Algorithms (Security Level 3)

KEM	DS	Latency (ms)	Bandwidth (kB)	Client / Server CPU (%)	Memory (%)
<i>[Legacy(KEM) + Legacy(DS) Algorithms]</i>					
ffdhe3072	rsa3072	12.49	5.12	4.44 / 1.61	0.153
ffdhe3072	ecdsa-p384	12.36	4.34	4.69 / 1.33	0.154
secp384r1	rsa3072	13.11	4.56	4.28 / 1.67	0.154
secp384r1	ecdsa-p384	12.95	3.75	4.77 / 1.37	0.153
<i>[PQC(KEM) + PQC(DS) Algorithms]</i>					
mlkem768	mldsa65	9.02	13.95	5.66 / 0.57	0.162
mlkem768	sphincsha2192f	21.67	76.06	2.50 / 3.51	0.163
hqc192	mldsa65	39.79	25.13	3.97 / 2.24	0.167
hqc192	sphincsha2192f	51.99	87.07	3.13 / 3.02	0.165
<i>[Legacy(KEM) + PQC(DS) Algorithms]</i>					
ffdhe3072	mldsa65	11.08	12.47	5.12 / 1.06	0.162
ffdhe3072	sphincsha2192f	23.60	74.59	2.47 / 3.46	0.159
secp384r1	mldsa65	11.82	11.91	4.89 / 1.19	0.163
secp384r1	sphincsha2192f	24.25	74.05	2.49 / 3.46	0.160
<i>[PQC(KEM) + Legacy(DS) Algorithms]</i>					
mlkem768	rsa3072	10.53	6.67	4.81 / 1.32	0.161
mlkem768	ecdsa-p384	10.37	5.78	5.10 / 0.87	0.162
hqc192	rsa3072	41.09	17.77	3.82 / 2.32	0.161
hqc192	ecdsa-p384	40.96	16.93	3.93 / 2.22	0.162

Table 7. DNS over TLS Benchmark Results by Algorithms (Security Level 5)

KEM	DS	Latency (ms)	Bandwidth (kB)	Client / Server CPU (%)	Memory (%)
<i>[Legacy(KEM) + Legacy(DS) Algorithms]</i>					
ffdhe4096	rsa4096	16.65	5.39	3.73 / 2.26	0.152
ffdhe4096	ecdsa-p521	16.56	4.26	4.17 / 1.76	0.153
ffdhe4096	ed448	13.51	4.13	4.63 / 1.40	0.152
secp521r1	rsa4096	18.74	4.66	3.59 / 2.37	0.153
x448	rsa4096	12.47	4.51	3.89 / 2.02	0.152
<i>[PQC(KEM) + PQC(DS) Algorithms]</i>					
mlkem1024	mldsa87	9.13	17.76	5.48 / 0.57	0.165
mlkem1024	falcon1024	9.29	10.28	5.42 / 0.71	0.165
hqc256	mldsa87	65.97	36.11	3.78 / 2.38	0.167
hqc256	falcon1024	65.54	28.64	3.75 / 2.39	0.166
<i>[Legacy(KEM) + PQC(DS) Algorithms]</i>					
ffdhe4096	mldsa87	13.54	15.70	4.63 / 1.41	0.162
ffdhe4096	falcon1024	13.83	8.09	4.49 / 1.48	0.159
secp521r1	mldsa87	16.64	14.95	4.28 / 1.65	0.162
secp521r1	falcon1024	15.90	7.36	4.31 / 1.68	0.159
x448	mldsa87	9.63	14.82	5.40 / 0.71	0.159
x448	falcon1024	9.90	7.21	5.31 / 0.84	0.158
<i>[PQC(KEM) + Legacy(DS) Algorithms]</i>					
mlkem1024	rsa4096	12.38	7.46	3.95 / 1.96	0.159
mlkem1024	ecdsa-p521	13.07	6.30	4.41 / 1.24	0.158
mlkem1024	ed448	9.13	6.19	5.44 / 0.56	0.158
hqc256	rsa4096	68.78	25.93	3.60 / 2.54	0.161
hqc256	ecdsa-p521	68.15	24.82	3.74 / 2.47	0.161

overhead. In terms of bandwidth, all configurations showed a clear trend: as the security level increased, so did the bandwidth consumption. This is due to the larger key and ciphertext sizes required to maintain a higher level of cryptographic strength, especially for code-based or stateless hash-based schemes such as HQC and SPHINCS+.

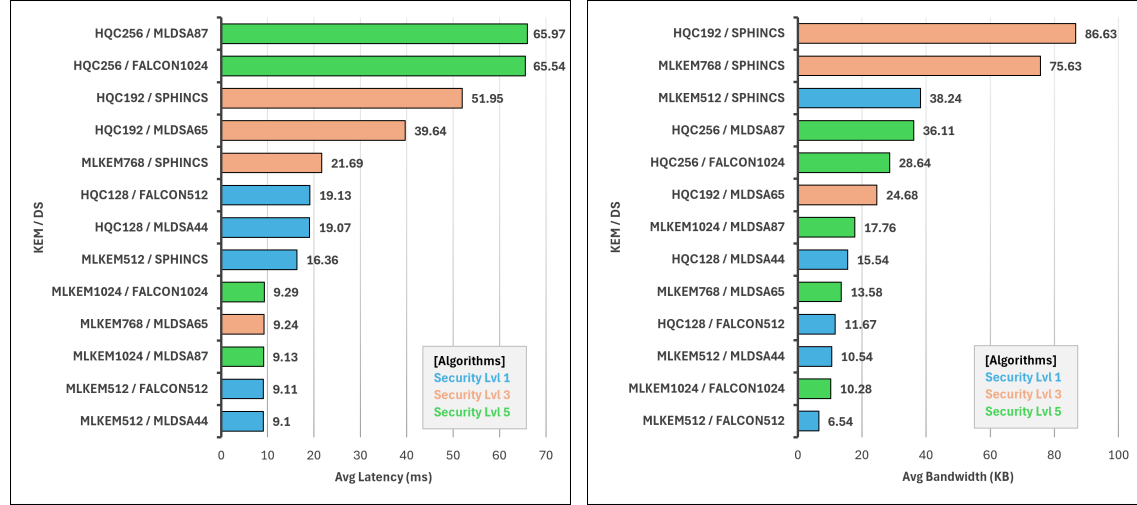


Fig. 5. DoT Latency (left) and Bandwidth(right) comparison chart by Security Level 1, 3, and 5

The benchmark in Table 8 presents DoH performance results at NIST security level 5. The results show no significant difference when compared to the previous DoT benchmark result. To avoid redundancy and enhance readability, a comparison chart is omitted.

Table 8. DNS over HTTPS Benchmark Results by Algorithms (Security Level 5)

KEM	DS	Latency (ms)	Bandwidth (kB)	Client / Server CPU (%)	Memory (%)
<i>[Legacy(KEM) + Legacy(DS) Algorithms]</i>					
ffdhe4096	rsa4096	16.78	5.84	3.68 / 2.27	0.153
ffdhe4096	ecdsa-p521	16.79	4.72	4.15 / 1.80	0.154
ffdhe4096	ed448	13.63	4.60	4.64 / 1.43	0.153
secp521r1	rsa4096	18.82	5.07	3.60 / 2.39	0.153
x448	rsa4096	12.70	4.95	3.89 / 2.03	0.153
<i>[PQC(KEM) + PQC(DS) Algorithms]</i>					
mlkem1024	mldsa87	9.41	18.17	5.43 / 0.59	0.166
mlkem1024	falcon1024	9.50	10.67	5.38 / 0.74	0.166
hqc256	mldsa87	65.52	36.58	3.77 / 2.41	0.168
hqc256	falcon1024	65.89	29.10	3.77 / 2.46	0.167
<i>[Legacy(KEM) + PQC(DS) Algorithms]</i>					
ffdhe4096	mldsa87	13.78	16.03	4.60 / 1.42	0.162
ffdhe4096	falcon1024	13.95	8.50	4.46 / 1.54	0.160
secp521r1	mldsa87	15.82	15.43	4.41 / 1.66	0.163
secp521r1	falcon1024	16.00	7.76	4.27 / 1.73	0.160
x448	mldsa87	9.75	15.17	5.39 / 0.73	0.162
x448	falcon1024	10.04	7.62	5.19 / 0.86	0.159
<i>[PQC(KEM) + Legacy(DS) Algorithms]</i>					
mlkem1024	rsa4096	12.36	7.86	3.90 / 1.97	0.160
mlkem1024	ecdsa-p521	12.06	6.72	4.56 / 1.27	0.161
mlkem1024	ed448	9.20	6.62	5.46 / 0.59	0.159
hqc256	rsa4096	68.44	26.41	3.62 / 2.59	0.162
hqc256	ecdsa-p521	68.17	25.28	3.74 / 2.46	0.162

This benchmark in Table 9 presents the DNSSEC performance results. While PQC-based DNSSEC algorithms exhibit higher bandwidth usage compared to legacy algorithms, this increase is primarily due to the larger size of

the cryptographic signatures and certificates. Despite this overhead, the latency remains nearly unaffected across all tested algorithms. For example, MLDSA44 and SPHINCS+ variants show significantly higher bandwidth consumption than RSA2048 or ED25519, yet maintain comparable latency values, indicating that DNSSEC verification remains computationally lightweight even with post-quantum algorithms.

Table 9. DNSSEC Benchmark Results of Algorithms

DNSSEC	Latency (ms)	Bandwidth (kB)	Client / Server CPU (%)	Memory (%)
<i>[Legacy(DNSSEC) Algorithms]</i>				
rsa2048sha256	6.22	0.53	6.08 / 0.10	0.141
ecdsap256sha256	6.28	0.34	6.11 / 0.10	0.141
ed25519	6.20	0.34	5.99 / 0.10	0.141
<i>[PQC(DNSSEC) Algorithms]</i>				
mldsa44	6.83	3.46	6.07 / 0.25	0.141
falconpadded512	6.29	0.93	6.16 / 0.10	0.141
sphincssha2128fsimple	6.88	8.89	5.91 / 0.26	0.142

The benchmark in Table 10 presents the performance results for DNSSEC combined with DoT using a range of cryptographic algorithms at NIST Security Level 1. The overall behavior of the algorithms remains consistent with the non-DNSSEC configurations, particularly in terms of latency, CPU, and memory usage. The primary difference observed is an increase in bandwidth, which is expected due to the additional DNSSEC-related cryptographic material. However, this increase does not have a significant impact on latency or other system metrics. Algorithms such as SPHINCS+, which already produce large signature sizes, contribute substantially to the bandwidth overhead. Consequently, configurations involving SPHINCS+ exhibit significantly higher bandwidth consumption compared to other algorithms.

Table 10. DNSSEC with DoT Benchmark Results by Algorithms (Security Level 1)

DNSSEC	KEM	DS	Latency (ms)	Bandwidth (kB)	Client / Server CPU (%)	Memory (%)
<i>[Legacy(DNSSEC) + Legacy(KEM) + Legacy(DS) Algorithms]</i>						
rsa2048	ffdhe2048	rsa2048	10.32	4.44	4.92 / 0.94	0.153
ecdsap256	ffdhe2048	ecdsa-p256	9.77	3.68	5.38 / 0.72	0.156
ed25519	ffdhe2048	ed25519	9.55	3.61	5.42 / 0.71	0.154
<i>[PQC(DNSSEC) + PQC(KEM) + PQC(DS) Algorithms]</i>						
mldsa44	mlkem512	mldsa44	9.21	12.95	5.55 / 0.51	0.166
falcon512	mlkem512	falcon512	9.05	7.24	5.51 / 0.59	0.165
sphincssha2128f	mlkem512	sphincssha2128f	16.31	45.96	3.18 / 2.79	0.165
<i>[Legacy(DNSSEC) + PQC(KEM) + PQC(DS) Algorithms]</i>						
rsa2048	mlkem512	mldsa44	9.04	10.84	5.83 / 0.50	0.166
ecdsap256	mlkem512	falcon512	9.02	6.66	5.54 / 0.58	0.165
ed25519	mlkem512	sphincssha2128f	16.35	38.35	3.16 / 2.78	0.165
<i>[PQC(DNSSEC) + Legacy(KEM) + Legacy(DS) Algorithms]</i>						
mldsa44	ffdhe2048	rsa2048	10.24	6.55	4.95 / 0.94	0.153
falcon512	ffdhe2048	ecdsa-p256	9.69	4.27	5.34 / 0.71	0.156
sphincssha2128f	ffdhe2048	ed25519	9.89	11.29	5.29 / 0.71	0.154

This benchmark in Table 11 presents DNSSEC with DoH performance results at NIST security level 1. The results show no significant difference when compared to the previous DoT benchmark result. To avoid redundancy and enhance readability, a comparison chart is omitted.

The results in Table 12 list DoT performance under a multi-thread scenario using 100 concurrent queries at NIST Security Level 1. The results show consistent trends with earlier benchmarks: PQC key exchange mechanisms such

Table 11. DNSSEC with DoH Benchmark Results by Algorithms (Security Level 1)

DNSSEC	KEM	DS	Latency (ms)	Bandwidth (kB)	Client / Server CPU (%)	Memory (%)
<i>[Legacy(DNSSEC) + Legacy(KEM) + Legacy(DS) Algorithms]</i>						
rsa2048	ffdhe2048	rsa2048	10.88	4.86	4.93 / 0.99	0.154
ecdsap256	ffdhe2048	ecdsa-p256	9.72	4.07	5.40 / 0.76	0.157
ed25519	ffdhe2048	ed25519	9.56	4.02	5.42 / 0.74	0.155
<i>[PQC(DNSSEC) + PQC(KEM) + PQC(DS) Algorithms]</i>						
mldsa44	mlkem512	mldsa44	9.18	13.39	5.56 / 0.53	0.167
falconp512	mlkem512	falcon512	9.06	7.64	5.49 / 0.60	0.166
sphincsha2128f	mlkem512	sphincsha2128f	16.38	46.42	3.27 / 2.79	0.166
<i>[Legacy(DNSSEC) + PQC(KEM) + PQC(DS) Algorithms]</i>						
rsa2048	mlkem512	mldsa44	9.01	11.25	5.68 / 0.57	0.167
ecdsap256	mlkem512	falcon512	9.06	7.06	5.46 / 0.62	0.166
ed25519	mlkem512	sphincsha2128f	16.46	38.78	3.25 / 2.78	0.166
<i>[PQC(DNSSEC) + Legacy(KEM) + Legacy(DS) Algorithms]</i>						
mldsa44	ffdhe2048	rsa2048	10.09	6.98	4.95 / 0.97	0.154
falcon512	ffdhe2048	ecdsa-p256	9.69	4.65	5.39 / 0.81	0.157
sphincsha2128f	ffdhe2048	ed25519	9.76	11.74	5.39 / 0.74	0.155

as MLKEM512 combined with signature schemes like MLDSA44 or Falcon512 yield comparable or even lower latencies than several legacy combinations. Notably, despite the significantly increased bandwidth-scaling linearly with the number of concurrent queries-the latency remains unaffected. This is likely due to the small size of each DNS query and response, which minimizes network congestion and avoids saturating the bandwidth capacity, especially under typical modern network conditions. With these observations, DNS performance confirms that latency is often dominated by cryptographic processing and handshake round-trips, not data volume per se. However, algorithms with heavier computational loads-such as SPHINCS+ and HQC-introduce higher latencies, correlating with increased server-side CPU usage. The observed CPU impact suggests that for algorithms with large key or signature sizes, the processing overhead (e.g., signature verification or key decoding) becomes the dominant latency factor under load, rather than network throughput.

Meanwhile, the results in Table 13 presents Multi-thread (100 Concurrent Queries) DoH performance results at NIST security level 1. The results show no significant difference when compared to the previous DoT benchmark result. To avoid redundancy and enhance readability, a comparison chart is omitted.

Compared to the 100-concurrent-query benchmark, the 1000-query scenario presented in Table 14 reveals important scalability distinctions between algorithmic combinations. While general latency trends remain consistent, the increased concurrency amplifies differences in resource handling, particularly CPU usage and bandwidth overhead. For example, combinations like MLKEM512 + Falcon512 continue to perform efficiently, but now exhibit slightly higher client CPU utilization, reflecting the cumulative impact of repeated cryptographic operations at scale. Conversely, resource-intensive algorithms such as HQC128 + SPHINCS+ and HQC128 + Falcon512 demonstrate more pronounced performance degradation: latencies exceed 2200 ms and server CPU usage approaches 30 percent, signaling stress under high load. Bandwidth scales predictably with query volume, but bandwidth-intensive schemes-especially those using SPHINCS+-now produce transfer volumes exceeding 38 MB per session, reinforcing concerns about deployment in constrained networks. Notably, hybrid combinations involving PQC signatures (e.g., ffdhe2048 + SPHINCS+) show similar trends, with CPU bottlenecks becoming more evident than in the lower-concurrency test.

Compared to the 1,000-concurrent-query scenario, the 10,000-query benchmark as presented in the Table 15 exposes sharper scalability limitations in both cryptographic processing and system resource usage. While high-performance

Table 12. Multi-thread (100 Concurrent Queries) DNS over TLS Benchmark Results by Algorithms (Security Level 1)

KEM	DS	Latency (ms)	Bandwidth (kB)	Client / Server CPU (%)	Memory (%)
<i>[Legacy(KEM) + Legacy(DS) Algorithms]</i>					
ffdhe2048	rsa2048	125.28	412.28	72.01 / 13.18	2.66
ffdhe2048	ecdsa-p256	111.55	354.97	74.71 / 9.61	2.09
ffdhe2048	ed25519	113.53	347.88	75.07 / 9.67	3.03
secp256r1	rsa2048	114.23	375.25	72.68 / 10.63	3.04
x25519	rsa2048	109.89	368.80	73.32 / 10.44	2.93
<i>[PQC(KEM) + PQC(DS) Algorithms]</i>					
mlkem512	mldsa44	106.08	1044.63	76.80 / 6.30	3.91
mlkem512	falcon512	107.54	651.29	76.52 / 7.33	3.50
mlkem512	sphincsha2128f	206.10	3827.23	44.88 / 42.60	6.08
hqc128	mldsa44	231.62	1553.43	65.56 / 26.24	3.74
hqc128	falcon512	234.98	1167.13	64.88 / 26.46	3.59
<i>[Legacy(KEM) + PQC(DS) Algorithms]</i>					
ffdhe2048	mldsa44	112.65	948.52	74.38 / 10.09	3.04
ffdhe2048	falcon512	114.85	549.03	72.28 / 10.86	2.91
ffdhe2048	sphincsha2128f	215.98	3724.60	45.17 / 42.33	7.98
secp256r1	mldsa44	105.98	907.35	76.50 / 7.13	3.94
x25519	falcon512	109.67	505.50	76.00 / 7.70	3.45
<i>[PQC(KEM) + Legacy(DS) Algorithms]</i>					
mlkem512	rsa2048	112.60	514.90	73.66 / 10.03	3.25
mlkem512	ecdsa-p256	110.05	450.78	77.69 / 5.92	3.54
mlkem512	ed25519	111.08	444.13	75.96 / 5.83	3.52
hqc128	rsa2048	242.12	1017.43	63.62 / 27.73	3.78
hqc128	ecdsa-p256	234.85	960.10	65.85 / 26.15	3.87

Table 13. Multi-thread (100 Concurrent Queries) DNS over HTTPS Benchmark Results by Algorithms (Security Level 1)

KEM	DS	Latency (ms)	Bandwidth (kB)	Client / Server CPU (%)	Memory (%)
<i>[Legacy(KEM) + Legacy(DS) Algorithms]</i>					
ffdhe2048	rsa2048	116.57	442.58	71.82 / 13.89	2.72
ffdhe2048	ecdsa-p256	114.43	386.64	74.09 / 9.82	3.69
ffdhe2048	ed25519	126.00	378.61	76.88 / 9.35	3.77
secp256r1	rsa2048	113.69	406.72	73.16 / 11.06	3.16
x25519	rsa2048	123.77	399.66	72.56 / 10.61	3.83
<i>[PQC(KEM) + PQC(DS) Algorithms]</i>					
mlkem512	mldsa44	117.57	1085.28	78.26 / 6.85	3.18
mlkem512	falcon512	128.04	683.36	79.03 / 7.34	3.63
mlkem512	sphincsha2128f	213.58	3857.46	44.32 / 42.27	6.47
hqc128	mldsa44	231.99	1581.33	65.17 / 26.22	3.77
hqc128	falcon512	236.47	1194.90	65.46 / 26.67	4.36
<i>[Legacy(KEM) + PQC(DS) Algorithms]</i>					
ffdhe2048	mldsa44	126.36	979.29	73.72 / 10.34	4.17
ffdhe2048	falcon512	127.36	579.55	72.97 / 11.28	3.97
ffdhe2048	sphincsha2128f	230.49	3754.98	46.35 / 42.37	5.07
secp256r1	mldsa44	114.97	943.96	76.35 / 7.50	4.38
x25519	falcon512	115.84	537.87	76.85 / 7.93	3.64
<i>[PQC(KEM) + Legacy(DS) Algorithms]</i>					
mlkem512	rsa2048	125.30	545.89	75.47 / 10.22	3.68
mlkem512	ecdsa-p256	116.64	491.30	78.84 / 6.33	3.50
mlkem512	ed25519	129.77	483.09	79.06 / 6.10	4.02
hqc128	rsa2048	240.28	1045.36	63.94 / 27.50	4.70
hqc128	ecdsa-p256	225.07	987.77	65.90 / 26.06	3.98

Table 14. Multi-thread (1000 Concurrent Queries) DNS over TLS Benchmark Results by Algorithms (Security Level 1)

KEM	DS	Latency (ms)	Bandwidth (kB)	Client / Server CPU (%)	Memory (%)
<i>[Legacy(KEM) + Legacy(DS) Algorithms]</i>					
ffdhe2048	rsa2048	1170.67	4135.29	81.76 / 16.36	3.17
ffdhe2048	ecdsa-p256	1128.47	3564.65	86.91 / 11.66	3.19
ffdhe2048	ed25519	1138.10	3495.04	86.47 / 11.42	3.17
secp256r1	rsa2048	1134.85	3766.40	85.14 / 12.80	3.03
x25519	rsa2048	1038.85	3700.32	84.26 / 12.16	2.93
<i>[PQC(KEM) + PQC(DS) Algorithms]</i>					
mlkem512	mlds44	1041.92	10525.63	88.90 / 7.23	3.14
mlkem512	falcon512	1015.81	6531.43	87.35 / 8.36	1.93
mlkem512	sphincsha2128f	2031.86	38334.88	51.76 / 49.66	3.33
hqc128	mlds44	2273.20	15597.85	71.99 / 28.91	3.02
hqc128	falcon512	2286.71	11736.69	71.76 / 29.43	3.28
<i>[Legacy(KEM) + PQC(DS) Algorithms]</i>					
ffdhe2048	mlds44	1129.35	9498.89	86.35 / 11.88	2.11
ffdhe2048	falcon512	1084.89	5504.62	84.53 / 12.80	1.90
ffdhe2048	sphincsha2128f	2099.34	37310.66	50.80 / 50.76	3.35
secp256r1	mlds44	1008.65	9129.04	87.34 / 8.05	1.82
x25519	falcon512	989.28	5069.88	87.17 / 8.72	1.91
<i>[PQC(KEM) + Legacy(DS) Algorithms]</i>					
mlkem512	rsa2048	1075.10	5161.51	85.06 / 11.65	1.97
mlkem512	ecdsa-p256	1050.44	4587.73	89.40 / 6.67	1.87
mlkem512	ed25519	1056.15	4518.04	89.91 / 6.70	2.00
hqc128	rsa2048	2378.82	10241.93	70.11 / 30.91	3.08
hqc128	ecdsa-p256	2319.31	9663.87	72.50 / 28.82	3.02

Table 15. Multi-thread (10000 Concurrent Queries) DNS over TLS Benchmark Results by Algorithms (Security Level 1)

KEM	DS	Latency (ms)	Bandwidth (kB)	Client / Server CPU (%)	Memory (%)
<i>[Legacy(KEM) + Legacy(DS) Algorithms]</i>					
ffdhe2048	rsa2048	12210.94	41409.08	85.04 / 16.81	3.24
ffdhe2048	ecdsa-p256	11527.69	35695.47	88.77 / 12.26	3.11
ffdhe2048	ed25519	11407.90	34987.19	88.88 / 11.83	3.2
secp256r1	rsa2048	11477.12	37709.48	87.05 / 13.52	3.34
x25519	rsa2048	11424.62	37058.06	87.45 / 13.28	3.28
<i>[PQC(KEM) + PQC(DS) Algorithms]</i>					
mlkem512	mlds44	11097.96	105253.99	92.55 / 8.02	3.16
mlkem512	falcon512	10841.17	65355.13	91.48 / 9.18	3.21
mlkem512	sphincsha2128f	21392.90	383485.47	57.28 / 54.17	4.28
hqc128	mlds44	24288.86	156244.86	79.65 / 32.49	4.89
hqc128	falcon512	24723.59	117645.91	75.73 / 31.36	4.55
<i>[Legacy(KEM) + PQC(DS) Algorithms]</i>					
ffdhe2048	mlds44	11867.66	95013.24	95.71 / 13.44	3.06
ffdhe2048	falcon512	12014.42	55072.27	94.09 / 14.55	3.03
ffdhe2048	sphincsha2128f	22821.37	373292.91	56.34 / 55.74	5.13
secp256r1	mlds44	11062.00	91298.88	91.69 / 8.75	3.09
x25519	falcon512	11249.60	50711.74	89.81 / 9.33	2.97
<i>[PQC(KEM) + Legacy(DS) Algorithms]</i>					
mlkem512	rsa2048	11224.52	51639.30	87.52 / 12.28	3.06
mlkem512	ecdsa-p256	11114.39	45836.77	92.10 / 7.08	3.01
mlkem512	ed25519	11560.73	45110.46	94.02 / 7.05	3.47
hqc128	rsa2048	24643.51	102661.15	73.80 / 31.28	4.69
hqc128	ecdsa-p256	23974.78	96905.00	73.32 / 30.27	4.95

combinations such as MLKEM512 + Falcon512 and MLKEM512 + MLDSA44 continue to demonstrate favorable latency-remaining near or slightly above 11,000 ms-client CPU usage now consistently exceeds 90-percent, suggesting that cryptographic operations are nearing saturation on the hardware. Algorithms with larger signature sizes and higher verification costs, notably SPHINCS+ and HQC, experience significant performance degradation under this load: latencies surpass 24,000 ms, server CPU usage rises above 30-percent, and memory consumption increases to nearly 5-percent in extreme cases. Bandwidth overhead scales linearly with the query volume as expected, yet the total transfer size becomes critical-e.g., over 380 MB for MLKEM512 + SPHINCS+-raising deployment concerns in environments with limited throughput capacity. Hybrid combinations such as FFDHE2048 + SPHINCS+ and FFDHE2048 + Falcon512 exhibit similar symptoms, with both latency and CPU overhead widening their gap compared to mid-scale tests. These results affirm that while many PQC algorithms remain viable at moderate concurrency levels, certain schemes-especially those with hash-based signatures or large ciphertexts-present low performance in high-throughput use cases.

4.4 Analysis and Discussion of the Benchmarking Metrics

The following analysis evaluates experimental benchmarking between PQC and conventional cryptographic techniques applied to DoT, DoH and DNSSEC configurations. The measurements were conducted in controlled Docker environments and focused on four primary performance metrics: Latency, bandwidth, CPU usage and memory consumption. The differences between the NIST security levels, the algorithm families (lattice, hash and code-based) and the protocol layers were investigated to understand the impact on real-world deployment.

Latency Usage: Traditional algorithms such as FFDHE and RSA consistently exhibited faster handshake latency due to compact key sizes and minimal arithmetic complexity. Among PQC schemes, Falcon, ML-KEM, and ML-DSA demonstrated competitive latency, benefiting from efficient implementations and hardware-accelerated integer operations. In contrast, HQC and SPHINCS+ exhibited higher latency due to complex decoding logic or deep Merkle tree structures [23]. The NIST security levels directly impacted latency. Higher levels require increased internal dimensions (e.g., lattice ring size, number of hash iterations), which translate to longer computation times during key encapsulation and signature verification. The latency was not only influenced by the bandwidth, but also by the computational effort. Algorithms with high arithmetic complexity or serialization overhead (e.g. syndrome decoding in HQC) significantly increased the handshake duration. Protocol differences (i.e., DoT vs. DoH) had a negligible effect on latency, with HTTP framing overhead being minimal.

Bandwidth Usage: Traditional schemes transmitted smaller public keys and cipher-texts, keeping total handshake sizes compact. PQC algorithms, especially those based on hash and code constructs, required significantly more bandwidth due to large key and signature sizes. Hash-based algorithms (e.g., SPHINCS+) embed large hash trees into their signatures, leading to particularly high message overheads. Code-based schemes like HQC involve expanded cipher-texts for error correction. Lattice-based schemes (e.g., ML-KEM) offered a middle ground, achieving strong security with moderate bandwidth increases-due to their compact structured matrices and avoidance of large random data. DoH showed slightly higher bandwidth usage than DoT because of the extra overhead from HTTP/2 framing and headers. This difference is protocol-related and not caused by the cryptographic algorithms, including Legacy and PQC schemes.

CPU Usage: CPU load during the establishment of the handshake exhibited a clear asymmetry between the client and the server. Across all algorithms, the client most likely experienced significantly higher CPU usage compared to the server. This reflects the dual burden of the client to perform both key encapsulation and signature verification, which are typically more computationally intensive than the decapsulation and signing operations of the server. *Lattice-based*

schemes such as ML-KEM and ML-DSA, used vectorized modular arithmetic (e.g., AVX2) to accelerate operations [43]. These schemes showed high CPU usage on the client side but relatively low load on the server, indicating efficient de-capsulation routines. *Hash-based schemes* such as SPHINCS+, consumed fewer CPU cycles per clock but required many sequential operations during signature verification. This resulted in longer handshake durations and moderate CPU usage on both the client and the server. *Code-based schemes* such as HQC, showed a more balanced CPU load between the client and server. The client's CPU usage is lower because its operations, while involving some sequential processing, are less computationally intensive. In contrast, the server's higher CPU usage is driven by the error correction process, which involves complex and sequential syndrome decoding, causing a heavier load on the server side. *Classical cryptographic schemes*, such as FFDHE with RSA or ECDSA, demonstrated stable and moderate CPU usage on both client and server sides. Their widespread optimization across platforms and decades of hardware support contributed to low cryptographic overheads, making them ideal for resource-constrained or latency-sensitive deployments. However, this efficiency comes at the cost of vulnerability to quantum attacks, underscoring the need to transition toward PQC alternatives despite the computational trade-offs. As security levels rise, the CPU load distribution between client and server becomes more evident. For higher security levels, the server CPU usage tends to increase due to the more complex de-capsulation and signature generation processes, while the client CPU usage generally decreases as key encapsulation and signature verification become more efficient, often benefiting from hardware acceleration or better optimizations. The underlying mathematical operations-such as number-theoretic transforms in lattice-based schemes, syndrome decoding in code-based schemes, or hash-tree traversal in hash-based schemes-significantly influence CPU usage. These operations affect not only the overall computational cost but also how efficiently the algorithms can be parallelized and optimized on modern hardware. Additionally, higher security levels typically increase computational demands, further impacting CPU utilization on both client and server systems.

Memory Usage: Across all test scenarios, memory consumption remained within manageable limits. Traditional algorithms like RSA and ECDSA showed minimal memory overhead due to compact key sizes and optimized cryptographic routines. Among post-quantum algorithms, SPHINCS+ had the highest memory footprint, attributed to the deep hash tree structures used in its stateless signature generation. Conversely, ML-KEM and ML-DSA exhibited moderate memory usage due to their reliance on structured lattices and matrix arithmetic. HQC, while demanding more memory on the server during decoding, maintained acceptable RAM usage overall. None of the tested algorithms had significant impact on the allocated container memory, suggesting feasibility for DNS deployments even on modest hardware, provided CPU trade-offs are addressed.

Impact of DNSSEC: DNSSEC introduced only minor increases in bandwidth when applied with traditional algorithms. When paired with PQC signatures (e.g., SPHINCS+), the increase became more pronounced, due to larger DNSKEY and RRSIG records, though it did not affect latency significantly. Applying DNSSEC without TLS caused no measurable latency penalty and introduced minimal resource overhead-highlighting its feasibility even in resource-constrained deployments. In combined DoT/DoH with DNSSEC scenarios, while bandwidth increased as expected, no significant differences were observed in other performance metrics such as latency or CPU usage between legacy and PQC algorithms.

Relationship of Metrics: Larger messages do contribute to increased bandwidth-but they are not the dominant cause of latency. Latency depends more heavily on algorithmic compute time and hardware optimization. High CPU usage may correlate with better performance, as it often indicates effective parallelism. For example, lattice-based schemes that fully utilized CPU resources achieved quicker handshakes despite high computational intensity. Some schemes with low CPU usage still had poor latency due to serial or complex internal processes that failed to take advantage of

available processing power. Bandwidth, CPU, and latency must be interpreted together rather than in isolation. No single metric accurately predicts overall performance across all protocols and algorithms.

Multi-threaded Benchmarking Results: Several metrics were evaluated for benchmarking purposes. The results of the analyses for the individual metrics are listed below:

- **Latency:** Compared to legacy algorithms, several PQC algorithm combinations- - especially ML-KEM with ML-DSA and Falcon- - showed strong performance at lower or comparable latency. This suggests that even under high concurrency, lattice-based methods can maintain responsiveness. However, algorithms such as SPHINCS+ and HQC required significantly more time to complete query transactions, highlighting their heavier cryptographic operations. Despite the transition to a multi-threaded environment, the overall latency trends remained consistent with those observed in the single-threaded test scenario.
- **Bandwidth:** As expected, the PQC algorithms consume significantly more bandwidth than their legacy counterparts. This increase is due to the inherently larger key sizes and message structures of PQC cryptography. Furthermore, the behaviour was consistent with what was observed for single-threaded methods -the bandwidth values were about 100 times larger than a single-query session, reflecting the batch size of 100 concurrent queries per session.
- **CPU Usage:** CPU utilization on the client side remained consistently high for legacy algorithms. In contrast, PQC algorithms showed varying CPU demand depending on the underlying cryptographic family. Lattice-based schemes like ML-KEM and Falcon maintained higher client CPU and lower server CPU use, while hash-based (e.g., SPHINCS+) and code-based (e.g., HQC) algorithms presented more server CPU usage compared to Legacy and Lattice-based algorithms. These trends resembled the single-threaded results, with no significant deviation observed in the multi-threaded context.
- **Memory Usage:** Unlike CPU behavior, memory usage showed a noticeable increase due to multi-threaded execution. While legacy and PQC algorithms both experienced higher memory consumption, the increase was more pronounced in algorithms with inherently larger operational footprints-again, such as SPHINCS+ and HQC. This shift reflects the expected outcome of parallelized query execution placing additional demands on system memory.

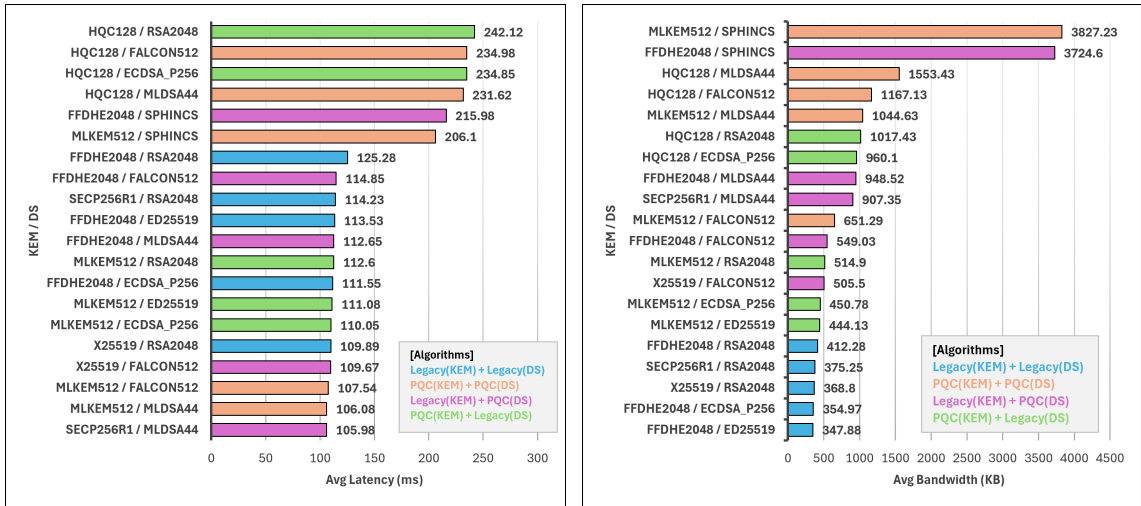


Fig. 6. Multi-thread (100 Concurrent Queries) DoT Latency (left) and Bandwidth (right) comparison chart - Security Level 1

Fig. 6 presents multi-thread (i.e., 100 concurrent clients) DoT latency and bandwidth comparison chart based on Security Level 1 in an increasing order, Fig. 7 shows for 1000 concurrent clients, and 10000 concurrent queries are displayed in Fig. 8. As with the single-threaded tests, DoH showed no significant performance differences compared to DoT, apart from the expected slight increase in bandwidth utilisation due to the HTTP header overhead. This pattern also remained consistent in the multi-threaded setting, indicating that protocol encapsulation does not result in additional performance degradation with concurrent query load.

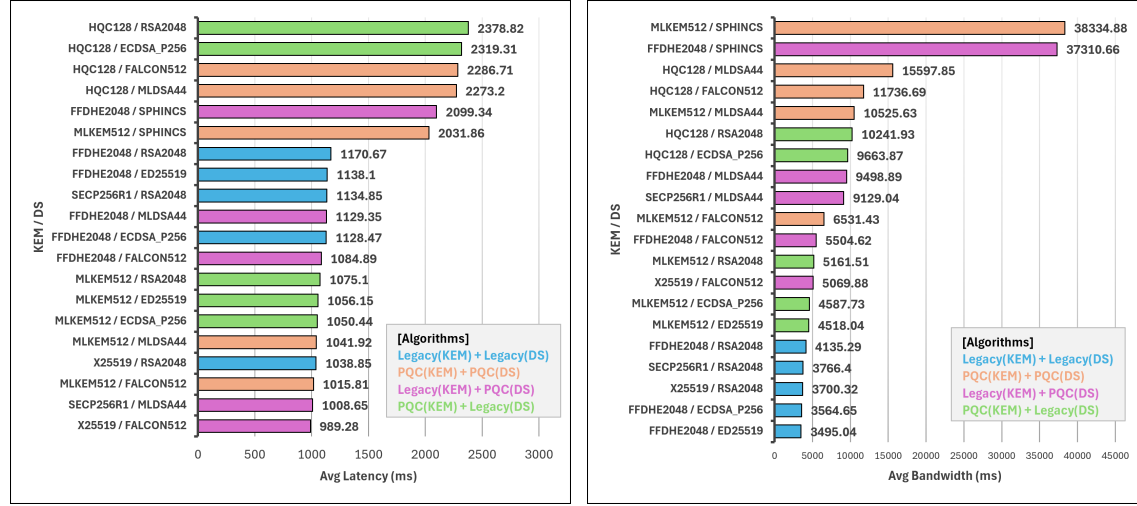


Fig. 7. Multi-thread (1000 Concurrent Queries) DoT Latency (left) and Bandwidth (right) comparison chart - Security Level 1

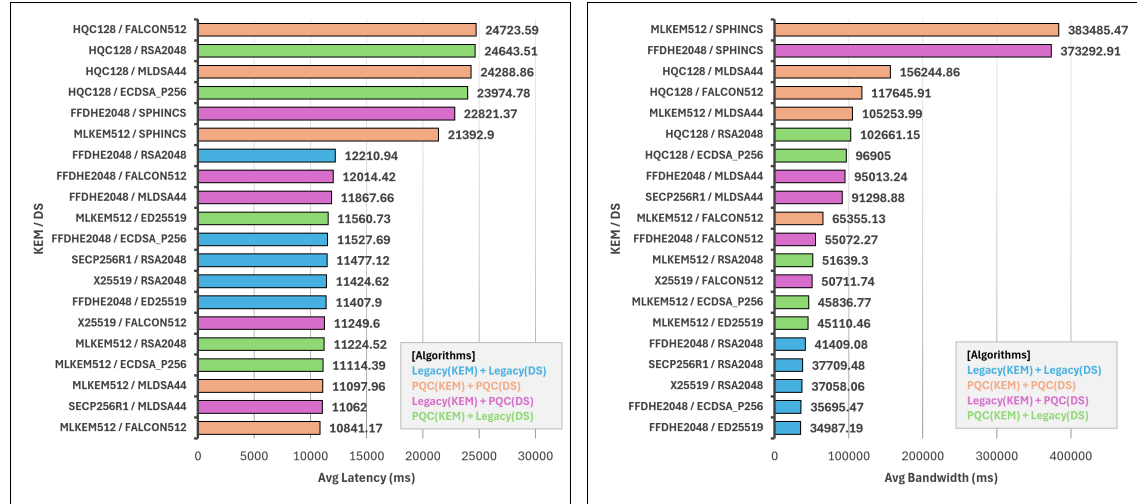


Fig. 8. Multi-thread (10000 Concurrent Queries) DoT Latency (left) and Bandwidth (right) comparison chart - Security Level 1

5 LIMITATIONS AND DISCUSSIONS

While our study presents a comprehensive performance evaluation of post-quantum DNS security mechanisms, several limitations and open issues remain that merit discussion.

Environment Configuration Complexity: During the initial phase of this study, configuring a working post-quantum DNS environment posed considerable challenges. The integration of OpenSSL, liboqs, oqsprovider, and a forked BIND implementation (OQS-BIND) required substantial manual effort due to a lack of existing documentation or established deployment practices. Configuration mismatches, cryptographic interface inconsistencies, and versioning incompatibilities across these libraries significantly delayed experimental progress. This reflects a broader challenge in PQC deployment, which is the absence of mature tooling and interoperability support for production-ready DNS applications.

Hardware-Dependent Benchmark Results: All performance metrics reported in this paper were obtained from a controlled local environment with fixed hardware specifications. While this ensures internal consistency and fair algorithmic comparisons, the results are inherently hardware-dependent and may not generalize to other platforms. In particular, CPU-bound operations such as lattice-based key encapsulations or hash-based signature verifications are sensitive to processor architecture, instruction set optimizations (e.g., AVX2), and system load. As such, these results should not be directly compared to benchmarks conducted in dissimilar environments. Moreover, network jitter, cross-traffic, and carrier-grade NAT behavior may impact real-world performance differently than reported here. Future work should extend this study to wide-area deployments or cloud-based DNS providers such as Cloudflare, Quad9, or Google DNS.

Security and Implementation Caveats: Our security model assumes ideal implementations of PQC primitives. In practice, side-channel resistance is highly dependent on careful software and hardware engineering. Recent studies [15] have shown that even constant-time implementations of Kyber and Dilithium can be vulnerable under real-world leakage. Furthermore, hybrid TLS deployments may expose endpoints to downgrade attacks if cipher suite negotiation is improperly enforced [38]. Ensuring downgrade resilience remains an open challenge, particularly during transitional deployments where backward compatibility with classical clients must be maintained.

DDoS and Operational Risks: One critical operational concern is the susceptibility of PQC-enhanced handshakes to denial-of-service attacks. Recent work [36] has demonstrated that the larger message sizes and increased CPU cycles required by post-quantum TLS can be exploited to launch resource exhaustion attacks against resolvers and servers. While our benchmarks included multi-threaded evaluations, future research must investigate rate-limiting, client puzzles, or adaptive throttling in high-load scenarios to maintain resolver availability.

Sustainability and Scalability Considerations: The long-term viability of post-quantum DNS deployment depends not only on cryptographic soundness but also on sustainability and scalability across diverse Internet environments. Post-quantum algorithms—particularly lattice- and hash-based schemes—introduce nontrivial increases in computation time, memory footprint, and message size. These overheads raise concerns about energy efficiency, especially in edge and embedded deployments where power and thermal budgets are tightly constrained. For instance, the use of hash-based signatures like SPHINCS+ can amplify CPU cycles and bandwidth usage, potentially leading to increased data center energy demands and greater environmental impact. While lattice-based schemes such as MLKEM and Falcon offer more favorable performance-energy trade-offs, even these incur latency and CPU penalties compared to classical counterparts like X25519 or ECDSA. As global DNS infrastructure spans thousands of recursive and authoritative servers, even modest per-query increases can aggregate into substantial operational cost and carbon footprint. *Scalability* is also

challenged by the asymmetric nature of PQC performance, where server-side decapsulation and signature verification may dominate processing costs. In high-throughput scenarios, such as those faced by large DNS providers or CDNs, this imbalance could limit the capacity to handle peak query loads without architectural optimizations such as hardware acceleration, TLS session resumption, or offloading cryptographic functions to secure enclaves. To ensure scalable and sustainable deployment, future work must include energy profiling under realistic workloads, exploration of post-quantum hardware accelerators, and protocol-level optimizations such as lightweight hybrid modes and session caching. These enhancements are critical for aligning post-quantum security with operational feasibility and environmental responsibility.

Standardization and Deployment Barriers: Although NIST has finalized several PQC algorithms for standardization, many production-grade DNS resolvers (e.g., Unbound, PowerDNS) and TLS libraries still lack stable PQC integration. Our implementation is based on OQS-BIND and patched OpenSSL versions, which may diverge from mainstream stacks. Ensuring ecosystem-wide adoption will require coordinated efforts across DNS software vendors, TLS library maintainers, and browser manufacturers. Moreover, regulatory frameworks for DNS security (e.g., ICANN or DNSSEC root signing authorities) may need to update operational policies to accommodate hybrid or post-quantum-only deployments.

Despite these challenges, our results demonstrate that carefully selected PQC primitives-particularly MLKEM and Falcon-can enable post-quantum DNS security without incurring prohibitive performance penalties. Our findings can inform future standardization and deployment strategies for quantum-resilient DNS infrastructures.

6 CONCLUSION AND FUTURE WORK

The findings presented in this study highlight the technical feasibility and practical considerations of deploying post-quantum cryptographic algorithms in DNS infrastructure, particularly in securing DNSSEC, DNS over TLS, DNS over HTTPS. By evaluating multiple algorithm classes across key performance metrics-latency, bandwidth, CPU, and memory usage-this work provides a foundation for informed decision-making in future DNS security designs. The demonstrated trade-offs emphasize that no single algorithm is universally optimal; rather, the suitability of a PQC scheme depends heavily on its operational context and intended role within the DNS protocol stack. As quantum-resistant standards continue to evolve, aligning DNS security mechanisms with these cryptographic advancements will be essential for maintaining long-term trust and resilience in global name resolution systems.

Future research should explore several key directions to advance the deployment of post-quantum secure DNS. First, evaluating the energy consumption and thermal behavior of PQC operations-particularly in edge computing environments-can help assess their sustainability and scalability. Second, integrating PQC mechanisms into emerging transport protocols such as DNS-over-QUIC (DoQ) would extend quantum resilience to modern, low-latency communication layers. Additionally, further investigation is needed into how PQC impacts resolver-side behaviors, including caching strategies and TTL (time-to-live) optimizations, which are critical for performance and efficiency at scale. Finally, conducting real-world user studies to measure latency perception and packet reliability under post-quantum DNS deployments will provide valuable insight into practical usability and quality-of-service implications.

Future work should also address these limitations by deploying PQC-enabled DNS in a production-like setting with real-world traffic patterns and multiple authoritative zones. In particular, scaling tests using distributed testbeds or cloud-based DNS resolvers could yield deeper insight into performance under load. Further, efforts should be made to measure protocol-level resilience, such as the effect of PQC on packet loss, retransmissions, and handshake failure rates

in lossy or mobile networks. Lastly, given the fast-evolving nature of PQC standardization, continuous tracking of NIST and IETF progress will be essential to align future DNS deployments with approved cryptographic profiles.

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