LiteQSign: Lightweight and Scalable Post-Quantum Authentication for Heterogeneous IoT Applications

Attila A. Yavuz, *Senior Member, IEEE*, Saleh Darzi, *Member, IEEE*, Saif E. Nouma

arXiv:submit/6246305 [cs.CR] 2 Mar 2025

Abstract*—Traditional digital signatures face significant challenges on low-end IoT devices due to limited computational power, memory, and energy resources. Simultaneously, the rise of quantum computing necessitates post-quantum (PQ) secure alternatives. However, PQ-secure signatures typically incur substantial costs, hindering their adoption in IoT applications like wearable health devices, trackers, and smart sensors, where efficient signature generation is critical for prolonged device lifespan and optimal resource utilization. To address these challenges, we present LightQSign (`LiteQS`), a novel lightweight PQ signature scheme that achieves near-optimal signature generation efficiency with only a small, constant number of hash operations per signing process. The core innovation lies in enabling verifiers to obtain one-time hash-based public keys without interacting with signers or third parties through secure computation. This design eliminates the need for non-colluding verification servers, secure enclaves, or trusted assisting entities, thereby reducing security risks and extending IoT device battery life with minimal cryptographic overhead. We formally prove the security of `LiteQS` in the random oracle model and conduct a thorough performance analysis, demonstrating that it outperforms NIST PQC standards with significantly lower computational overhead, minimal memory usage, and a compact signature footprint. Experiments on an 8-bit microcontroller show that `LiteQS` achieves 20× faster signature generation while producing smaller signature and private key sizes compared to state-of-the-art schemes.

***Index Terms*—Internet of Things, Lightweight Authentication, Digital Signatures, Post-Quantum Security**

I. Introduction

The proliferation of resource-constrained IoT devices, coupled with their extensive integration into critical domains such as healthcare, industrial automation, and financial services, introduces significant security challenges. While these devices deliver substantial utility and advancements, their operation in challenging environments and inherent limitations make them the most vulnerable link in the security chain. With billions of IoT devices interconnected across networks, many function in environments that process sensitive or personal data, including healthcare records [1], military communications [2], and security logs [3], [4], while executing essential operations such as unlocking smart doors, regulating industrial machinery [5], and administering medical treatments [6]. For instance, compromised authentication undermines the integrity of data from implantable devices, rendering them ineffective and potentially endangering patients, such as failing to correct a slow heartbeat in time [7]. Therefore, ensuring the authenticity of these devices and the integrity of their processed data is imperative to safeguarding networks from malicious entities, preserving the integrity of transmitted information, and preventing unauthorized access to critical system controls. Also, IoT devices require periodic updates to address security vulnerabilities and enhance functionality. Verifying the authenticity and integrity of firmware and software updates is crucial to preventing the installation of updates from untrusted sources, thereby maintaining overall system security [8], [3].

A "*digital signature*" serves as the cornerstone cryptographic solution for ensuring authentication and data integrity while providing essential features such as non-repudiation, public verifiability, and scalability [9]. These properties enable IoT systems to operate securely and efficiently, mitigating risks of unauthorized access, data breaches, device manipulation, and network disruptions. Given the diverse operational constraints of IoT applications—particularly in computation, latency, and energy efficiency—authentication mechanisms must be tailored accordingly. Here, we focus on IoT-enabled applications that prioritize fast signing due to resource constraints and real-time operational demands, while slower verification is acceptable on backend systems. Numerous IoT use cases align with this model, including environmental and industrial sensors that periodically transmit data, such as temperature or air quality, to central servers, while smart utility meters (e.g., energy, water, gas) frequently report usage data [10], [11]. Wearable health devices continuously collect biometric metrics, forwarding them to paired devices or the cloud [12], [13]. Remote IoT nodes, including wildlife trackers and agricultural sensors [14], operate in power-constrained environments, transmitting critical updates. RFID/NFC-based asset tracking systems enable real-time identification with backend verification [15], while smart city sensors for traffic, pollution, and waste management autonomously collect and transmit data on low power, prioritizing rapid signing for real-time operations and deferred verification [16].

Therefore, designing practical authentication solutions for these heterogeneous IoT-enabled applications necessitates addressing the following key considerations:

(I) Post-Quantum Security: The rise of quantum computing threatens traditional digital signatures based on number-theoretic assumptions (e.g., factorization, discrete logarithm) [17], [18], [19], necessitating long-term security solutions with PQ guarantees for IoT applications handling sensitive data and critical operations. Many IoT devices have long lifespans and cannot easily transition to new cryptographic frameworks once deployed, making immediate PQ adoption essential [20]. For instance, updating heart implants requires surgery, while upgrading mass-produced smart meters at scale is costly and impractical [21]. Moreover, resource constraints

Attila A. Yavuz, Saleh Darzi, and Saif E. Nouma are with the Department of Computer Science, University of South Florida, Tampa, 33620, Florida, USA (e-mail: attilaayavuz@usf.edu, salehdarzi@usf.edu, saifeddine-nouma@usf.edu)

such as limited processing power, memory, and battery life (e.g., 8-bit microcontrollers) further exacerbate PQ deployment. Addressing these challenges is critical for securing IoT-enabled environments, ensuring long-term resilience against emerging quantum threats [22].

(II) Computationally Efficient Signature Generation with Minimal Energy Usage: The primary consideration is fast and efficient signature generation with low latency on the signer side to enable real-time operations with minimal delays. Also, many embedded IoT devices are battery-powered [23], making energy efficiency crucial. For instance, in wearables, prolonged battery life enhances usability [4], while for implantable devices, it directly impacts patient well-being, as replacements may require surgical intervention [23]. Hence, the underlying cryptographic mechanism must minimize energy consumption to extend device longevity. However, even standard digital signatures based on conventional security (e.g., Elliptic Curve Cryptography) have been shown to degrade battery life in low-end IoT devices [24], [25]. This challenge is further intensified when PQ security is considered [26], [20].

(III) Minimal Cryptographic Memory and Bandwidth Usage: *(i)* Embedded IoT devices often have a compact memory space, such as the widely used 8-bit ATxmega128A1 MCU, which provides only $128KB$ of static flash memory[1]. Given these constraints, an ideal lightweight signature should feature compact key sizes and minimal memory expansion during computation. (ii) Cryptographic memory usage is also affected by code size, where simpler implementations using basic operations (e.g., hashing) over complex computations (e.g., EC scalar multiplication [27], sampling [28]) improve efficiency and reduce energy consumption. (iii) Additionally, signature size impacts memory, bandwidth, and power usage, as larger transmissions increase battery drain [29]. The large key and signature sizes of PQ-secure signatures further complicate deployment on low-end IoT devices.

(IV) Scalability, Minimal Security Assumptions, and Improved Robustness *(i)* Scalability and Interoperability: Ensuring seamless communication among diverse devices in heterogeneous IoT ecosystems requires an authentication scheme that efficiently scales across millions of interconnected, resource-limited devices. Given the challenges of key management in large-scale IoT networks with constrained connectivity, maintaining constant-size public keys and lightweight mechanisms for key distribution, renewal, and revocation is essential. *(ii)* Minimal Security Assumptions: While some schemes improve efficiency by assuming semi-honest, non-colluding servers or secure enclaves [22], [3]—the security-sensitive nature of IoT-enabled applications necessitates avoiding such dependencies. Eliminating extra architectural assumptions strengthens long-term trust, not only through PQ cryptographic guarantees but also by enhancing resilience against emerging threats. *(iii)* Robustness Against Side-Channel Attacks: PQ signatures involve Gaussian sampling [30], rejection sampling [28], and complex arithmetic [31], [26], making them vulnerable to side-channel attacks [32], [33]. These risks are amplified in embedded architectures due to the difficulty of implementing countermeasures [4]. Additionally, low-end IoT devices often generate low-quality random numbers, exposing them to cryptographic vulnerabilities [34]. Addressing these challenges is essential for securing IoT systems.

[1]https://www.microchip.com/en-us/product/atxmega128a1

A. Related Work and Limitations of the State-of-the-Art

This section examines state-of-the-art signatures that address key considerations for IoT-enabled applications, with a focus on schemes offering PQ security, computationally efficient signing, and compact public key and signature sizes. Given the extensive range of proposed signatures, we first provide a brief overview of prominent conventional signatures before shifting to PQ alternatives, including both standardized schemes and those optimized for signing efficiency.

Conventional lightweight signatures: These schemes offer efficient signature generation, compact key sizes, and additional security guarantees [35], [25], [36], [37]. Among conventional signatures, EC Schnorr-based schemes [27] are particularly efficient compared to pairing-based [38] and factorization-based [39] alternatives. For instance, a recent EC-based scheme [25] enhances signer efficiency and supports single-signer signature aggregation, while Chen et al. [37] integrate confidentiality with authentication. However, despite their advantages, none of these ECC-based schemes or similar conventional signatures provide PQ security.

Standard PQ signatures: NIST has recently standardized Dilithium (FIPS 204) as a lattice-based and SPHINCS+ (FIPS 205) as a hash-based digital signature standard [40]. The following discusses these domains in detail.

Known for their minimal intractability assumptions, hash-based signatures provide strong security guarantees. The stateless SPHINCS+ [41], derived from a variant of the one-time signature scheme HORS [42], employs a hyper-tree structure for multiple-time signatures. While SPHINCS+ ensures PQ security with strong assumptions, its signing time and signature size are orders of magnitude slower and larger than ECDSA, making it unsuitable for resource-constrained IoT devices. Similarly, stateful hash-based signatures (e.g., RFC-standardized XMSS-MT [43] and LMS [44]), built on HORS variants like W-OTS [45], offer comparable security and forward security. However, their state management requirements, high computational cost, and memory demands render them impractical for low-end IoT devices.

Based on module lattice problems (e.g., LWE [28]), lattice-based signatures offer a balanced trade-off between signing and verification efficiency. NIST-selected schemes, Dilithium [28] and Falcon [30], achieve smaller signatures and faster signing than SPHINCS+. However, they remain unsuitable for resource-constrained IoT devices due to their computational complexity and larger signature sizes compared to conventional signatures. Additionally, techniques such as Gaussian and rejection sampling introduce vulnerabilities to side-channel attacks [32]. To date, no open-source lattice-based signature implementation is optimized for highly constrained devices like 8-bit microcontrollers, except for BLISS [31], which was not selected as a NIST PQC standard [46] and is susceptible to side-channel attacks [33].

Additional PQ Signatures for Standardization: o diversify PQ signature standards, NIST launched a competition alongside its standardized schemes, emphasizing fast verification and compact signatures. Currently in its second round, it includes submissions across various PQC categories, such as code-based [47], multivariate-based [48], and symmetric-based [49] signatures. For instance, Shim et al. [26] improves upon NIST PQC standards with efficient signing and smaller signatures but suffers from large private key and code sizes, making it impractical for IoT devices. Its 12.6*KB* private key is an order of magnitude larger than ECDSA, and its implementation occupies 62.6% of the total flash memory on an ATxmega128A1 MCU, imposing significant memory overhead. Despite PQC advancements, computational and memory constraints remain major obstacles for low-end IoT devices, particularly those operating on 8-bit MCUs [46]. Also, many multivariate signatures not only demand extensive memory and stack resources but are also susceptible to polynomial-time attacks, compromising their unforgeability [50].

Lightweight PQ signatures with Additional Assumptions: These schemes achieve highly efficient signature generation but rely on additional assumptions [3], [22], [51]. For example, ANT [3], a lattice-based signature, delegates costly commitment generation to distributed, non-colluding, semi-honest servers [52]. However, verifiers must interact with these servers before verification, introducing potential network delays and outage risks. Another approach leverages Trusted Execution Environment (TEE)-assisted signatures, offloading computational overhead to TEE-enabled servers [51], [9], [22]. For instance, HASES [9] and its extension [22], derived from the one-time HORS [42], use a single TEE-enabled cloud server to issue one-time public keys. However, reliance on a centralized TEE server introduces key escrow risks and a single point of trust. Due to these additional assumptions, such signatures may not be ideal for IoT-enabled applications that require adherence to traditional public key settings.

Given the limitations of existing digital signatures and the gap in achieving all desirable properties for IoT-enabled applications, there is a critical need for efficient PQ signatures that balance performance and security while enabling signer-optimal generation and deferred verification. This work explores the following key research questions: *(i) Can an efficient PQ signature scheme be designed with optimal signature generation while meeting IoT constraints on memory, processing, and bandwidth? (ii) Is it possible to achieve energy-efficient signing without introducing unconventional or risky assumptions for verifiers? (iii) Can these requirements be met in a scalable multi-user setting for IoT networks?*

B. Our Contribution

We propose `LiteQSign`, a novel lightweight PQ signature that enables verifiers to derive one-time public keys independently, eliminating the need for interaction with signers or third parties. By extending the one-time `HORS` scheme into a multiple-time signature, `LiteQS` allows verifiers to extract one-time keys from a master public key via encrypted pseudo-random function evaluations using fully homomorphic encryption (FHE). To the best of our knowledge, this is the first `HORS`-type hash-based scheme that lifts message-signing constraints without relying on semi-honest servers (ANT [3]), trusted hardware (HASES [9]), or the high computational and storage costs of XMSS [53] and SPHINCS+ [41]. Our design offers several desirable properties, as follows:

- ***Signer-Optimal Computation with Energy Efficiency***: Our scheme makes a single call to the one-time `HORS` signature scheme while maintaining identical signature sizes, achieving *optimal efficiency* relative to `HORS`. Consequently, `LiteQS` requires only a small, constant number (e.g., 16) of Pseudo-Random Function (PRF) calls per signing. As shown in Table II, `LiteQS` achieves 19.5× and 1130× faster signature generation compared to NIST PQC standards Dilithium-II and Falcon-512, respectively. Moreover, it surpasses even the most efficient ECC-based conventional signatures. As detailed in Section VI, this computational efficiency translates directly into significant energy savings.
- ***Minimal Memory Requirements and Bandwidth Efficiency***: The private key of `LiteQS` consists solely of a single random seed (e.g., 128-bit), and it transmits only one `HORS` signature per message (i.e., 256 bytes), making it the most compact among PQ counterparts (see Table II). Unlike multivariate- [26] and lattice-based [31] schemes, `LiteQS` has a minimal code size for signature generation. It requires only a few PRF calls and a single hash call, avoiding costly operations like EC scalar multiplication [36] and sampling [33]. Moreover, its use of AES-128 as the PRF and SHA-256 as the hash function ensures standard compliance, facilitating an efficient transition to PQC [22].
- ***Advanced Security Features and Robustness***: *(i)* `LiteQS` adheres to the standard public key model, avoiding unconventional assumptions such as non-colluding or trusted key distribution servers [3], which introduce architectural risks. *(ii)* Unlike lattice-based schemes prone to side-channel and timing attacks due to Gaussian and rejection sampling [32], `LiteQS` relies solely on symmetric cryptographic primitives, eliminating these vulnerabilities. Also, its deterministic signature generation prevents weaknesses from poor random number generators, a common issue in resource-limited IoT devices.
- ***Compact Multi-User Storage and Online/Offline Verification***: `LiteQS` offers a scalable solution, enabling verifiers to derive one-time public keys for any valid signer and state from a constant-size master public key. This eliminates the need to store individual public keys and certificates, even for large-scale deployments (e.g., 2^{20} users). Additionally, verifiers can generate one-time public keys on-demand or precompute them before verification. While key construction involves computational overhead due to encrypted function evaluations, it can be performed independently by the verifier or offloaded to a resourceful cloud server, significantly reducing its practical impact.
- ***Limitations and Potential Use-Case***: These properties make `LiteQS` an ideal PQ signature for lightweight and scalable authentication in resource-limited IoT applications, offering near-optimal signer efficiency with delay-tolerant, resourceful verifiers. `LiteQS` prioritizes high PQ security and robustness, excelling in IoT scenarios where the signer is non-interactive and must operate with maximum efficiency (e.g.,

medical wearables, trackers), while verification can tolerate some delay and storage overhead. In such use cases, device efficiency and battery longevity are paramount. As detailed in Section III (Figure 1), `LiteQS` is well-suited for heterogeneous IoT environments [54].

II. Preliminaries

Notation: $|x|$, $||$, and $x \xleftarrow{\$} \mathcal{S}$ denote the bit length of the variable x, concatenation, and choosing x randomly from the set $\mathcal{S}$, respectively. $\oplus$ is the bitwise-XOR operation. $\{q_i\}_{i=1}^{n}$ denotes the set of items $\{q_1, q_2, \ldots, q_n\}$. $H : \{0,1\}^* \to \{0,1\}^\kappa$ is a cryptographic hash function. $\texttt{PRF} : \{0,1\}^* \times \{0,1\}^* \to \{0,1\}^\kappa$ is a Pseudo-Random Function (PRF) $x \leftarrow \texttt{PRF}(k, M)$ that takes a key k and message M as input, and produces x as the output. $f : \{0,1\}^* \to \{0,1\}^\kappa$ is a one-way function. $\{0,1\} \leftarrow \texttt{CMP}(x, y)$ denotes the equality comparison function (circuit) of two numerical values (*e.g.*, x and y can be 64-bit integers). $C \leftarrow E_k(m)$ denotes as the encryption of message m with the key k producing ciphertext C. E is an Indistinguishability under Chosen-Plaintext Attack (IND-CPA)-secure block cipher.

Definition 1 Hash to Obtain Random Subset (`HORS`) [42] is a one-time digital signature comprised of three algorithms:

- $\underline{(sk, PK, I_{\texttt{HORS}}) \leftarrow \texttt{HORS.Kg}(1^\kappa)}$: Given the security parameter κ, it selects $I_{\texttt{HORS}} \leftarrow (k, t)$, generates t random κ-bit strings $\{s_i\}_{i=1}^{t}$, and computes $v_i \leftarrow f(s_i), \forall i = 1, \ldots, t$. Finally, it sets $sk \leftarrow \{s_i\}_{i=1}^{t}$ and $PK \leftarrow \{v_i\}_{i=1}^{t}$.
- $\underline{\sigma \leftarrow \texttt{HORS.Sig}(sk, M)}$: Given sk and message M, it computes $h \leftarrow H(M)$. It splits h into k substrings $\{h_j\}_{j=1}^{k}$ (where $|h_j| = \log_2 t$) and interprets them as integers $\{i_j\}_{j=1}^{k}$. It outputs $\sigma \leftarrow \{s_{i_j}\}_{j=1}^{k}$.
- $\underline{b \leftarrow \texttt{HORS.Ver}(PK, M, \sigma)}$: Given PK, M, and σ, it computes $\{i_j\}_{j=1}^{k}$ as in $\texttt{HORS.Sig}(.)$. If $v_{i_j} = f(\sigma_j), \forall j = 1, \ldots, k$, it returns $b = 1$, otherwise $b = 0$.

Definition 2 A Fully Homomorphic Encryption scheme (FHE) [55] consists of four probabilistic polynomial-time algorithms $\texttt{FHE} = (\texttt{Kg}, \texttt{Enc}, \texttt{Eval}, \texttt{Dec})$ defined as below:

- $(sk', PK', I_{\texttt{FHE}}) \leftarrow \texttt{FHE.Kg}(1^\kappa)$: Given κ, it creates the auxiliary argument $I_{\texttt{FHE}}$ and generates `FHE` private/public key pair (sk', PK').
- $C \leftarrow \texttt{FHE.Enc}(PK', M)$: Given PK' and a plaintext M, it encrypts M and returns the ciphertext C.
- $C \leftarrow \texttt{FHE.Eval}(PK', \mathcal{F}(\overrightarrow{c} = \{c_j\}_{j=1}^{n}))$: Given PK', a function $\mathcal{F}$, and a set of input arguments $\overrightarrow{c}$, it evaluates $\mathcal{F}$ on $\overrightarrow{c}$ under encryption.
- $M \leftarrow \texttt{FHE.Dec}(sk', C)$: Given sk' and C, it decrypts C via sk' and outputs the plaintext M.

For illustration, $\texttt{FHE.Eval}(PK', \texttt{PRF}(Y, x))$ and $\texttt{FHE.Eval}(PK', \texttt{CMP}(x_1, x_2))$ evaluate $\texttt{PRF}(y, x)$ and $\texttt{CMP}(X_1, X_2)$ functions under encryption, where the key Y and the numerical values (X_1, X_2) are the encryption of y, x_1, and x_2 under PK' (i.e., $Y \leftarrow \texttt{FHE.Enc}(PK', y)$, $X_1 \leftarrow \texttt{FHE.Enc}(PK', x_1)$, $X_2 \leftarrow \texttt{FHE.Enc}(PK', x_2)$), respectively. We choose an IND-CPA secure FHE instantiated with the Ring Learning With Error (R-LWE) variant of the BGV cryptosystem [56]. Note that these FHE instantiations also have a post-quantum security premise [57].

The Davies-Meyer scheme (`DM`) [58] is an iterated cryptographic hash function based on a block cipher. In `LiteQS`, we only rely on the one-wayness (`OWF`) of `DM`, which is based on the IND-CPA security of the symmetric cipher E.

Definition 3 $\underline{B_n \leftarrow \texttt{DM}(M, B_0)}$: Given a message $M = \{m_i\}_{i=1}^{n}$ with n blocks, a pre-defined initial value $I_{\texttt{DM}} = B_0$, block cipher E of length k, it computes $n = \lceil \frac{|M|}{k} \rceil$, and $B_i = E_{m_i}(B_{i-1}) \oplus m_i, \forall i = 1, 2, ..., n$. It outputs B_n.

Definition 4 A Public Key Outsourced Signature scheme $\texttt{PKO-SGN} = (\texttt{Kg}, \texttt{Sig}, \texttt{PKConstr}, \texttt{Ver})$ is as follows:

- $(PK, sk, I) \leftarrow \texttt{PKO-SGN.Kg}(1^\kappa, \overrightarrow{ID})$: Given κ and a set of users' identifiers $\overrightarrow{ID}$, it returns PK with both `FHE` and master public keys $PK = \langle PK', MPK \rangle$, the private key $sk = \overrightarrow{\gamma}$, and the system-wide parameters $I \leftarrow I_{\texttt{FHE}}$.
- $\sigma_i^j \leftarrow \texttt{PKO-SGN.Sig}(\gamma_i, M_j)$: Given the seed $\gamma_i \in \overrightarrow{\gamma}$ of ID_i and a message M_j, it returns the signature σ_i^j.
- $cv_i^j \leftarrow \texttt{PKO-SGN.PKConstr}(PK, ID_i, j)$: Given the signer ID_i, state j, and PK, it constructs the required public keys under encryption cv_i^j via $\texttt{FHE.Eval}(.)$.
- $b \leftarrow \texttt{PKO-SGN.Ver}(PK_i^j, M_j, \sigma_i^j)$: Given PK_i^j, M_j, and σ_i^j, it outputs $b = 1$ if σ_i^j is valid, or $b = 0$ otherwise.

III. System Architecture and Security Model

System Model: We adopt the traditional public-key-based broadcast authentication model, tailored for diverse IoT-enabled applications while addressing key design considerations. Figure 1 illustrates the entities in our architecture, detailed as follows:

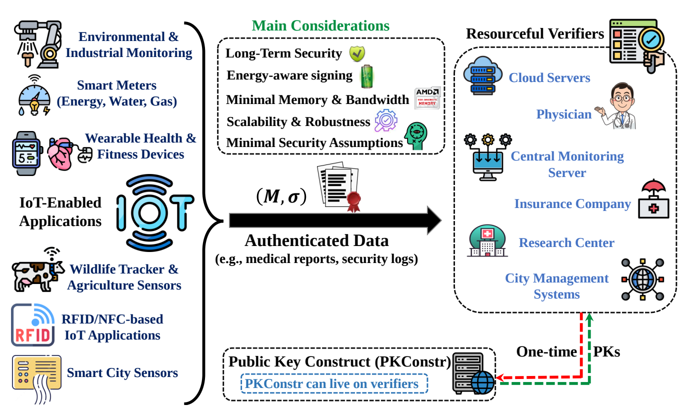


Fig. 1: System model

- *Signer:* A resource-constrained IoT device, such as a smart sensor, pacemaker, or implantable medical device (see Figure 1), responsible for signing and broadcasting messages to verifiers. These messages often contain sensitive data (e.g., heart rate, security logs), where data integrity and source authenticity are crucial for usability. The signer prioritizes efficient, energy-aware computations with minimal memory and bandwidth usage, while ensuring long-term security.

• *Verifier:* A resourceful entity (e.g., cloud server, physician, monitoring center) that authenticates messages from signers. It independently constructs one-time public keys from the master public key (MPK), enabling it to derive any public key PK_i^j for any user ID_i in a network of (e.g., $N = 2^{20}$) signers. Additionally, we propose an optional approach where non-resourceful verifiers can outsource public key derivation to a resourceful entity (e.g., a cloud server) via FHE computations, without relying on semi-honest entities or trusted parties.

Threat and Security Model: Our threat model is based on an adversary $\mathcal{A}$ equipped with the following capabilities:

1) *Passive attacks:* aim to monitor and interpret the output of the signature generation interface.
2) *Active attacks:* aim to intercept, forge, and modify messages and signatures sent from IoT devices. We assume that the adversary is equipped with a quantum computer.

We follow the standard Existential Unforgeability under Chosen Message Attack (EU-CMA) model [59]. It captures a Probabilistic Polynomial Time (PPT) adversary ($\mathcal{A}$) aiming at forging message-signature pairs. $\mathcal{A}$ is able to run passive and active attacks. The EU-CMA experiment is defined as follows:

Definition 5 The EU-CMA experiment $Expt^{\texttt{EU-CMA}}_{\texttt{PKO-SGN}}$ for an PKO-SGN digital signature scheme is defined as follows:

- $(PK, sk, I) \leftarrow \texttt{PKO-SGN.Kg}(1^\kappa, \overrightarrow{ID})$
- $(M^*, \sigma^*) \leftarrow \mathcal{A}^{\texttt{PKO-SGN.Sig}_{sk}(.),\ \texttt{PKO-SGN.PKConstr}(.)}(PK)$:
- If $1 \leftarrow \texttt{PKO-SGN.Ver}(PK, M^*, \sigma^*)$ and M^* was not queried to $\texttt{PKO-SGN.Sig}_{sk}(.)$, then return 1, else 0.

The advantage of $\mathcal{A}$ in this experiment is defined as $Adv^{\texttt{EU-CMA}}_{\texttt{PKO-SGN}}(\mathcal{A}) = Pr[Expt^{\texttt{EU-CMA}}_{\texttt{PKO-SGN}} = 1]$. The EU-CMA advantage of PKO-SGN is defined as $Adv^{\texttt{EU-CMA}}_{\texttt{PKO-SGN}}(t, q_s) = \max_{\mathcal{A}}\{Adv^{\texttt{EU-CMA}}_{\texttt{PKO-SGN}}(\mathcal{A})\}$, where t is the time complexity of $\mathcal{A}$ and q_s is the number of queries to the public key constructor and signing oracles. $\texttt{PKO-SGN.Sig}_{sk}(.)$ and $\texttt{PKO-SGN.PKConstr}(.)$ are as follows:

1) *Signing oracle* $\texttt{PKO-SGN.Sig}_{sk}(.)$: Given an input message M, it output a signature $\sigma \leftarrow \texttt{PKO-SGN.Sig}_{sk}(M)$.
2) Public key construct oracle $\texttt{PKO-SGN.PKConstr}(.)$: Given the public key PK, user identity ID_i, and counter j, it returns the one-time public key PK_i^j. Note that unlike previous public key constructors (e.g., [9], [3]), $\texttt{PKO-SGN.PKConstr}(.)$ does not require a root of trust on introduced entities (e.g., [3], [22]) and can be run based on public key data. $\texttt{PKO-SGN.PKConstr}(.)$ may be run by the verifier or a resourceful third party.

IV. The Proposed Scheme

We first present our proposed scheme, LiteQS. We then describe its instantiations, design rationale, and optimizations. The main bottleneck of hash-based digital signatures is the generation and management of one-time public keys. As outlined in Section I-A, the existing alternatives rely on hyper-tree structures that incur extreme signature generation and transmission overhead. A trivial yet insecure approach would be to share the master secret key with a trusted party that replenishes one-time keys for the verifiers (e.g., [51]). However, this invalidates the non-repudiation and makes the system vulnerable to key compromises. Moreover, it is not scalable to large-IoTs due to the massive transmission overhead.

We address this public key management conundrum by introducing a novel approach that permits verifiers to construct one-time keys from a master public key via encrypted evaluations. Our idea is to wrap the master secret key with homomorphic encryption and then enable any verifier to retrieve one-time public keys for any valid signer ID_i and message M_i^j. This allows signers to achieve optimal efficiency concerning HORS since it only computes and broadcasts one HORS signature per message. The verifiers can construct one-time public keys via encrypted evaluations without the risk of private key compromises. Our approach effectively transforms one-time HORS into practically unbounded hash-based signature with minimal signer computations, and therefore, fittingly, we name our new scheme LiteQSign (LiteQS). We provide the details of LiteQS in Algorithm 1.

The key generation algorithm LiteQS.Kg, first derives the master signing key msk and sets up the public parameters I including HORS, FHE, and DM parameters as in Definition 1, 2, 3, respectively (Step 1). It derives the initial private key γ_i (seed) of each signer ID_i (Step 2-3). It then generates an FHE key pair (sk', PK'), encrypts msk with PK' to generate the master public key MPK, and sets LiteQS public key as $PK = (PK', MPK)$ (Step 5). As elaborated in public key construction, this permits any verifier to extract a one-time public key from the master public key under encryption without exposing it. Finally, all key pairs are distributed to the verifiers and signers (Step 6).

The signature generation LiteQS.Sig for signer ID_i begins by deriving the private key sk_i^j from the seed γ_i based on the message state (counter) j (Step 1). The signing process follows HORS.Sig, except that the signature elements $\{s_i^{j,\ell}\}_{\ell=1}^k$ are computed via PRF evaluations using sk_i^j instead of random generation (Steps 2-4). Finally, the signer updates the state j and discloses the HORS signature (Step 5).

LiteQS.PKConstr algorithm enables any verifier to generate the one-time public key PK_i^j under FHE encryption associated with a valid $ID_i \in \overrightarrow{ID}$ without any interaction with the signer or having to access private keys (msk, sk'). It first derives the initial seed γ_i of ID_i under FHE encryption that is preserved in $c\gamma_i$ (Step 1). It then pinpoints the private key sk_i^j of state j, which is sealed under csk_i^j (Step 2). Note that the signer used sk_i^j to derive HORS signature components for M_i^j. Finally, it generates the FHE encryption of HORS one-time public key for the state j by evaluating $f(.)$ and PRF under encryption (Step 4-5).

The signature verification LiteQS.Ver resembles HORS.Ver, but starts by constructing public keys using LiteQS.PKConstr and the signature verification is performed under encryption. The verifier performs f evaluations on the received k elements of the signature subset and encrypts the output using FHE. Next, the verifier evaluates the comparison function CMP under encryption via FHE.Eval. As we will shortly discuss in Section IV-A, the verifier may construct public keys offline

Algorithm 1 LiteQSign Scheme ($\texttt{LiteQS}$)

$(PK, \overrightarrow{\gamma}, I) \leftarrow \texttt{LiteQS.Kg}(1^\kappa, \overrightarrow{ID} = \{ID_i\}_{i=1}^N)$:

1: $msk \xleftarrow{\$} \{0,1\}^\kappa$ and set $I \leftarrow (I_{\texttt{HORS}} = (k,t), I_{\texttt{FHE}}, I_{\texttt{DM}})$ according to Definitions 1, 2, 3.
2: **for** $i = 1, \ldots, N$ **do**
3: $\quad \gamma_i \leftarrow \texttt{PRF}(msk, ID_i)$
4: $(sk', PK', I_{\texttt{FHE}}) \leftarrow \texttt{FHE.Kg}(1^\kappa)$
5: $MPK \leftarrow \texttt{FHE.Enc}(PK', msk)$, $PK = \langle PK', MPK \rangle$
6: **return** $(PK, \overrightarrow{\gamma} = \{\gamma_i\}_{i=1}^N, I)$, where γ_i is securely given to ID_i

$\sigma_i^j \leftarrow \texttt{LiteQS.Sig}(\gamma_i, M_i^j)$: The signer ID_i computes a signature on a message M_i^j as follows:

1: $sk_i^j \leftarrow \texttt{PRF}(\gamma_i, j)$
2: $h_i^j \leftarrow H(M_i^j)$, split h_i^j into k sub-strings $\{h_i^{j,\ell}\}_{\ell=1}^k$ where $|h_i^{j,\ell}| = \log_2 t$, and interpret each $\{h_i^{j,\ell}\}_{\ell=1}^k$ as an integer $\{x_i^{j,\ell}\}_{\ell=1}^k$.
3: **for** $\ell = 1, \ldots, k$ **do**
4: $\quad s_i^{j,\ell} \leftarrow \texttt{PRF}(sk_i^j, x_i^{j,\ell})$
5: Set $j \leftarrow j+1$
6: **return** $\sigma_i^j = (s_i^{j,1}, s_i^{j,2}, ..., s_i^{j,k}, j)$

$cv_i^j \leftarrow \texttt{LiteQS.PKConstr}(PK, ID_i, j)$: Performed by the verifier for a given $ID_i \in \overrightarrow{ID}$ and state j, in *offline* mode before receiving signatures, or optionally outsourced to a powerful entity.

1: $c\gamma_i \leftarrow \texttt{FHE.Eval}(PK', \texttt{PRF}(MPK, ID_i))$
2: $csk_i^j \leftarrow \texttt{FHE.Eval}(PK', \texttt{PRF}(c\gamma_i, j))$
3: **for** $\ell = 1, \ldots, t$ **do**
4: $\quad cv_i^{j,\ell} \leftarrow \texttt{FHE.Eval}(PK', f(\texttt{PRF}(csk_i^j, \ell)))$
5: **return** $cv_i^j \leftarrow (cv_i^{j,1}, cv_i^{j,2}, ..., cv_i^{j,t})$

$b_i^j \leftarrow \texttt{LiteQS.Ver}(PK, M_i^j, \sigma_i^j)$:

1: $cv_i^j \leftarrow \texttt{LiteQS.PKConstr}(PK, ID_i, j)$
2: Execute Step 2 in $\texttt{LiteQS.Sig}$
3: **for** $\ell = 1, \ldots, k$ **do**
4: $\quad v_i^{j,\ell} \leftarrow f(s_i^{j,\ell})$
5: $\quad CV_\ell^j \leftarrow \texttt{FHE.Enc}(PK', v_\ell^j)$
6: $\quad b_i^{j,\ell} \leftarrow \texttt{FHE.Eval}(PK', \texttt{CMP}(cv_i^{j,x_i^{j,\ell}}, CV_i^{j,\ell}))$
7: **if** $b_i^{j,\ell} = 1, \forall \ell = 1, \ldots, k$ **then**, **return** $b_i^j = 1$ **else**, **return** $b_i^j = 0$

before receiving the message-signature pair. Additionally, to reduce the storage demands, the verifier may use an alternative method by providing the indices (i.e., $\{x_i^{j,\ell}\}_{\ell=1}^k$ in Step 2, $\texttt{LiteQS.Sig}$) instead of the counter j to the $\texttt{LiteQS.PKConstr}$ routine.

A. $\texttt{LiteQS}$ *Instantiations and Optimizations*

The generic $\texttt{LiteQS}$ in Algorithm 1 can be instantiated with any $\texttt{FHE}$, $\texttt{PRF}$ and $f(.)$ as $\texttt{OWF}$. However, these instantiation choices make a drastic impact on performance, security, and practicality. In the following, we articulate our instantiation rationale and their potential optimizations.

BGV Cryptosystem as the $\texttt{FHE}$ *Instantiation*: There exist various classes and schemes of FHE [60]. We instantiated our $\texttt{FHE}$ with BGV cryptosystem [56] for the following reasons: (i) BGV is considered as a benchmark for $\texttt{FHE}$ instantiations. It is well-studied and implemented in different libraries like HElib. (ii) We employ the Ring-Learning With Error (R-LWE) based BGV that offers an ideal security-efficiency trade-off. (iii) BGV is amenable to parallelism and supports CRT-based encoding techniques to allow entry-wise arithmetic. (iv) It facilitates leveled-FHE, enabling the evaluation of a predetermined depth circuit without necessitating any bootstrapping.

Performance Hurdles of Traditional Cryptographic Hash Functions in $\texttt{FHE}$ *Settings:* Presuming it takes hundreds of clock cycles for a modern processor to handle a single block cipher encryption, it takes millions of clock cycles to complete the same task under $\texttt{FHE}$. Since $\texttt{LiteQS.PKConstr}$ requires $\texttt{FHE}$ evaluations, we require FHE-friendly cryptographic primitives that suit the needs of $\texttt{LiteQS}$. The hash-based signatures usually rely on traditional hash functions H to realize both the message compression and one-way function $f(.)$. However, it was shown that ARX-based primitives like SHA-256 and BLAKE are not suitable for $\texttt{FHE}$ evaluations. For instance, SHA-256 requires 3311 $\texttt{FHE}$ levels, which is infeasible for many practical purposes [61]. Recent efforts have explored homomorphic evaluation of hash functions such as SHA256, SM3, etc., utilizing FHE schemes like TFHE [62] that enable rapid bootstrapping. However, they remain considerably distant from practical application, with execution times on the order of minutes [63], [64].

Mitigating Encrypted Evaluation Hurdles via Davies-Meyer as $\texttt{OWF}$*:* We made a key observation that $f(.)$ needs only $\texttt{OWF}$ property but not a full cryptographic hash function. This permits us to consider alternative hash designs that rely on symmetric ciphers that are suitable for $\texttt{FHE}$ evaluations. Consequently, we can leverage the best properties from both cryptographic realms.

The symmetric ciphers generally have lower multiplicative complexity (depth and size) compared to the traditional hash functions, with cheaper linear operations favoring more efficient $\texttt{FHE}$ evaluations. Moreover, when evaluated under encryption, they can serve as $\texttt{OWF}$ with proper instantiations. We have investigated various options and identified that a block cipher-based hash function named, Davies-Meyer (DM) [58], satisfies our efficiency and $\texttt{OWF}$ prerequisites for the encrypted evaluation purposes. Compared to other constructions, $\texttt{DM}$ structure is lighter than one-way double-block-length compression methods (e.g. Hirose [65]), and allows for key-setup and encryption parallelization as opposed to other single-block-length one-way compression functions.

Selection of Suitable Cipher for $\texttt{DM}$ *Instantiaton:* We decided that AES is a suitable choice for our $\texttt{DM}$ instantiation: (i) It is widely deployed with several optimized implementations. (ii) It has a low number of rounds with no integer operations. (iii) The AES circuit has an algebraic structure that is compliant with parallelism, packing techniques, and GPU optimizations [61]. (iv) Compared to other hash functions, the AES-based $\texttt{DM}$ has a smaller and fixed-size memory to store hash values iteratively. (v) Finally, homomorphic evaluation of AES has been well-studied and available in existing libraries (e.g., HElib [66]).

Optimizations: We introduce online-offline optimizations to permit an efficient signature verification. (i) The public key construction is independent of messages to be verified and can be executed for any ID_i and state information beforehand. Therefore, the verifier can run LiteQS.PKConstr with batch processes offline, and use these encrypted public keys to efficiently verify signatures online. As shown in Section VI, this offers tremendous performance gains for the online verification. (ii) Instead of generating full-set of t keys, the verifier can only construct k one-time public key components required for verification, thereby reducing the numbers of FHE evaluations. (iii) Recall that LiteQS.PKConstr does not take any private input and can be publicly executed by any entity. Therefore, optionally, the verifier can offload offline execution of LiteQS.PKConstr to a resourceful entity (e.g., cloud server). In exchange for a transmission delay, this approach can lift the major burden of FHE evaluations from the verifier, while enabling the resourceful entity to employ several parallelization and GPU-acceleration capabilities that are amenable to our LiteQS instantiations.

V. Security Analysis

We prove that LiteQS is EU-CMA secure as follows.

Theorem 1 *$Adv^{\text{EU-CMA}}_{\text{LiteQS}}(t, q_s) \leq q_s \cdot Adv^{\text{EU-CMA}}_{\text{HORS}}(t', q'_s)$, where $q'_s = q_s + 1$ and $\mathcal{O}(t') = \mathcal{O}(t) + q_s \cdot (k \cdot \texttt{PRF} + (t+2) \cdot \texttt{FHE.Eval}(\texttt{PRF}))$ (we omit terms negligible in terms of κ).*

Proof: Let $\mathcal{A}$ be the LiteQS attacker. We construct a simulator $\mathcal{F}$ that uses $\mathcal{A}$ as a subroutine to break one-time EU-CMA secure HORS, where $(\overline{sk}, \overline{PK}, I_{\text{HORS}}) \leftarrow \texttt{HORS.Kg}(1^\kappa)$ (Definition 1). $\mathcal{F}$ is given the challenge $\overline{PK}$, on which $\mathcal{A}$ aims to produce a forgery. $\mathcal{F}$ has access to the HORS signing oracle under secret key $\overline{sk}$. $\mathcal{F}$ maintains two lists $\mathcal{LM}$ and $\mathcal{LS}$ to record the queried messages and $\texttt{LiteQS.Sig}_{sk}(.)$ outputs. $\mathcal{F}$ randomly chooses a target forgery index[2] $w \in [1, q_s]$. $\mathcal{A}$ uses a user identity $ID_i \in \overrightarrow{ID}$, where $i \xleftarrow{\$} \{1, \ldots, N\}$.

Algorithm $\mathcal{F}$ $(\overline{PK}, I_{\text{HORS}})$

- *Setup:* $\mathcal{F}$ is run as in Definition 5:

(1) $msk \xleftarrow{\$} \{0,1\}^\kappa$.
(2) $I \leftarrow (I_{\text{HORS}}, I_{\text{FHE}}, I_{\text{DM}})$, where $(I_{\text{FHE}}, I_{\text{DM}})$ are as in Definition 2-3, respectively.
(3) $(sk', PK', I_{\text{FHE}}) \leftarrow \texttt{FHE.Kg}(1^\kappa)$.
(4) $MPK \leftarrow \texttt{FHE.Enc}(PK', msk)$; $PK = (PK', MPK)$.
(5) $sk_i^0 \leftarrow \texttt{PRF}(msk, ID_i)$.
(6) $sk = \{sk_i^j \leftarrow \texttt{PRF}(sk_i^0, j)\}_{j=1, j \neq w}^{q_s}$.
(7) $\{cv_i^j \leftarrow \texttt{LiteQS.PKConstr}(PK, ID_i, j)\}_{j=1, j \neq w}^{q_s}$.

Execute $\mathcal{A}^{\texttt{LiteQS.Sig}_{sk}(\cdot),\ \texttt{LiteQS.PKConstr}(\cdot),\ \texttt{HORS.Sig}_{\overline{sk}}(\cdot)}(PK, \overline{PK})$:

- *Queries:* $\mathcal{F}$ handles $\mathcal{A}$'s queries as follows:

(1) $\texttt{LiteQS.Sig}_{sk}(.)$: $\mathcal{F}$ returns $\sigma_i^w \leftarrow \texttt{HORS.Sig}_{\overline{sk}}(M_i^w)$ by querying HORS signing oracle, if $j = w$. Otherwise, $\mathcal{F}$ runs the steps (2-5) in LiteQS.Sig to compute σ_i^j under sk_i^j. $\mathcal{F}$ inserts M_i^j to $\mathcal{LM}$and (M_i^j, σ_i^j) to $\mathcal{LS}$as $\sigma_i^j \leftarrow \mathcal{LS}[M_i^j]$.

(2) $\texttt{LiteQS.PKConstr}(.)$ Queries: If $j = w$ then $\mathcal{F}$ returns $cv_i^w = \texttt{FHE.Enc}(PK', \overline{PK})$. Otherwise, $\mathcal{F}$ returns cv_i^j.

- *Forgery of $\mathcal{A}$:* $\mathcal{A}$ produces a forgery (M^*, σ^*) on PK. $\mathcal{A}$ wins the EU-CMA experiment if $1 \leftarrow \texttt{LiteQS.Ver}(PK, M^*, \sigma^*)$ and $M^* \notin \mathcal{LM}$ conditions hold, and returns 1, else returns 0.

- *Forgery of $\mathcal{F}$:* If $\mathcal{A}$ fails to win the EU-CMA experiment for LiteQS, $\mathcal{F}$ also fails to win the EU-CMA experiment for HORS. As a result, $\mathcal{F}$ *aborts* and returns 0. Otherwise, $\mathcal{F}$ checks if $1 \leftarrow \texttt{HORS.Ver}(\overline{PK}, M^*, \sigma^*)$ and M^* was not queried to the HORS signing oracle (i.e., $\texttt{HORS.Sig}_{\overline{sk}}(.)$). If these conditions hold, $\mathcal{F}$ wins the EU-CMA experiment against HORS and returns 1. Otherwise, $\mathcal{F}$ *aborts* and returns 0.

- *Success Probability Analysis:* We analyze the events that are needed for $\mathcal{F}$ to win the EU-CMA experiment as follows:

(1) $\mathcal{F}$ does not abort during $\mathcal{A}$'s queries with $Pr[\overline{Abort1}]$: $\mathcal{F}$ can answer all of $\mathcal{A}$'s signature queries, since it knows all private keys except $j = w$, for which it can retrieve the answer from HORS signature oracle. $\mathcal{F}$ sets $PK_i^w = \texttt{FHE.Enc}(PK', \overline{PK})$ and can answer all other queries by running the public key construction algorithm. The only exception occurs if $\texttt{FHE.Eval}(.)$ produces an incorrect PK_i^j during the simulation, which occurs with a negligible probability in terms of κ due to the correctness property of FHE. Therefore, we conclude $Pr[\overline{Abort\ 1}] \approx 1$.

(2) $\mathcal{A}$ produces a valid forgery with $Pr[Forge|\overline{Abort1}]$: If $\mathcal{F}$ does not abort during the queries, then $\mathcal{A}$ also does not abort, since its simulated view is computationally indistinguishable from the real view (see indistinguishability argument below). Hence, the probability that $\mathcal{A}$ produces a forgery against LiteQS is $Pr[Forge|\overline{Abort1}] = Adv^{\text{EU-CMA}}_{\text{LiteQS}}(q_s, t)$. There are three events that may also lead to $\mathcal{A}$'s forgery: (i) $\mathcal{A}$ breaks the subset-resiliency of H, whose probability is negligible in terms of κ [42]. (ii) $\mathcal{A}$ breaks IND-CPA secure FHE and recovers the master secret key msk, which permits a universal forgery. The probability that this happens is negligible in terms of κ for sufficiently large security parameters [56]. (iii) $\mathcal{A}$ breaks the evaluation of the comparison circuit for all k signatures (i.e., $b_i^{j,\ell} = 1, \forall \ell = 1, \ldots, k$), which occurs with a probability that is $\frac{1}{k} \times$ negligible in relation to κ. (iv) $\mathcal{A}$ inverts DM by breaking the underlying IND-CPA cipher, which also happens with negligible probability in terms of κ [58]. Therefore, they are omitted in the theorem statement.

(3) $\mathcal{F}$ does not abort after $\mathcal{A}$'s forgery with $Pr[\overline{Abort2}|\overline{Abort1} \wedge Forge]$: $\mathcal{F}$ does not abort if $\mathcal{A}$'s forgery is on the target public key PK_i^w. Since w is randomly selected from $[1, q_s]$, this occurs with $1/q_s$.

(4) $\mathcal{F}$ wins the EU-CMA experiment with $Adv^{\text{EU-CMA}}_{\text{HORS}}(t', q'_s)$: $Pr[Win] = Pr[\overline{Abort1}] \cdot Pr[Forge|\overline{Abort1}] \cdot Pr[\overline{Abort2} |\overline{Abort1} \wedge Forge]$. Therefore, $Pr[Win]$ is bounded as:

$$Adv^{\text{EU-CMA}}_{\text{LiteQS}}(t, q_s) \quad \leq \quad q_s \cdot Adv^{\text{EU-CMA}}_{\text{HORS}}(t', q'_s)$$

- *Execution Time Analysis:* The running time of $\mathcal{F}$ is that of $\mathcal{A}$ plus the time required to respond to q_s public key and signature queries. Each signature query demands H and $k \cdot$

[2] We follow SPHNICS+ [41] where the maximum number of signing queries is $2^{40} \leq q_s \leq 2^{60} \ll 2^\kappa$

$\texttt{PRF}(.)$; and each $\texttt{LiteQS.PKConstr}(.)$ query needs $(t+2)\cdot\texttt{FHE.Eval}(\texttt{PRF})$. The approximate running time of $\mathcal{F}$ is $\mathcal{O}(t') = \mathcal{O}(t) + q_s \cdot (k \cdot \texttt{PRF} + (t+2)\texttt{FHE.Eval}(\texttt{PRF}))$.

- *Indistinguishability Argument*: In the real view of $\mathcal{A}$ ($\mathcal{A}_{real}$), all values are computed from the master secret key and seeds as in the key generation, signing, and public key construction algorithms. The simulated view of $\mathcal{A}$ ($\mathcal{A}_{sim}$) is identical to $\mathcal{A}_{real}$, except PK_i^w is replaced with the challenge HORS public key. This implies that $(sk_i^w = \overline{sk}, PK_i^w = \overline{PK})$ holds. Since $\texttt{HORS.Kg}(.)$ generates the secret keys random uniformly (Definition 1), the joint probability distribution of (sk_i^w, PK_i^w) in $\mathcal{A}_{sim}$ is similar to that of $\mathcal{A}_{real}$. Therefore, $\mathcal{A}_{real}$ and $\mathcal{A}_{sim}$ are computationally indistinguishable. ■

Corollary 1 *The* LiteQS *scheme provides PQ promises.*

Proof: Based on our preceding formal security analysis and the incorporation of cryptographic primitives such as FHE, PRF, and hash functions, the LiteQS scheme ensures PQ assurances. Specifically, the PRF and hash functions, being symmetric cryptography primitives, remain unaffected by Shor's algorithm, while the impact of Grover's probabilistic algorithm can be mitigated by scaling up the sizes, considering the potential of quantum computers. Additionally, the FHE schemes, exemplified by our instantiation, the BGV scheme [56], are constructed upon lattice-based hard problems (e.g., General-LWE), which provide PQ security. ■

VI. Performance Analysis and Comparison

In this section, we give a detailed performance analysis of LiteQS and compare it with its counterparts.

A. Evaluation Metrics and Experimental Setup

Evaluation Metrics: Our analysis evaluates LiteQS and its analogous counterparts, with a main focus on the signer efficiency that includes: **(i)** private key and signature sizes which translates into small memory footprint and low memory access requirements. This not only reduces the energy consumption but also frees up more memory for main applications. It is particularly important for low-end IoT devices, which are characterized by limited memory space and relatively expensive memory access (e.g., 8-bit AVR microcontrollers). **(ii)** signing computational efficiency which translates into reduced energy consumption and longer battery lifetime for resource-limited devices. **(iii)** long-term security (i.e., PQ security) in order to offer resiliency against the quantum computing breaches (e.g., Shor's algorithm [17]).

Parameter Selection: Our system-wide parameters are $I = (I_{\texttt{HORS}}, I_{\texttt{FHE}}, I_{\texttt{DM}})$. We choose $I_{\texttt{HORS}} \leftarrow (k = 16, t = 1024)$, where SHA-256 and DM are used as H and f (i.e., OWF), respectively. In $I_{\texttt{DM}}$, we choose AES-128 as our PRF. In $I_{\texttt{FHE}}$, we set the plaintext space of mod 2, the lattice dimension $\phi(m) = 46080$, where the m-th cyclotomic is $m = 53261$. We utilize a packing technique that empowers us to evaluate 120 blocks of AES at once. We set $N = 2^{20}$ as the number of resource-constrained signers within the IoT network.

Hardware Configuration: We tested LiteQS on both commodity hardware and two selected embedded devices.
- *Commodity Hardware:* is a resourceful desktop equipped with an Intel i9-9900K@3.6GHz processor and 64GB of RAM.
- *Embedded device:* We evaluate LiteQS on an 8-bit ATxmega128A1 microcontroller to assess its efficiency on embedded IoT devices. The microcontroller features 128 KB flash memory, 2 KB RAM, 8 KB EEPROM, and operates at a 32 MHz clock frequency.

Software Configuration: For the commodity hardware, we utilized the following libraries (i) OpenSSL[3] to implement SHA-256 (ii) HElib[4] to implement FHE functionalities (*e.g.*, evaluation and comparison under encryption[5]). (iii) DM is implemented using the hardware-optimized AES-NI [69]. For the 8-bit AVR device, we employed the AVR cryptographic library[6] to implement AES-128. This library offers an optimized assembly implementation, resulting in mimimal cycles for evaluating hashing and PRF calls.

Selection Rationale of Counteparts: The selection of our counterparts is based on the discussed evaluation metrics and the availability of open-source implementation and/or open-access benchmarks. Numerous digital signatures have been proposed in the literature that address the resource limitations of IoT devices. Nevertheless, few schemes address low-end embedded devices, such as our target 8-bit AVR MCU. In order to cover different signatures with the knowingly existing post-quantum intractability assumptions, we carefully selected *(i) lattice-based*: the NIST PQC standards Dilithium-II [28] and Falcon-512 [30]. They are considered the most prominent lattice-based signatures, with balanced efficiency between key sizes and signing efficiency. We also selected BLISS-I because it is the only lattice-based signature with a benchmark on an 8-bit AVR MCU [70]. *(ii) hash-based*: generally suffer from an expensive signing cost with larger key sizes. We selected the NIST PQC standard SPHINCS+ [41], a stateless signature scheme. We also selected XMSS^{MT} [53] as a standard stateful hash-based signature with forward security. To our knowledge, there is no hash-based signature with a benchmark on 8-bit AVR MCUs. *(iii) multivariate-based*: are known to be computationally efficient in terms of signing and verification with small signature and public key sizes. However, they generally suffer from large private key sizes, resulting in high memory usage and frequent access. This limitation might be problematic when deployed on highly constrained 8-bit devices with 128KB of static flash memory. There exist numerous multivariate-based digital signatures that have been proposed (e.g., [71], [26]). We identified $\text{HiMQ-3}^{\text{Big}}$ [26] that achieve a high signing efficiency on an 8-bit AVR ATxmega384C3. However, we observed a high memory usage that includes

[3]https://github.com/openssl/openssl
[4]https://github.com/homenc/HElib
[5]https://github.com/iliailia/comparison-circuit-over-fq/tree/master
[6]https://github.com/cantora/avr-crypto-lib

TABLE I: Performance comparison of `LiteQS` and its counterparts on commodity hardware

Scheme	Signing Time (μs)	Private Key	Signature Size	Verification Time (μs)	Verifier Storage: Pub Key	Verifier Storage: Cert.	Verifier Storage: Tot. (2^{20} users) (GB)	Post-Quantum Promise	Sampling Operations	Simple Code Base
ECDSA [67]	16.98	0.06	0.06	46.41	0.09	0.06	0.16	×	×	×
Ed25519 [68]	16.39	0.06	0.06	39.75	0.09	0.06	0.16	×	×	×
BLISS-I [31]	244.97	2.00	5.6	25.21	7.00	5.6	12.6	✓	✓	×
Dilithium-II [28]	93.76	2.29	2.36	18.73	1.28	2.36	3.75	✓	✓	×
Falcon-512 [30]	184.74	1.29	0.65	32.16	0.88	0.65	1.53	✓	✓	×
SPHINCS+ [41]	$5,441.58$	0.13	32.63	549.63	0.06	32.63	32.69	✓	×	×
XMSS^{MT}[53]	$10,682.35$	3.11	2.61	$2,098.84$	0.75	2.61	3.36	✓	×	×
LiteQSign	**4.81**	**0.02**	**0.25**	**Ver (Online)** $\mathbf{1.91}$ ***s***; **PKConstr (Offline)** $\mathbf{41.22}$ ***s***	**9.42 MB**			✓	×	✓

The private/public key, signature, and certificate sizes are in KB. `LiteQS` and NIST PQC candidates use architecture-specific optimizations (i.e., AESNI, AVX2 instructions). For XMSS^{MT}, we choose the XMSST_MT_SHA2_20_256 variant. For SPHINCS+, we set $n = 256, h = 63, d = 9, b = 12, k = 29, w = 16$. The total verifier storage denotes the storage required to verify ($J = 2^{30}$) signatures for ($N = 2^{20}$) signers.

the private key size and code size, occupying 72.38% of the flash read-only memory of our target ATxmega128A1. Therefore, we omit it from our performance analysis due to the high memory usage. *(iv) conventional signatures*: We also considered non-PQ signature schemes. Although they do not achieve long-term security, ECC-based signature schemes are signer-efficient with small key sizes. We selected the mostly-used standards, ECDSA [67] and Ed25519 [68]. Other conventional (e.g., pairing-based [72]) digital signatures incur expensive operations during signature generation, therefore not practical for resource-limited IoT devices.

B. Performance on Signer

Performance comparisons on commodity hardware and the embedded device are shown in Tables I and II, respectively.

• *Memory Usage:* `LiteQS` achieves the lowest memory usage by having the smallest private key size among its counterparts. For example, the private key of `LiteQS` is 3× and 114× smaller than that of the conventional signer-efficient Ed25519 and PQ-secure Dilithium standards, respectively. The private key is 22× smaller than that of the most efficient lattice-based counterpart, BLISS-I [31], respectively. It is without incurring large code size and expensive costly sampling operations that may result in side-channel attacks [33]. Notably, `LiteQS` consumes less memory than its most signer-efficient and PQ-secure counterpart, HiMQ-3^{Big} [26], by having a significantly smaller private key size. The cryptographic storage (including the code size) of HiMQ-3^{Big} utilizes 72.38% of the overall flash memory size of an 8-bit AVR ATxmega128A1, whereas `LiteQS` utilizes only 2.8%. We argue that the cryptographic data should occupy minimal space, particularly in resource-limited devices (e.g., pacemakers, medical implants). Indeed, the embedded devices generate system-related (e.g., log files) and application-related (e.g., sensory information) data, which may cause memory overflow, considering the high memory cryptographic usage. It is noteworthy that we do not assess the impact of memory access on the battery lifetime of the embedded device. We foresee a high energy usage of multivariate-based signatures compared to that of `LiteQS`, considering the high cost of both memory and stack usage.

• *Bandwidth Overhead:* `LiteQS` boasts a compact signature size that is 9.4× and 2.6× smaller than the NIST PQC standards, Dilithium-II and Falcon-512, respectively. The signature size of `LiteQS` is also 22× smaller than that of the most-efficient lattice-based BLISS-I. A small signature size results in low transmission overhead, thereby minimizing energy consumption on resource-constrained IoT devices. This reduced energy expenditure is crucial for extending the operational lifespan of devices that often operate on limited power sources.

• *Signature Generation:* Table I demonstrates that among our counterparts (i.e., conventional-secure and post-quantum), `LiteQS` exhibits the fastest signing time and the lowest signer storage overhead. It is 10× and 43× faster than the NIST PQC standards, Dilithium-II and Falcon-512, respectively. The computational performance advantages at the signer of `LiteQS` become even more apparent on embedded devices. Based on 8-bit AVR MCU results in Table II, the signing time of `LiteQS` is 20× and 44× faster than the most efficient PQ-secure BLISS-I and conventional-secure Ed25519, respectively.

• *Energy Consumption:* The high signing efficiency translates into better energy awareness on low-end IoT devices. To demonstrate the potential of `LiteQS`, in Figure 2, we profiled the battery depletion with respect to the signing operations. Specifically, we plot the battery status while solely performing signature generation operations on the 8-bit ATxmega128A1 MCU. Remind that, to the best of our knowledge, none of the selected NIST PQC signatures have an open-source implementation available on such resource-limited devices (i.e., 8-bit microcontrollers). The most prominent PQ alternatives with a reported performance on this platform are HiMQ-3^{big} [26] and BLISS-I [31]. We also included the most efficient ECC-based alternative Ed25519 and the widely-used ECDSA in our energy comparison to assess `LiteQS` performance with respect to (pre-quantum) conventional schemes. Figure 2 showcases that `LiteQS` offer the longest battery lifetime when only the cryptographic computation is considered. Hence, we confirm that `LiteQS` is the most suitable signature scheme for highly resource-constrained IoT devices.

We note that BLISS-I is vulnerable to side-channel attacks, which hinders its use in practice. Side-channel attack resiliency and ease of implementation are important factors for the prac-

TABLE II: Performance comparison of `LiteQS` and its counterparts at the signer side on 8-bit AVR AtMega2560 MCU

Scheme	Signing (cycles)	Secret Key (KB)	Signature Size (KB)	Post-Quantum Promise	Rejection Sampling	Ease of Implementation
ECDSA [67]	$34,903,000$	0.06	0.06	×	×	×
Ed25519 [68]	$22,688,583$	0.06	0.06	×	×	×
BLISS-I [31]	$10,537,981$	2	5.6	✓	✓	×
LiteQSign	**514,788**	**0.02**	**0.25**	✓	×	✓

The counterpart selection covers existent the most efficient conventional (ECDSA, Ed25519) and PQ-secure (BLISS) with an available benchmark on the selected 8-bit AVR MCU.

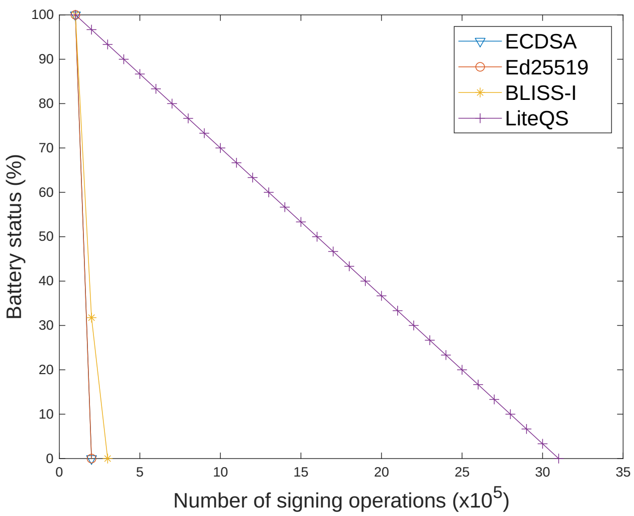


Fig. 2: Impact of signing on battery lifetime for AVR ATxmega128A1

tical deployment of signature schemes on embedded devices. Lattice-based signatures require various types of sampling operations (e.g., Gaussian, rejection samplings) that make them vulnerable to side-channel attacks [32]. Moreover, due to their complexity, they are notoriously difficult to implement on such platforms. As an example, Falcon needs 53 bits of precision to implement without emulation [73], which hinders its deployment on 8-bit microcontrollers. `LiteQS` signature generation requires only a few `PRF` calls. Hence, it is free from the aforementioned specialized side-channel and timing attacks that target sampling operations. Moreover, it is easy to implement since it only requires a suitable symmetric cipher (e.g., AES) and a cryptographic hash function (e.g., SHA256) with a minimal code size. Our analysis validates that `LiteQS` is the most suitable alternative among its counterparts to be deployed for signing on IoT applications due to its high computational efficiency, compact key and signature sizes, and high security.

C. Performance on Verifier

While `LiteQS` is a signer-optimal scheme, we also introduced strategies to minimize the verifier computational and storage overhead. As explained in Section IV-A, the verifiers can generate public keys in offline mode (before signature verification), thereby improving the efficiency of online verification. Moreover, the verifiers have the option to outsource offline public key construction to a resourceful entity.

Online Verification: The online verification cost is comprised of $k \times$ PRF(.), $k \times$ FHE.Enc(.), and $k \times$ FHE.Eval(.) of the comparison circuit. According to our implementation parameters, this is estimated to be approximately 1.913 seconds. Also, for further cost reduction, we strongly recommend an offline generation of public keys whenever possible.

Offline Public Key Construction: The main computational bottleneck of `LiteQS` is the offline phase. In our tests, the average cost of a single homomorphic AES evaluation per block is 2.29 seconds. Hence, the overall cost of generating k public key components is 41.22 seconds. We note that the offline computational overhead can be significantly reduced with parallelizations. For example, since each component of the `HORS` public key can be generated independently, they can be assigned to different threads or computing units. Moreover, as discussed in Section IV-A, encrypted AES evaluations via BGV are highly parallelizable, which is one of our reasons to opt for AES as our `DM` building block.

Verifier Storage Overhead: The total size of the master public key PK with the expansion per block evaluation is around 9.42 MB. If only a single signer is considered, the size of PK is much larger than that of its counterparts. However, `LiteQS` enables a verifier to construct public keys for *any valid* signer ID_i of any state. This unique property permits `LiteQS` to achieve compact storage for a large number of signers since the verifier does not need to store a certificate for their public keys. For example, the total storage (public key plus certificate) for 2^{20} users is still 9.42 MB for `LiteQS`, while it is around 1.52 GB and 3.74 GB for Falcon-512 and Dilithium-II, respectively. The total storage advantage increases with a growing number of signers.

VII. Conclusion

Given the widespread deployment of IoT devices in major real-world applications coupled with their imposed security concerns, we introduced *LiteQSign* (`LiteQS`), a lightweight PQ signature scheme tailored for resource-constrained IoT-enabled applications. By leveraging `FHE`, `LiteQS` allows verifiers to generate one-time public keys independently, removing the need for signer interaction or third-party trust. It is the first HORS-based scheme to support unbounded signing with minimal architectural overhead. Our results demonstrate that `LiteQS` surpasses NIST PQC standards with lower computational cost, reduced memory footprint, and efficient signing. Unlike existing solutions, it operates without trusted servers or secure enclaves, mitigating security risks while prolonging device battery life. Formal security proofs and experimental evaluations confirm that `LiteQS` delivers faster signing with smaller key and signature sizes, making it a practical and scalable authentication solution for IoT networks.

VIII. Acknowledgment

This work is supported by Cisco Research Award (220159) and National Science Foundation CAREER Award CNS (1917627).

References

[1] A. Ahad, M. Tahir, M. Aman Sheikh, K. I. Ahmed, A. Mughees, and A. Numani, "Technologies trend towards 5G network for smart healthcare using iot: A review," *Sensors*, vol. 20, no. 14, p. 4047, 2020.

[2] M. Pradhan and J. Noll, "Security, privacy, and dependability evaluation in verification and validation life cycles for military iot systems," *IEEE Communications Magazine*, vol. 58, no. 8, pp. 14–20, 2020.

[3] R. Behnia and A. A. Yavuz, "Towards practical post-quantum signatures for resource-limited internet of things," in *Annual Computer Security Applications Conference*, 2021, pp. 119–130.

[4] C. Camara, P. Peris-Lopez, J. M. De Fuentes, and S. Marchal, "Access control for implantable medical devices," *IEEE Transactions on Emerging Topics in Computing*, vol. 9, no. 3, pp. 1126–1138, 2020.

[5] D. C. Nguyen, M. Ding, P. N. Pathirana, A. Seneviratne, J. Li, D. Niyato, O. Dobre, and H. V. Poor, "6G internet of things: A comprehensive survey," *IEEE Internet of Things Journal*, 2021.

[6] Y.-H. Joung, "Development of implantable medical devices: from an engineering perspective," *International neurourology journal*, vol. 17, no. 3, p. 98, 2013.

[7] J. Sametinger, J. Rozenblit, R. Lysecky, and P. Ott, "Security challenges for medical devices," *Communications of the ACM*, vol. 58, no. 4, pp. 74–82, 2015.

[8] A. Mudgerikar and E. Bertino, "Iot attacks and malware," *Cyber Security Meets Machine Learning*, pp. 1–25, 2021.

[9] S. E. Nouma, , and A. A. Yavuz, "Post-quantum forward-secure signatures with hardware-support for internet of things," ser. IEEE International Conference on Communications (ICC). IEEE, 2023.

[10] S. Darzi, B. Akhbari, and H. Khodaiemehr, "Lpm2da: a lattice-based privacy-preserving multi-functional and multi-dimensional data aggregation scheme for smart grid," *Cluster Computing*, vol. 25, no. 1, pp. 263–278, 2022.

[11] A. Goudarzi, F. Ghayoor, M. Waseem, S. Fahad, and I. Traore, "A survey on iot-enabled smart grids: emerging, applications, challenges, and outlook," *Energies*, vol. 15, no. 19, p. 6984, 2022.

[12] P. B. Adamson, "Pathophysiology of the transition from chronic compensated and acute decompensated heart failure: new insights from continuous monitoring devices," *Current heart failure reports*, vol. 6, no. 4, pp. 287–292, 2009.

[13] M. R. Zile, T. D. Bennett, M. St. John Sutton, Y. K. Cho, P. B. Adamson, M. F. Aaron, J. M. Aranda Jr, W. T. Abraham, F. W. Smart, L. W. Stevenson *et al.*, "Transition from chronic compensated to acute decompensated heart failure: pathophysiological insights obtained from continuous monitoring of intracardiac pressures," *Circulation*, vol. 118, no. 14, pp. 1433–1441, 2008.

[14] A. Vangala, A. K. Das, V. Chamola, V. Korotaev, and J. J. Rodrigues, "Security in iot-enabled smart agriculture: Architecture, security solutions and challenges," *Cluster Computing*, vol. 26, no. 2, pp. 879–902, 2023.

[15] M. R. Rieback and B. Crispo, "Rfid guardian: A battery-powered mobile device for rfid privacy management," in *Australasian Conference on Information Security and Privacy*. Springer, 2005, pp. 184–194.

[16] H. Zhang, M. Babar, M. U. Tariq, M. A. Jan, V. G. Menon, and X. Li, "Safecity: Toward safe and secured data management design for iot-enabled smart city planning," *IEEE Access*, pp. 145 256–145 267, 2020.

[17] P. W. Shor, "Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer," *SIAM review*, vol. 41, no. 2, pp. 303–332, 1999.

[18] J.-P. Aumasson, "The impact of quantum computing on cryptography," *Computer Fraud & Security*, vol. 2017, no. 6, pp. 8–11, 2017.

[19] S. Darzi, K. Ahmadi, S. Aghapour, A. A. Yavuz, and M. M. Kermani, "Envisioning the future of cyber security in post-quantum era: A survey on pq standardization, applications, challenges and opportunities," *arXiv preprint arXiv:2310.12037*, 2023.

[20] C. Cheng, R. Lu, A. Petzoldt, and T. Takagi, "Securing the internet of things in a quantum world," *IEEE Communications Magazine*, vol. 55, no. 2, pp. 116–120, 2017.

[21] M. Adeli, N. Bagheri, H. R. Maimani, S. Kumari, and J. J. Rodrigues, "A post-quantum compliant authentication scheme for iot healthcare systems," *IEEE Internet of Things Journal*, 2023.

[22] S. E. Nouma and A. A. Yavuz, "Trustworthy and efficient digital twins in post-quantum era with hybrid hardware-assisted signatures," *ACM Transactions on Multimedia Computing, Communications and Applications*, vol. 20, no. 6, pp. 1–30, 2024.

[23] C. Camara, P. Peris-Lopez, and J. E. Tapiador, "Security and privacy issues in implantable medical devices: A comprehensive survey," *Journal of biomedical informatics*, vol. 55, pp. 272–289, 2015.

[24] A. L. Martínez, M. G. Pérez, and A. Ruiz-Martínez, "A comprehensive model for securing sensitive patient data in a clinical scenario," *IEEE Access*, vol. 11, pp. 137 083–137 098, 2023.

[25] S. E. Nouma and A. A. Yavuz, "Practical cryptographic forensic tools for lightweight internet of things and cold storage systems," in *Proceedings of the 8th ACM/IEEE Conference on Internet of Things Design and Implementation*, 2023, pp. 340–353.

[26] K.-A. Shim, C.-M. Park, N. Koo, and H. Seo, "A high-speed public-key signature scheme for 8-b iot-constrained devices," *IEEE Internet of Things Journal*, vol. 7, no. 4, pp. 3663–3677, 2020.

[27] C. Costello and P. Longa, "SchnorrQ: Schnorr signatures on fourQ," *MSR Tech Report, 2016*, 2016.

[28] L. Ducas, E. Kiltz, T. Lepoint, V. Lyubashevsky, P. Schwabe, G. Seiler, and D. Stehlé, "Crystals-dilithium: A lattice-based digital signature scheme," *IACR Transactions on Cryptographic Hardware and Embedded Systems*, pp. 238–268, 2018.

[29] A. Sehgal, V. Perelman, S. Kuryla, and J. Schonwalder, "Management of resource constrained devices in the internet of things," *IEEE Communications Magazine*, vol. 50, no. 12, pp. 144–149, 2012.

[30] P.-A. Fouque, J. Hoffstein, P. Kirchner, V. Lyubashevsky, T. Pornin, T. Prest, T. Ricosset, G. Seiler, W. Whyte, and Z. Zhang, "Falcon: Fast-fourier lattice-based compact signatures over NTRU," *Submission to the NIST's post-quantum cryptography standardization process*, 2018.

[31] L. Ducas, A. Durmus, T. Lepoint, and V. Lyubashevsky, "Lattice signatures and bimodal gaussians," in *Cryptology Conf.*, 2013.

[32] E. Karabulut and A. Aysu, "Falcon down: Breaking falcon post-quantum signature scheme through side-channel attacks," in *2021 58th ACM/IEEE Design Automation Conference (DAC)*, 2021, pp. 691–696.

[33] M. Tibouchi and A. Wallet, "One bit is all it takes: a devastating timing attack on BLISS's non-constant time sign flips," *Journal of Mathematical Cryptology*, vol. 15, no. 1, pp. 131–142, 2021.

[34] T. Pornin, "Deterministic Usage of the Digital Signature Algorithm (DSA) and Elliptic Curve Digital Signature Algorithm (ECDSA)," RFC 6979, Aug. 2013.

[35] A. A. Yavuz and M. O. Ozmen, "Ultra lightweight multiple-time digital signature for the internet of things devices," *IEEE Transactions on Services Computing*, no. 1, pp. 215–227, 2019.

[36] G. K. Verma, B. Singh, N. Kumar, and V. Chamola, "Cb-cas: Certificate-based efficient signature scheme with compact aggregation for industrial internet of things environment," *IEEE Internet of Things Journal*, vol. 7, no. 4, pp. 2563–2572, 2019.

[37] X. Chen, D. He, M. K. Khan, M. Luo, and C. Peng, "A secure certificateless signcryption scheme without pairing for internet of medical things," *IEEE Internet of Things Journal*, vol. 10, pp. 9136–9147, 2022.

[38] H. Liu, D. Han, M. Cui, K.-C. Li, A. Souri, and M. Shojafar, "Idenmultisig: Identity-based decentralized multi-signature in internet of things," *IEEE Transactions on Computational Social Systems*, 2023.

[39] G. Zhang, Y. Liao, Y. Fan, and Y. Liang, "Security analysis of an identity-based signature from factorization problem," *IEEE Access*, vol. 8, pp. 23 277–23 283, 2020.

[40] NIST, "Post-Quantum Cryptography Standardization," https://csrc.nist.gov/Projects/post-quantum-cryptography/post-quantum-cryptography-standardization, accessed: May 23, 2024.

[41] D. J. Bernstein, A. Hülsing, S. Kölbl, R. Niederhagen, J. Rijneveld, and P. Schwabe, "The SPHINCS+ signature framework," in *Proceedings of the 2019 ACM SIGSAC conference on computer and communications security*, 2019, pp. 2129–2146.

[42] L. Reyzin and N. Reyzin, "Better than BiBa: Short one-time signatures with fast signing and verifying," in *Australasian Conference on Information Security and Privacy*, 2002, pp. 144–153.

[43] A. Hülsing, L. Rausch, and J. Buchmann, "Optimal parameters for XMSS MT," in *International conference on availability, reliability, and security*, 2013, pp. 194–208.

[44] D. McGrew, M. Curcio, and S. Fluhrer, "Leighton-Micali Hash-Based Signatures," RFC 8554, Apr. 2019.

[45] R. C. Merkle, "A certified digital signature," in *Conference on the Theory and Application of Cryptology*. Springer, 1989, pp. 218–238.

[46] A. A. Yavuz, K. Sedghighadikolaei, S. Darzi, and S. E. Nouma, "Beyond basic trust: Envisioning the future of nextgen networked systems and digital signatures," in *2023 5th IEEE International Conference on Trust, Privacy and Security in Intelligent Systems and Applications (TPS-ISA)*. IEEE Computer Society, 2023, pp. 267–276.

[47] M. Baldi, S. Bitzer, A. Pavoni, P. Santini, A. Wachter-Zeh, and V. Weger, "Zero knowledge protocols and signatures from the restricted syndrome decoding problem," in *IACR International Conference on Public-Key Cryptography*. Springer, 2024, pp. 243–274.

[48] W. Beullens, "Mayo: practical post-quantum signatures from oil-and-vinegar maps," in *International Conference on Selected Areas in Cryptography*. Springer, 2021, pp. 355–376.

[49] S. Kim, J. Ha, M. Son, B. Lee, D. Moon, J. Lee, S. Lee, J. Kwon, J. Cho, H. Yoon *et al.*, "Aim: symmetric primitive for shorter signatures with stronger security," in *Proceedings of the 2023 ACM SIGSAC Conference on Computer and Communications Security*, 2023, pp. 401–415.

[50] Y. Hashimoto, T. Takagi, and K. Sakurai, "General fault attacks on multivariate public key cryptosystems," in *Post-Quantum Cryptography: 4th International Workshop, PQCrypto 2011, Taipei, Taiwan, November 29–December 2, 2011. Proceedings 4*. Springer, 2011, pp. 1–18.

[51] W. Ouyang, Q. Wang, W. Wang, J. Lin, and Y. He, "Scb: Flexible and efficient asymmetric computations utilizing symmetric cryptosystems implemented with intel sgx," in *2021 IEEE International Performance, Computing, and Communications Conference (IPCCC)*. IEEE, 2021.

[52] K. Sedghighadikolaei and A. A. Yavuz, "A comprehensive survey of threshold digital signatures: Nist standards, post-quantum cryptography, exotic techniques, and real-world applications," *arXiv preprint arXiv:2311.05514*, 2023.

[53] A. Hülsing, L. Rausch, and J. Buchmann, "Optimal parameters for XMSSˆ MT," *Cryptology ePrint Archive, Paper 2017/966*, 2017.

[54] A. A. Yavuz, "Eta: efficient and tiny and authentication for heterogeneous wireless systems," in *Proceedings of the sixth ACM conference on Security and privacy in wireless and mobile networks*, 2013, pp. 67–72.

[55] F. Armknecht, C. Boyd, C. Carr, K. Gjøsteen, A. Jäschke, and Reuter, "A guide to fully homomorphic encryption," *Cryptology Archive*, 2015.

[56] Z. Brakerski, C. Gentry, and V. Vaikuntanathan, "(leveled) fully homomorphic encryption without bootstrapping," *ACM Transactions on Computation Theory (TOCT)*, vol. 6, no. 3, pp. 1–36, 2014.

[57] Y. Yu and X. Xie, "Privacy-preserving computation in the post-quantum era," *National Science Review*, vol. 8, no. 9, 07 2021, nwab115.

[58] B. Preneel, "Davies-meyer hash function," in *Encyclopedia of Cryptography and Security*, 2005, pp. 136–136.

[59] F. Guo, W. Susilo, Y. Mu, F. Guo, and W. Susilo, "Notions, definitions, and models," *Introduction to Security Reduction*, pp. 5–12, 2018.

[60] S. Darzi, A. A. Yavuz, and R. Behnia, "Post-quantum security for trustworthy artificial intelligence: An emerging frontier," 2024.

[61] S. Mella and R. Susella, "On the homomorphic computation of symmetric cryptographic primitives," in *Proceedings of the 14th IMA International Conference on Cryptography and Coding - Volume 8308*, ser. IMACC 2013. Berlin, Heidelberg: Springer-Verlag, 2013, p. 28–44.

[62] I. Chillotti, N. Gama, M. Georgieva, and M. Izabachène, "Tfhe: fast fully homomorphic encryption over the torus," *Journal of Cryptology*, vol. 33, no. 1, pp. 34–91, 2020.

[63] A. A. Bendoukha, O. Stan, R. Sirdey, N. Quero, and L. Freitas, "Practical homomorphic evaluation of block-cipher-based hash functions with applications," in *International Symposium on Foundations and Practice of Security*. Springer, 2022, pp. 88–103.

[64] B. Wei, R. Wang, Z. Li, Q. Liu, and X. Lu, "Fregata: Faster homomorphic evaluation of aes via tfhe," in *International Conference on Information Security*. Springer, 2023, pp. 392–412.

[65] S. Hirose, "Some plausible constructions of double-block-length hash functions," in *Fast Software Encryption*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2006, pp. 210–225.

[66] S. Halevi and V. Shoup, "Design and implementation of HElib: a homomorphic encryption library," *Cryptology Archive*, 2020.

[67] D. Johnson, A. Menezes, and S. Vanstone, "The elliptic curve digital signature algorithm (ECDSA)," *International journal of information security*, vol. 1, no. 1, pp. 36–63, 2001.

[68] D. J. Bernstein, N. Duif, T. Lange, P. Schwabe, and B.-Y. Yang, "High-speed high-security signatures," *Journal of cryptographic engineering*, vol. 2, no. 2, pp. 77–89, 2012.

[69] G. Hofemeier and R. Chesebrough, "Introduction to intel aes-ni and intel secure key instructions," *Intel, White Paper*, vol. 62, 2012.

[70] T. Pöppelmann, T. Oder, and T. Güneysu, "High-performance ideal lattice-based cryptography on 8-bit atxmega microcontrollers," in *International conference on cryptology and information security in Latin America*. Springer, 2015, pp. 346–365.

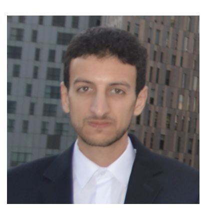
[71] Q. Li, D. He, Y. Chen, J. Wen, and Z. Yang, "An efficient quantum-resistant undeniable signature protocol for the e-voting system," *Journal of Information Security and Applications*, vol. 81, p. 103714, 2024.

[72] D. Boneh, B. Lynn, and H. Shacham, "Short signatures from the weil pairing," in *International conference on the theory and application of cryptology and information security*. Springer, 2001, pp. 514–532.

[73] J. Howe and B. Westerbaan, "Benchmarking and Analysing the NIST PQC Finalist Lattice-Based Signature Schemes on the ARM Cortex M7, Paper 2022/405," *Cryptology ePrint Archive*, 2022.

Dr. Attila Altay Yavuz is an Associate Professor in the Department of Computer Science and Engineering, and the Director of Applied Cryptography Research Laboratory at the University of South Florida (USF). He was an Assistant Professor in the School of Electrical Engineering and Computer Science, Oregon State University (2014-2018) and in the Department of Computer Science and Engineering, USF (2018-June 2021). He was a member of the security and privacy research group at the Robert Bosch Research and Technology Center North America (2011-2014). He received his Ph.D. degree in Computer Science from North Carolina State University (2011). He received his MS degree in Computer Science from Bogazici University (2006) in Istanbul, Turkey. He is broadly interested in the design, analysis, and application of cryptographic tools and protocols to enhance the security of computer systems. Attila Altay Yavuz is a recipient of the NSF CAREER Award, Cisco Research Award (thrice - 2019,2020,2022), unrestricted research gifts from Robert Bosch (five times), USF Faculty Outstanding Research Achievement Award, USF Excellence in Innovation Award, and USF College of Engineering's Outstanding Research Achievement Award. His research on privacy-enhancing technologies and intra-vehicular network security is in the process of technology transfer with potential worldwide deployments. He has authored more than 95 products including research articles in top conferences, journals, and patents. He is a senior member of IEEE.

Saleh Darzi is a Ph.D. Candidate in Computer Science and Engineering Department, actively engaged in research within the Applied Cryptography Research Laboratory (ACRL) under the supervision of Dr. Attila Yavuz at the University of South Florida. His primary research pursuits revolve around post-quantum and applied cryptography, with a focus on addressing challenges in the privacy and security of IoT, Blockchain technology, and network security. Saleh holds a Master of Science degree in Electrical Engineering (Communication-System) from K. N. Toosi University of Technology, Tehran, Iran, obtained in 2021.



Saif Eddine Nouma received his bachelor's degree from Ecole Polytechnique de Tunisie, Tunisia. He is currently pursuing a Ph.D. degree in the Department of Computer Science and Engineering, University of South Florida. His research interests include lightweight cryptography for Internet of Things, digital twins, and post-quantum cryptography.