LVPDA: A Lightweight and Verifiable Privacy-Preserving Data Aggregation Scheme for Edge-Enabled IoT

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Abstract—Edge computing is envisioned to be a powerful platform that provides efficient data storage and computation services in smart IoT systems. In this data-intensive architecture, protecting user-side data privacy is one of the most critical concerns to prevent privacy leakage from any other untrusted entities. Aiming to resist this concern, lots of privacy-preserving data aggregation (PPDA) schemes have been proposed for various cloud-enabled IoT applications. However, due to the resource-constraint nature of smart IoT devices, the conventional PPDA solutions, in terms of both privacy and performance requirements, are unsuitable in edge computing. To address this challenge, we propose a lightweight and verifiable privacy-preserving data aggregation scheme, named LVPDA, for the edge computing enabled IoT system, where the Paillier homomorphic encryption method and online/offline signature technique are combined to ensure the privacy-preserving and integrity verification during the data aggregation process. Detailed security analysis indicates that LVPDA is existentially unforgeable under the chosen message attack (EU-CMA) and the data integrity can be guaranteed with formal proof under $\eta$-Strong Diffie-Hellman ($\eta$-SDH) assumptions. Compared with other PPDA methods, our scheme can achieve lightweight privacy-preserving data aggregation in terms of less computational complexity and communication overhead.

Index Terms—Edge computing, Privacy-preserving, Data aggregation, Paillier cryptosystem, Online/offline signature.

I. INTRODUCTION

With the widely deployed Internet of Things (IoT) infrastructures, the IoT technologies have shown great potential in smart services like smart grid [1, 2], smart healthcare [3, 4], smart city [5, 6], and vehicular sensing system [7]. However, the conventional cloud-based data processing paradigm [8] could hardly meet the requirements of these smart services, especially those serving in the real time manner, due to the bandwidth limitation and computation resources constraint [9] in the edge. To realize these envisions, the computation paradigm of IoT is developing in the track of edge computing [10], rather than traditional cloud computing, for supporting the real-time processing of the big sensing data generated by IoT devices. As shown in Fig. 1, the sensing data are gathered by the smart IoT devices and forwarded to the edge server for the local processing, such as aggregation, sharing, and mining. Then, the locally processed data are sent to the remote cloud center for further processing and analysis, providing various data services for IoT applications. Here, the edge server can be seen as a preliminary processing unit to provide efficient local services through the combination of the cloud server [11]. In this way, the resources of computation and communication can be significantly reduced, overcoming the bottleneck of conventional cloud-based architecture.

Although the edge computing IoT system is beneficial for big data analysis, potential security and privacy risks are still present since the distributed nature of edge computing also enhances the activity of internal and external attackers [12]. Firstly, these additional edge nodes are not fully trusted, which might leak users’ private data and thus destroy the privacy, accuracy, and robustness of the data aggregation protocol [13]. For example, in edge-cloud and smart grid systems [14], customers frequently transmit their sensitive data, e.g., electricity usage information, to the central server in order to benefit from centralized services, while these data usually contain users’ privacy information [15]. Moreover, the external attackers could also eavesdrop on the communication channel among the involved entities, so as to modify the in-network messages, forge the signatures, or even launch a replay attack to compromise the normal data transmission procedure.

To solve this privacy issue, lots of privacy-preserving data aggregation (PPDA) schemes have been proposed to prevent privacy leakage from the untrusted entities [16–22]. Most of them are using the homomorphic cryptosystem to realize specific functions, such as Min, Max, and Sum, which can...
guarantee data confidentiality and further preserve privacy. Li et al. [16] present the first data aggregation scheme for smart grid systems by using a homomorphic cryptosystem. Following this work, many embedded functionalities were explored to enhance the security and availability of PPDA, such as the high-dimensional reduction [17], key evolution technique [18], resisting internal attackers [19], data integrity verification [20], random noisy technique [21] and so on.

However, the aforementioned PPDA schemes are facing several practical challenges. Firstly, frequent data transmission requirements are crucial to edge computing IoT systems. It is impractical to tolerate high communication delay when executing real-time data processing tasks. Secondly, data source authentication and verification are necessary to prevent the attackers from forging, modifying, and replaying the messages and signatures. At last, the huge computation requirements of the authentication and verification operations greatly hinder their realization in the resource-constraint IoT devices. Therefore, it is highly desirable to design a novel PPDA scheme that can reduce the computational overheads on mobile devices while still fulfilling the data privacy requirements.

In this paper, to address the above challenges, we propose LVPDA: a Lightweight and Verifiable Privacy-preserving Data Aggregation scheme for edge computing enabled smart IoT systems, which simultaneously supports the data source authentication and lightweight verification. In LVPDA, the heavy computation cost of data integrity operations can be significantly reduced by an online/offline signature mechanism, hence is more suitable for the resource-constraint smart IoT devices. The main contributions of this paper are summarized as follows:

- We adopt the edge computing enabled IoT architecture to improve the computational efficiency of data aggregation and meanwhile present the corresponding PPDA framework.
- We further propose a novel lightweight and verifiable PPDA scheme based on the designed edge-enabled IoT system, called LVPDA, where the time-consuming operations are securely outsourced to the edge servers, so as to reduce the computing burden of the smart IoT devices.
- We give the detailed security analysis to show how our proposed LVPDA scheme can achieve data integrity, authentication, confidentiality and privacy-preserving under our defined security model.
- We conduct the exhaustive experiments of LVPDA and the results indicate that the computation and communication overheads are significantly reduced.

The remainder of this paper is going to be structured in the following way. We summarize the related work in Section II and introduce the preliminaries in Section III. The system model and design goals are introduced in Section IV. The description of our proposed LVPDA is detailed in Section V. Security and performance analysis of the proposed scheme are demonstrated in Section VI and Section VII, respectively. Finally, we conclude the paper in Section VIII.
A. Bilinear Pairing Setting

We assume that \( G \) and \( G_T \) are two multiplicative cyclic groups with the prime order \( p \), and \( g \) is a generator of group \( G \). Consider a non-degenerated and efficiently computable bilinear map \( e : G \times G \rightarrow G_T \) satisfies the following properties [28]:

- **Bilinear**: For all \( u, v \in G \) and \( a, b \in \mathbb{Z}_p^* \), we have \( e(u^a, v^b) = e(u, v)^{ab} \).
- **Non-degenerate**: The generator \( g \) of group \( G \) should satisfy \( e(g, g) \neq 1_{G_T} \).
- **Computable**: For any \( u, v \in G \), there exists an efficient algorithm to compute \( e(u, v) \).

To prove the security of LVPDA, we recall the following complexity problems:

**Definition 1.** (\( q \)-Strong Diffie-Hellman Problem (\( q \)-SDH)). Let \( G \) be a cyclic group of prime order \( p \), \( g \) a generator of \( G \), and \( x \) be a random element in \( \mathbb{Z}_p^* \). For a given \((q+1)\)-tuple \((g,g^x,g^{x^2},...,g^{x^q})\), \( q \)-SDH problem is to calculate a pair \((m,Σ_m)\) where \( m \in \mathbb{Z}_p^* \). We define the \( q \)-SDH as \((q,t,ε)\)-hard problem, only if the following equation holds for any \( t \)-time adversary \( A \).

\[
Pr[A(g,g^x,g^{x^2},...,g^{x^q})|(m,Σ_m),m∈\mathbb{Z}_p^*]<ε. \tag{1}
\]

**Theorem 1.** We define that the \((q,t,ε)\)-SDH assumption holds if and only if the advantage to solve the \( q \)-SDH problem in \( G \) for any \( t \)-time algorithm is less than \( ε \).

Note that, the probability is decided by the random choice of \( x \) in \( \mathbb{Z}_p^* \) and the random bits consumed by \( A \). The detailed proof of Theorem 1 can be found in [29], so we skipped the detailed description.

B. Paillier Homomorphic Cryptosystem

To guarantee the data confidentiality during the aggregation process, we utilize the Paillier homomorphic cryptosystem, which can achieve additive homomorphism property. It can be described as the following three algorithms.

- **KeyGen**: Input two large primes \((p,q)\), calculate the RSA modulus and Carmichael function as \( n = pq \) and \( λ = (p−1)(q−1) \). Define a function \( L(u) = \frac{u−1}{n} \) and compute \( μ = (L(g^λ \mod n^2))^{-1} \). Then, the key materials can be formed as \((pk,sk) = \{(n,g),(λ,μ)\} \).
- **ENC**: For any plaintext \( m \in \mathbb{Z}_n \), randomly generate a number \( r \) where \( \gcd(r,n) = 1 \), the ciphertext can be calculated as \( c = g^m \cdot r^n \mod n^2 \).
- **DEC**: Given a ciphertext \( c \in \mathbb{Z}_n^2 \), the corresponding plaintext message can be recovered as \( m = L(c^λ \mod n^2)μ \mod n \).

Paillier cryptosystem is proved to be semantically secure against chosen plaintext attacks, which means the mathematical expression is to decide whether an integer \( s \) is an \( n \)-residue modulo \( n^2 \) for some composite \( n \).

C. Online/Offline Signatures

In an online/offline signature and verification method, the whole procedure can be divided into online and offline phases, where the latter can be outsourced to an untrusted third party. Double Trapdoor Chameleon Hash (DTCH) function [30] is an efficient mathematical tool to achieve online/offline signatures. For a given large prime \( p_1 \) and a generator \( g_1 \) from \( \mathbb{Z}_{p_1}^* \), pick two trapdoor keys \( y, z \in \mathbb{Z}_p^* \). Then the DTCH function can be computed as \( H_{ch}(r,s,u) = g_1^y \cdot g_2^z \cdot g_1^r \), where \( g_2 = g_1^y \cdot g_3 = g_1^i \) and \( (r,s,u) \) are elements generated from the chameleon hash. Note that, the DTCH function carries the following properties:

- **Computable**: Given a public key \( pk \in G \) and an input triple \((r, o, c) \in \mathbb{Z}_p^* \), the DTCH function \( H_{ch}(r,o,c) \) is computable in polynomial time.
- **Collision Resistance**: Without at least one of the trapdoor keys, it is infeasible to find two chameleon hash pairs \((r_1,s_1,u_1),(r_2,s_2,u_2)\) which satisfy \( r_1 \neq r_2 \) and \( H_{ch}(r_1,s_1,u_1) = H_{ch}(r_2,s_2,u_2) \).
- **Trapdoor Collision**: Given the hash function \( H_{ch} \) and public/private key pair \((pk,sk)\), also given a chameleon hash pair \((r_1,s_1,u_1)\) and an additional message \( r_2 \in \mathbb{Z}_p^* \), we want to find \( s_2 \in \mathbb{Z}_p^* \) such that \( H_{ch}(r_1,s_1,u_1) = H_{ch}(r_2,s_2,u_2) \).

According to the above-described properties of DTCH function, the online/offline signature and verification method used in our scheme can be constructed using the "hash-sign-switch" method, which consists of the following algorithms.

- **Setup**: On input a security parameter \( 1^λ \), the Setup algorithm returns a random verification (public) key \( V_{er \_pk} \) and the corresponding signature (private) key \( S_{ig \_sk} \).
- **Sign.on**: On input signature key \( S_{ig \_sk} \), the offline signature algorithm returns an offline signature token \( Σ_{off} \) and the state information \( St \).
- **Ver.off**: On input verification key \( V_{er \_pk} \) and the offline signature \( Σ_{off} \), the offline verification algorithm returns accept if \( Σ_{off} \) is valid; Otherwise, outputs reject.
- **Sign.on**: On input state information \( St \) and a message \( m \), the online signature algorithm returns an online signature token \( Σ_{on} \).
- **Ver.on**: On input verification key \( V_{er \_pk} \), a message \( m \), the online signature \( Σ_{on} \) and the offline signature \( Σ_{off} \), the verification algorithm returns accept if \( Σ_{on} \) is valid; Otherwise, it outputs reject. The signature of \( m \) is defined as \( Σ = (Σ_{off},Σ_{on}) \).

D. Security Definitions

**Definition 2.** (Unforgeability). The security definition of an online/offline signature and verification mechanism is existential unforgeability under chosen message attacks (EUCMA), which can be formalized as an adversary-challenger game. We assume that the adversary \( A \) can make multi-times queries to the online and offline signature oracles \((sig_{on}(sk,St,mi),sig_{off}(sk))\), where \( st \) is the state information of the signer.

By this way, the EU-CMA can be illustrated as follows [31]:

- **Initiation**: The Challenger \( C \) runs the key generation algorithm on input \( 1^k \) to obtain a pair of public/private key \((pk,sk)\). Then, \( pk \) is given to the adversary \( A \).
**Sign.off Queries:** The adversary requests the $i$-th offline signature, and the challenger replies to the adversary with $\Sigma_{i}^{off}$ while the state information $St_{i}$ is stored by itself.

Assume that the adversary can make $q_{1}$ queries at most in this phase.

**Sign.on Queries:** The adversary requests the $i$-th online signature of message $m_{i}$, and the challenger $C$ computes the online signature $\Sigma_{i}^{on}$ using $st_{i}$ and returns $\Sigma_{i}^{on}$ to the adversary. Assume that the adversary can make $q_{2}$ queries at most in this phase.

**Forgery:** The adversary $A$ forges a message-signature pair $(m^{*}, \Sigma^{*})$, and sends it to the challenger $C$. The challenger checks the validity of the signature by computing $Ver_{on}(pk, m^{*}, \Sigma^{*})$, it outputs 1 (success) when the forged signature is valid; otherwise outputs 0 (failure).

The advantage in existentially forging a signature of the adversary $A$ is:

$$Adv_{A} = Pr \left[ Ver_{on}(pk, m^{*}, \Sigma^{*}) = 1 : (pk, sk) \leftarrow KeyGen(1^{k}); (m^{*}, \Sigma^{*}) \leftarrow A(\Sigma^{off}, \Sigma^{on}) \right] .$$  

(2)

Where $A$ has never requested the signature of $m^{*}$ from the online signing oracle.

**IV. SYSTEM MODEL AND DESIGN GOALS**

In this section, we present the system model, workflow of LVPDA scheme, security model and design goals.

**A. System Model**

The system model of the proposed LVPDA scheme is shown in Fig. 2, which consists of four entities: control center (CC) like cloud server, edge servers (ES), smart IoT devices (SD), and a trust authority (TA).

- TA bootstraps the whole system and distributes key materials as well as system parameters (see step 1 in Fig. 2). We assume that the communication channels between TA and other entities are secure to transmit private key information. After the setup phase, TA will turn to offline.
- CC can collect all the aggregated data packages from edge servers and further make some intelligent decisions. Then it sends the corresponding responses back to the edge servers (see step 10, 11, 12 in Fig. 2). CC also provides the registration service for smart IoTs.
- ES plays the role as aggregators to aggregate the encrypted data from SD and transmit the aggregated data and responses between CC and SD (see step 8, 9, 13 in Fig. 2). ES also executes the online/offline integrity verification phases (see step 4, 7 in Fig. 2).
- SD represents a set of smart IoT devices owned by users. The private data $m_{i}$ are collected by SD through sensors on the registered devices and transmitted to the CC via ES in encrypted form (see step 2, 3, 5, 6 in Fig. 2).

Note that, since the SD are usually resource constrained equipment, the privacy-preserving data aggregation processes with high computational complexity, especially the cryptographic operations involved in data integrity mechanism, cannot be efficiently executed. This main drawback motivates us to explore a lightweight PPDA mechanism for edge computing enabled smart IoT systems.

**B. Workflow of LVPDA**

According to the above-described system model, the proposed LVPDA scheme can be divided into the following phases and algorithms:

1) **System Initialization Phase.**

- Setup $(k, k_{1}) \rightarrow (SP_{pub}, msk)$: on input two security parameters $(k, k_{1})$, it outputs the system parameters $SP_{pub}$ and the master key $msk$.

2) **Registration Phase.**
3) Report Generation Phase.
- **Register** \((X_i, k_i) \rightarrow (\alpha_i, \beta_i)\): on input a random value \(X_i\) and a blind factor \(k_i\), it outputs the verification public key \(Y_i\) and the knowledge of registration \((\alpha_i, \beta_i)\).
- **Sign.off** \((y, z, s_i, u_i) \rightarrow (St, H_{ch_i}, \Sigma_i^{off}, Ver_{on})\): on input two sets of random values \((y, z)\) and integers \((s_i, u_i)\), it outputs the state information \(St\), DTCH function, offline signature \(\Sigma_i^{off}\), and online verification key \(Ver_{on}\).

4) Report Aggregation Phase.
- **Ver.off** \((Ver_{pk}, \Sigma_i^{off}) \rightarrow b_1\): on input \(Ver_{pk}\) and \(\Sigma_i^{off}\), it outputs a bit \(b_1 \in \{0, 1\}\), where \(b_1 = 1\) indicates the result of offline verification is \(accept\) and \(b_1 = 0\) represents \(reject\).
- **Encrypt** \((PK_P, m_i, v_i) \rightarrow c_i\): on input the public key \(PK_P\), a message \(m_i\), and an integer \(v_i\), it outputs an encrypted report \(c_i\).
- **Sign.on** \((c_i, St, s'_i) \rightarrow \Sigma_i^{on}\): on input \(c_i\), \(St\), and a number \(s'_i\), it outputs the online signature \(\Sigma_i^{on}\).

5) Report Reading Phase.
- **Ver.on** \((\Sigma_i^{on}, Ver_{on}) \rightarrow b_2\): on input \(Ver_{on}\) and \(\Sigma_i^{on}\), it outputs a bit \(b_2 \in \{0, 1\}\), where \(b_2 = 1\) indicates the result of online verification is \(accept\) and \(b_2 = 0\) represents \(reject\).
- **Aggregate** \((c_i) \rightarrow c\): on input \(c_i\), it outputs the aggregation result \(c\).
- **Sign.Agg** \((X_j, c) \rightarrow (Y_j, \Sigma_{Agg})\): on input \(c\) and a random number \(X_j\), it outputs the aggregation signature public key \(Y_j\) and the aggregation signature \(\Sigma_{Agg}\).

6) Response Phase.
- **Response** \((e(g_1, g_1)^\alpha, \beta, Q, Y, M_R) \rightarrow (\tilde{C}_1, \tilde{C}_2, \tilde{C}_3)\): on input two random numbers \((\beta, Q)\), the respond public key \((e(g_1, g_1)^\alpha, Y)\) and the respond message \(M_R\), it outputs respond ciphertexts \((\tilde{C}_1, \tilde{C}_2, \tilde{C}_3)\).
- **Recover.Agg** \((\alpha k_i, \tilde{C}_1, \tilde{C}_2, \tilde{C}_3) \rightarrow M_R\): on input the respond ciphertexts \((\tilde{C}_1, \tilde{C}_2, \tilde{C}_3)\) and the authorized key \(\alpha k_i\), it outputs the respond plaintext \(M_R\).

C. Security Model

Security is crucial for the success of privacy-preserving data aggregation. In our security model, the TA and CC are assumed to be fully trusted. However, the trustworthy of ES may be semi-trusted or honest-but-curious. That is, it will not arbitrarily tamper with the user’s sensitive data, but try to reveal the embedded private information during the aggregation procedure. Moreover, we also consider an external adversary \(A\) hidden in the communication channels, whose main purpose is to threaten the data integrity mechanism and steal the private data by launching the active attacks. On the one hand, \(A\) can eavesdrop on the data in transit or intrude the servers in ES and CC to steal the data in process. On the other hand, the adversary \(A\) could actively forge the signatures of data reports and further compromise the data integrity. In summary, our security model should satisfy the data confidentiality, authentication, integrity, and privacy-preserving simultaneously. The corresponding security analyses of our proposed LVPDA scheme are detailed in Section VI.

D. Design Goals

Based on the above-mentioned system and security models, the design goal of our scheme can be described as the following four objectives:

- **Confidentiality and privacy-preserving**: user’s sensitive raw data should always remain in ciphertext form once it departs from the devices. Meanwhile, the internal adversary, such as the ES, cannot access any individual’s data except with aggregated results.
- **Authentication and Integrity**: all the users that participate in our LVPDA system should be authorized as the legal participants by CC. Besides, adversaries cannot modify the data in transit and any illegal operations of data packets can be detected by the CC and ES.
- **Computation efficiency**: the complex computation operations on the smart IoT devices should be reduced as much as possible. In addition, high communication efficiency is also expected to handle the frequent aggregation requests.
- **Scalability**: the designed LVPDA scheme can be easily applied to other networking scenarios, such as the smart grid and vehicle sensing systems. In addition, the lightweight properties embedded in our LVPDA scheme can be perfectly inherited.

V. PROPOSED LVPDA SCHEME

This section presents the proposed lightweight and verifiable privacy-preserving data aggregation scheme, LVPDA, for edge computing enabled smart IoT systems, which consists of six phases: system setup, registration, report generation, report aggregation, report reading, and response. In addition, the correctness of the LVPDA scheme is given.

A. System Setup

When receiving the data aggregation request sent by CC, TA first generates the Paillier public and private key pair \((SK_P, PK_P) = \{(\mu, \lambda), (n, g)\}\) based on the homomorphic cryptosystem described in III-B. After that, TA chooses two security parameters \((k, k_1)\) randomly and a bilinear map \(e : \mathbb{G} \times \mathbb{G} \rightarrow \mathbb{G}_T\) of prime order \(p_1\), where \(|p_1| = k_1\).

Then, TA further defines three one-way hash functions: \(H_0: \{0, 1\}^* \rightarrow G, H_1: \{0, 1\}^* \rightarrow \mathbb{Z}_{p_1}, H_2: \mathbb{G} \rightarrow \mathbb{Z}_{p_1}\), a Chameleon hash function \(H_{ch}: \mathbb{Z}_{p_1} \rightarrow \mathbb{G}\), three random elements \(\bar{a}, \bar{x} \in \mathbb{Z}_{p_1}, Q \in \mathbb{G}\), and computes \(e(g_1, g_1)^\alpha, \bar{Y} = g_1^\alpha\). In addition, we assume that the number of IoT devices in a certain aggregation request period is \(\omega\). At last, TA publishes the system parameters as

\[
SP_{pub} = \left\{ p_1, n, g, \mathbb{G}, \mathbb{G}_T, e, g_1, \omega, \bar{Y}, Q, e(g_1, g_1)^\alpha, H_0, H_1, H_2, H_{ch} \right\}.
\]
Correspondingly, the master private keys will be kept secret and sent to CC via a secure channel as
\[ msk = (p, q, \lambda, \mu, \hat{\alpha}, \hat{x}). \]  

\section*{B. Registration}

When a user’s smart device SD first participates in the LVPDA system, it is required to register to the CC for the purpose of authentication. Then, the offline signature step will be executed once the authentication succeeds. The registration process is shown in Fig. 3 and the descriptions are as follows.

- **User Registration:** SD first selects a value \( X_i \in Z_{p_i}^* \) and computes \( Y_i = g_i^{X_i} \) based on the random signature method \( Sig_{\text{sk}}() / Ver_{\text{pk}}() \). Correspondingly, the signature private key and verification public key can be formed as \( (Sig_{\text{sk}}, Ver_{\text{pk}}) = (X_i, Y_i) \). Then, SD further picks a blinding factor \( k_i \in Z_{p_i}^* \) and calculates \( r_i = H_1(ID_i || TS_i || k_i) \), where \( ID_i \) is SD's identity and \( TS_i \) is the current timestamp. At last, SD generates the registration knowledge \( \{\alpha_i = g_i^{r_i}, \beta_i = r_i - X_i H_2(\alpha_i)\} \) and sends \( \{Y_i, \alpha_i, \beta_i\} \) to the CC.

- **Authentication:** Upon receiving \( \{Y_i, \alpha_i, \beta_i\} \) from SD, CC verifies \( \alpha_i \) by checking \( \alpha_i = g_i^{r_i} Y_i^{-H_2(\alpha_i)} \) based on the discrete logarithm problem. Once a user \( \omega_i \) is successfully authenticated, CC firstly chooses a random number \( t_i \in Z_{p_i}^* \), and further generates the authorized user-related key \( a_k_i \) to \( \omega_i \), where \( a_k_i = (g_i^{\hat{\alpha} \cdot Y_i^{\hat{t}}} Q_i, g_1^{\hat{t}}) \). Then, it publishes \( \{Y_i, \alpha_i, \beta_i\} \).

- **Offline Signature Generation:** SD firstly chooses two random values \( y, z \in Z_{p_i}^* \), and sets \( g_2 = g_1^y, g_3 = g_1^z \). Without loss of generality, our LVPDA scheme would select the BLS signature method as the basic construction of the offline signature. SD also selects two integers \( (s_i, u_i) \in Z_{p_i}^* \) and stores \( St = (r_i, s_i, u_i) \) as the state information, where \( r_i = H_1(ID_i || TS_i || k_i) \). Then, SD calculates the DTCH function value as
\[ H_{ch_i} = g_1^{r_i} \cdot g_2^{s_i} \cdot g_3^{u_i}, \]  

and the BLS signature on \( H_{ch_i} \) can be formed as
\[ \Sigma_{i}^{BLS} = (H_0(H_{ch_i}))^{X_i}, \]  

At last, SD sends the offline tag \( T_{i}^{off} = (ID_i || TS_i || \Sigma_{i}^{off}) \) to the ES, where \( \Sigma_{i}^{off} = (\Sigma_{i}^{BLS}, H_{ch_i}) \). and publishes the online verification key \( Ver_{on} = (g_1, g_2, g_3) \) to the CC.

\section*{C. Report Generation}

After receiving the offline tag \( T_{i}^{off} \) from SD, ES first executes the offline verification algorithm and SD sends the ciphertext along with online signature to ES nearby once the offline signature is verified. Fig. 4 shows the report generation processes and the detailed steps are as follows.

- **Offline Signatures Batch Verification:** Upon ES receiving the offline tags from SD, \( 1 \leq i \leq \omega \), it verifies all signatures by checking if \( e(g_1, \Sigma_{i}^{BLS}) = e(Y_i, H_0(H_{ch_i})) \) holds with the verification public key \( Ver_{pk} \). To reduce the computation costs on repeatedly verifying \( \omega \) signatures, we utilize the batch verification method as
\[ \prod_{i=1}^{\omega} e(Y_i, H_0(H_{ch_i})) = \prod_{i=1}^{\omega} e(g_1^{X_i}, H_0(H_{ch_i})) = \prod_{i=1}^{\omega} e(g_1, \Sigma_{i}^{BLS}) \]  

If it does hold, the algorithm outputs accept, otherwise outputs reject.

- **Data Encryption:** Once the offline signature has been successfully verified, SD collects the sensitive data \( m_i \) and calculates the ciphertext based on the Paillier encryption mechanism as
\[ c_i = g^{m_i} \cdot v_i^n \mod n^2, \]  

where \( v_i \) is a randomly selected integer in \( Z_{n^2}^* \).

- **Online Signature Generation:** SD uses the state information \( St = (r_i, s_i, u_i) \) to compute the online signature as
\[ u'_i = ((r_i - c_i) + (s_i - s_i') y + u_i z)z^{-1}, \]  

where \( s_i' \in Z_{p_i}^* \) and \( \Sigma_{i}^{on} = (s_i', u'_i) \). At last, SD sends its data report \( P_i = ID_i || c_i || TS_i || \Sigma_{i}^{on} \) to ES nearby, where \( TS_i \) is the current timestamp.
D. Report Aggregation

Upon ES receiving the users’ reports \( P_i, 1 \leq i \leq \omega \), from SD, it adopts the online verification algorithm to check the validity of \( \Sigma_{agg}^\omega \) and aggregates all the ciphertexts. The high-level illustration is shown in Fig. 5.

- **Online Signature Verification**: After receiving \( \Sigma_{agg}^\omega \), ES first checks the validity by verifying whether \( H_{ch}(c_i, s'_i, u'_i) = H_{ch}(c_i, s'_i, u'_i) \) holds or not. The correctness of online signature verification phase is shown as follows.

\[
H_{ch}(c_i, s'_i, u'_i) = g_1^{c_i} \cdot g_2^{s'_i} \cdot g_3^{u'_i} = g_1^{c_i} \cdot (g_1^y)^{s'_i} \cdot g_3^{u'_i} = g_1^{c_i} \cdot (g_1^y)^{s'_i} \cdot g_3^{u'_i} = (g_1^{c_i})^{s'_i} \cdot (g_1^y)^{u'_i} = g_1^{c_i} \cdot g_2^{s'_i} \cdot g_3^{u'_i} = H_{ch}(c_i, s'_i, u'_i).
\]

This step outputs accept if the above equation holds, otherwise outputs reject.

- **Report Aggregation**: Once the online signature is verified, ES computes the aggregated ciphertext as

\[
c = \prod_{i=1}^{\omega} c_i \mod n^2. \tag{11}
\]

- **Aggregation Signature Generation**: ES randomly selects an aggregation signature private key \( X_j \in \mathbb{Z}_{p_1} \) to generate the aggregation signature as

\[
\Sigma_{agg} = (H_0(ID_j||c||TS_i))^{X_j}, \tag{12}
\]

where \( ID_j \) is the identity of a certain edge server \( ES_j \). At last, \( ES_j \) sends the aggregated report \( P = ID_j||c||TS_i||\Sigma_{agg} \) to the control center.

E. Report Reading

When receiving \( P \) from \( ES_j \), CC performs the following steps to read the aggregated result and sends the corresponding response to SD. The detailed description of report reading and the response phase was shown in Fig. 6.

- **Aggregation Signature Verification**: CC first verifies the received data report \( P \) by checking the validity of aggregation signature \( \Sigma_{agg} \) as

\[
e(g_1, \Sigma_{agg}) = e(g_1, (H_0(ID_j||c||TS_i))^{X_j})
\]

\[
= e(g_1^{X_j}, H_0(ID_j||c||TS_i))
\]

\[
= e(Y_j, H_0(ID_j||c||TS_i)) \tag{13}
\]

where \( Y_j = g_1^{X_j} \). If it does hold, the verification algorithm outputs accept, otherwise outputs reject.

- **Report Reading and Decryption**: Upon the aggregation signature has been verified, CC transforms the aggregated ciphertext \( c \) as

\[
c = \prod_{i=1}^{\omega} c_i \mod n^2 = \prod_{i=1}^{\omega} g_1^{m_i} \cdot v_i^n \mod n^2
\]

\[
= g_1^{\sum_{i=1}^{\omega} m_i} \cdot \prod_{i=1}^{\omega} v_i^n \mod n^2 \tag{14}
\]

\[
= g_1^{m} \cdot \prod_{i=1}^{\omega} v_i^n \mod n^2.
\]

Since the above-transformed ciphertext is also satisfied with the form of Paillier cryptosystem, thus CC can easily decrypt it and obtain the aggregated plaintext as

\[
m = \sum_{i=1}^{\omega} m_i = \frac{L(e^\lambda \mod n^2)}{L(g^\lambda \mod n^2)} \mod n. \tag{15}
\]

F. Response

After analyzing the aggregated plaintext \( m \), the CC response with a message \( M_R \in \mathbb{Z}_p \) to the edge server in a certain coverage area. To guarantee the privacy of respond message, \( M_R \) should be transmitted under a ciphertext form. The concrete steps are performed as follows:

- **Step-1**: The CC firstly chooses a random number \( \hat{\beta} \in \mathbb{Z}_{p^*} \), and computes \( \hat{C} = (\hat{C}_1, \hat{C}_2, \hat{C}_3) \), where

\[
\begin{cases}
\hat{C}_1 = M_R \cdot e(g_1, g_1)^{\alpha \hat{\beta}} \mod n, \\
\hat{C}_2 = g_1^{\hat{\beta}}, \hat{C}_3 = (Y/Q)^{\hat{\beta}}.
\end{cases}
\] \tag{16}

Then, the CC makes the signature \( \Sigma_{Res} = (H_0(\hat{C}||TS_i))^{X_{Res}} \), where \( TS_i \) is the current time.
stamp, and sends back \( \tilde{C}||\Sigma_{Res} \) to the edge server, which covered some smart IoT devices.

- **Step-2:** Upon receiving \( \tilde{C}||\Sigma_{Res} \), the edge server verifies the validity of \( \tilde{C} \) by checking whether \( e(g_1, \Sigma_{Res}) = e(Y, H_0(\tilde{C}||TS_e)) \). If it does holds, the edge server broadcasts \( \tilde{C} \) in its covered area.

- **Step-3:** After receiving the authenticated \( \tilde{C} \) from the edge server, each user \( \omega_i \in \omega \) uses the authorized key \( ak_i = (g_1^\alpha, Y^i, Q^i, g_1^{t_i}) \) to recover \( M_R \) from \( \tilde{C} \) in the followings:

\[
\frac{e(\tilde{C}_2, g_1^\alpha \cdot Y^i)}{e(\tilde{C}_2, Q^i)} = \frac{e(g_1^\beta, g_1^{\alpha})}{e(g_1^\beta, Y^i)}
\]

\[
= \frac{e(g_1^\beta, Q^i)(e(Y^i, Y^i))/e(Q^i, g_1^{t_i})}{e(g_1^\beta, g_1^{t_i})} = e(Y^i, g_1^{\alpha \beta}).
\]

Finally, in the report generation phase, \( SD_i \)’s private data \( m_i \) are encrypted as \( c_i = g^{m_i} \cdot v_i^n \mod n^2 \), which is a standard ciphertext form of Paillier cryptosystem. Since the Paillier cryptosystem is proved to be semantically secure against the Chosen Plaintext Attack (CPA) based on the decisional Diffie-Hellman problem [33], no sensitive information will be leaked.

Secondly, in the report aggregation phase, ES cannot recover each individual’s plaintext without the private key \( (\lambda, \mu) \), but aggregate all the received ciphertexts as \( c = g^{\Sigma_{res}} \cdot m \), \( (\prod_{e=1}^\infty v_i)^n \mod n^2 \), which is still a valid ciphertext form of Paillier cryptosystem. Therefore, the users’ data confidentiality and privacy can be ensured even when ES is untrusted.

Thirdly, imagine there exists an external attacker who can eavesdrop on the whole communication channel from SD to CC and obtain both the individual ciphertexts \( c_i \) and aggregated ciphertext \( c \), and aggregated plaintext \( m \), then he is still unable to recover the individual plaintext \( m_i \), since all the plaintexts are compressed through the report aggregation process. In summary, the confidentiality and privacy of each individual \( SD_i \)’s sensitive data can be perfectly protected.

### C. Integrity and Unforgeability

In the proposed LVPDA, we designed an online/offline signature method to ensure the data integrity and meanwhile reduce the computation costs. Here, we prove that our scheme is existentially unforgeable under the chosen message attack (EU-CMA), thus guaranteeing the data integrity. According to the Definition 2, without querying the online signing oracle token on a given \( m^* \in \mathbb{Z}_p^* \), an adversary \( A \) cannot forge any pair \( (m^*, \Sigma^*) \) to ensure the validity of signature \( \Sigma^* \) with private key \( SK_{sk}(\Sigma) \) in probabilistic polynomial time. Combined with Definition 1 and Theorem 1, the problem can be transformed into proving the following theorem.

**Theorem 2.** We say that an online/offline signature scheme is \((t, q_1, q_2, e)\) secure against EU-CMA if the \( q\)-SDH problem can be solved by an algorithm \( B \) in polynomial time with a non-negligible probability \( \epsilon \geq \frac{1}{t} - \frac{2e}{p} \).

**Proof.** We use the contradiction method to prove this theorem, assume that \( A \) queries the offline and online signature oracle on message \( m_i \) for \( q_1 \) and \( q_2 \) times respectively, where \( q_2 = q \leq q_1 \). Let \( (\Sigma_{off}, \Sigma_{on}) \) be the full signatures from the real online/offline signing oracle after \( q_2 \) queries by \( A \), and \( A \) returns a valid forgery signature \( (\Sigma_{off}^*, \Sigma_{on}^*) \) on a new message \( m^* \) with probability of at least \( \epsilon \). Moreover, suppose \( (g, g^q, g^{q^2}, \cdots, g^{q^r}) \) is a \( q\)-SDH instance generated by algorithm \( B \), which aims to construct a new valid online/offline signature \( (\Sigma_{off}^*, \Sigma_{on}^*) \) and successfully solve the \( q\)-SDH problem. In this way, the attacks from \( A \) fall into the following cases:

**Case 1:** \( g^{m_i} q_i^2 g_2^3 \neq g^{m_i} q_i^3 g_3^3 \) for all \( i \in \{1, \cdots, q_2\} \).

**Case 2:** \( g^{m_i} q_i^2 g_2^3 = g^{m_i} q_i^3 g_3^3 \) for some \( i \in \{1, \cdots, q_2\} \), and \( s^* \neq s_i \).

**Case 3:** \( g^{m_i} q_i^2 g_2^3 = g^{m_i} q_i^3 g_3^3 \) for some \( i \in \{1, \cdots, q_2\} \), and \( s^* = s_i \) but \( u^* \neq u_i \).

**[CASE 1.]**

- **Initiation:** Algorithm \( B \) randomly chooses two numbers \( y, z \in \mathbb{Z}^*_p \) and sets signature private key as \( SK = \).
(a, y, z). Then, it gives the verification public key \( VK = (g_1, g_2, g_3) \) to \( \mathcal{A} \), where \( g_1 = g^a \), \( g_2 = g^b \), \( g_3 = g^z \).

- **Sign.off Queries**: Adversary \( \mathcal{A} \) first takes the \( i \)-th offline query, where \( 1 \leq i \leq q_1 \). Then, \( \mathcal{B} \) responds with \( \sum_i^{q_1} = (H_0(H_{ch})^i, H_{ch}) \) to \( \mathcal{A} \) as the \( i \)-th offline signature, where \( H_{ch} = g^{y_1}g_2^{y_2}g_3^{y_3} = g^{r_1 + s_iy + u_iz} \) and \( (r_1, s_i, u_i) \in \mathbb{Z}_p^* \) are stored by \( \mathcal{B} \). Apparently, \( \sum_i^{q_1} \) is valid because \( e(g_1, H_0(H_{ch})^n) = e(g_1, H_0(H_{ch})) \). For simplicity, we use \( c_i \) to represent \( r_i + s_iy + u_iz \).

- **Sign.on Queries**: Adversary \( \mathcal{A} \) takes the \( i \)-th offline query, where \( 1 \leq i \leq q_2 \). Correspondingly, \( \mathcal{B} \) returns \( \sum_i^{q_2} = (s_i^{'}, u_i^{'}) \) to \( \mathcal{A} \) as the \( i \)-th offline signature, where \( u_i^{'} = (r_i - m_i) + (s_i - s_i^{'})y + u_iz \) and \( s_i^{'}, u_i^{'}) \in \mathbb{Z}_p^* \). Also, the validity of \( \sum_i^{q_1} \) can be guaranteed by \( H_{ch}, (r_i, s_i, u_i) = H_{ch}, (m_i, s_i^{'}, u_i^{'}) \).

- **Forgery**: Finally, \( \mathcal{A} \) submits a valid forgery signature \((m^*, s^*, u^{'}, s_i^{'}, u_i^{'})\) satisfying the condition in **Case 1**. Since \( g^{m^*}g_2^{s^*}g_3^{u^{'}} \neq g^{m'}g_2^{s'}g_3^{u_i^{'}} \), then we have \( c^* = m^* + s^{'}, y + u^{'}, z \neq c_i \), which means there exists an algorithm \( \mathcal{B} \) to solve the \( q \)-SDH problem with probability at least \( \epsilon/3 \) (the same with **Case 1** occurred).

Note that, the only difference between **Case 1**, **Case 2**, and **Case 3** on the **Initiation**, **Sign.off Queries**, and **Sign.on Queries** phases is that the algorithm \( \mathcal{B} \) forges a new Chameleon hash function \( H_{ch}^* \) in **Case 1** while the trapdoor \( y \) and \( z \) are forged in **Case 2** and **Case 3**. Therefore, we only focus on the forging step in the subsequent two cases.

**[CASE 2.]**

- **Forgery**: In **Case 2**, one of the double trapdoors \( y \) is forged by \( \mathcal{B} \), whose the signature private key is set as \( SK = (x, a, z) \). As described above, we know that the probability of **Case 2** occurring is \( \epsilon/3 \) at least, and \( s^* = s_i \) occurs with probability \( 1/p \) since \( s_i \) is randomly selected from \( \mathbb{Z}_p^* \). Thus, for the whole game, \( s^* = s_i \) occurs with probability of at most \( q_2/p \). In this situation, once adversary \( \mathcal{A} \) requests a forged signature \((m^*, \sum_{off}^*(a, r^{'}, s^{'}, u^{'}) \sum_{on}^*(s_i^{'}, u_i^{'}) \) which fulfills the conditions in **Case 2**, then algorithm \( \mathcal{B} \) can successfully calculate \( a = y = (m^* - m_i) + (u^* - u_i)z)(s_i - s^{'})^{-1} \).

In other words, \( \mathcal{B} \) can succeed with probability of at least \( \epsilon/3 - q_2/p \) to solve the \( q \)-SDH problem.

**[CASE 3.]**

- **Forgery**: In **Case 3**, \( \mathcal{B} \) forges another trapdoor \( z \) and sets the corresponding signature private key as \( SK = (x, y, a) \), where the maximum probability of \( u^* = u_i \) is \( q_3/p \). Similar to **Case 2**, \( \mathcal{B} \) can solve the \( q \)-SDH problem with probability of at least \( \epsilon/3 - q_2/p \) in polynomial time by computing \( a = z = ((m^* - m_i) + (s_i - s^{'})z)(u_i - u^{'})^{-1} \) for some \( i \), where \((m^*, \sum_{off}^*(a, r^{'}, s^{'}, u^{'}) \sum_{on}^*(s_i^{'}, u_i^{'}) \) is a valid signature forged by \( \mathcal{A} \) which meets the condition of **Case 3**.

In summary, there exists an algorithm \( \mathcal{B} \) to solve the \( q \)-SDH problem with probability at least \( \epsilon/3 - q_2/p \) in polynomial time. Correspondingly, **Theorem 2** is proved due to the contradictions between the reasoning result and the original \( q \)-SDH assumption.

---

**TABLE I**

<table>
<thead>
<tr>
<th>Description</th>
<th>Time Cost (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{E_1} )</td>
<td>Exponentiation in ( \mathbb{Z}_n^2 )</td>
</tr>
<tr>
<td>( T_{E_2} )</td>
<td>Exponentiation in ( \mathbb{G} )</td>
</tr>
<tr>
<td>( T_{M} )</td>
<td>Multiplication in ( \mathbb{G} )</td>
</tr>
<tr>
<td>( T_P )</td>
<td>Pairing Operation</td>
</tr>
</tbody>
</table>

**Fig. 7. Overall computational cost comparison**

**VII. NUMERICAL EVALUATION**

This section evaluates the performance of the proposed LVPDA scheme, in terms of the computational complexity as well as communication overhead. As a comparison, we take three classic homomorphic cryptosystem based schemes into consideration, namely EPPA [17], PEDA [19], and SEDA [20], to demonstrate the efficiency of our scheme. Without loss of generality, we use the public Pairing-Based Cryptography (PBC) library to estimate the time costs operations in Paillier cryptosystem, in which the RSA modulus \( n \) is set to 1024 bits and the security parameter \( p_1 \) is 160 bits. All the experiments are implemented on a Linux machine with Intel Core i7-4710U CPU at 2.5GHz and 4.00 GB memory. The notations of cryptographic operations and corresponding time costs are shown in Table I.

**A. Computational Complexity**

For the proposed LVPDA scheme, the report generation of a new smart device \( SD_i \) requires two exponentiation operations in \( \mathbb{Z}_n^2 \) to generate ciphertext \( c_1 \), and three multiplication operation in \( \mathbb{G} \) to compute the online signature \( \Sigma_{on}^m \). In the report aggregation phase, \( ES_j \) needs to verify the online signature and further aggregates all the collected ciphertexts, which consumes three exponentiation operations in \( \mathbb{G} \) and \( \omega \) multiplication operations in \( \mathbb{Z}_n^2 \). Note that, the Hash operations and multiplication operations in \( \mathbb{Z}_n^2 \) are regarded as negligible compared to exponentiation and pairing operations. Then, \( ES_j \) also performs one exponentiation operation in \( \mathbb{G} \) to generate the aggregation signature \( \Sigma_{Agg} \). Upon receiving the aggregated report from \( ES_j \), CC verifies \( \Sigma_{Agg} \) and decrypts the aggregated ciphertext \( c \) to obtain sum-plaintext which exe-
TABLE II  
SIGNATURE AND VERIFICATION COMPUTATION COST COMPARISONS

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVPDA</td>
<td>$2T_P + (3\omega + 1)T_{E_2} + \omega T_M$</td>
</tr>
<tr>
<td>EPPA [17]</td>
<td>$(\omega + 3)T_P + (\omega + 1)T_M$</td>
</tr>
<tr>
<td>PEDA [19]</td>
<td>$(\omega + 1)T_P + (2\omega + 1)T_{E_2} + (\omega + 1)T_M$</td>
</tr>
<tr>
<td>SEDA [20]</td>
<td>$2T_P + (6\omega + 3)T_{E_2} + \omega T_M$</td>
</tr>
</tbody>
</table>

The above computation complexity analysis indicates that there are fewer time-consuming cryptographic operations required in terms of $SD_1$, especially the signature operations. The overall computational costs comparison in the four schemes are illustrated in Fig. 7. It shows that our proposed LVPDA scheme has significant efficiency in computational costs compared to the other three schemes [17, 19, 20] because a major part of complex operations is shifted into the offline phase. In particular, Table II shows the detailed computation cost comparisons on signature and verification method and Fig. 8 further depicts the change tendency of time cost among the four schemes. Obviously, the time cost of signature and verification in our LVPDA scheme is at least 50% lower than EPPA, PEDA, and SEDA. Furthermore, we also compare the computation costs in the aggregation phase and the result is demonstrated in Fig. 9, which shows that our scheme also has an advantage in aggregation computation costs comparison. In summary, the above evaluation results indicate that our scheme is more efficient than the other three schemes in terms of signature, verification, aggregation, and overall computation costs. However, it requires sufficient computational resources on the registration phase since the system needs to execute the authentication and offline signature operations.

B. Communication Overhead

According to our system model described in IV-A, the communication interactions involved in our LVPDA scheme fall into two phases: one phase is from smart devices SD to edge server communication, noted as SD-to-ES, and the other phase is from edge server ES to control center CC communication, abbreviated as ES-to-CC. In the SD-to-ES phase, the data report generated by $SD_i$ is sent to the target $ES_j$ which can be formed as $P_i = ID_i||c_i||TS_i||\Sigma_{c_i}$. Here, we set the RSA modulus $n = 1024$ bits and security parameter $p_1 = 106$ bits and the size of data report should be $S_{SD_i} = |ID_i| + 2048 + |TS_i| + 160$ bits. Considering there exist a total of $\omega$ users to participate in our LVPDA system in a certain time slot, thus the overall communication overheads are $S_{TS} = \omega S_{SD_i}$. In the second communication phase, $ES_j$ aggregates $\omega$ users’ data reports and sends the aggregated report $F = ID_i||c_i||TS_i||\Sigma_{Agg}$ to CC, where the report size is $S_{SC} = |ID_j| + 2048 + |TS_i| + 160$ bits. Note that, the aggregation mechanism can significantly reduce the communication overhead compared with the conventional cloud-based data transmission scenario where each individual’s data report is separately transmitted to the CC and the total data size is $(|ID_j| + 2048 + |TS_i| + 160) \ast \omega$ bits. Since the PEDA scheme [19] does not consider the perspective of communication overhead, we mainly focus on the EPPA [17], SEDA [20], and our proposed LVPDA scheme. Fig. 10 presents the communication overhead comparison on both SD-to-ES and ES-to-CC phases, where the size of |ID| and |TS| is set to be 160 bits. The results indicate that the LVPDA scheme is indeed more efficient than the other two schemes. Particularly, we can see that the evaluation results shown in Fig. 10(b) are close to the constant, which is mainly because the communication overheads in the ES-to-CC phase have no correlation with the number of users.

VIII. CONCLUSION

In this paper, we present a lightweight and verifiable privacy-preserving data aggregation scheme for smart IoT systems, named LVPDA, which simultaneously achieves the authentication, lightweight integrity verification, confidentiality, and privacy-preserving. The scheme exploits the Paillier homomorphic cryptosystem and online/offline signature method to significantly reduce the computation and communication costs of conventional PPDA schemes. Moreover, benefiting from the edge computing, LVPDA can efficiently shift the time-consuming cryptographic operations to the edge server...
and meanwhile minimize the online computation costs. Due to the efficiency property, our designed LVPDA scheme can be used in lots of smart IoT systems, such as the smart grid and vehicular network. Thorough security analysis illustrated that the proposed scheme is secure under our defined security model. Extensive evaluation results demonstrated the lightweight and effectiveness of LVPDA. However, our method, to an extent, is vulnerable to collusion attacks launched by edge servers and malicious users. In regard to future work, we plan to further improve the security properties under more powerful adversaries and active attack models.

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