End to End Secure Data Exchange in Value Chains with Dynamic Policy Updates

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Abstract. Data exchange among value chain partners provides them with a competitive advantage, but the risk of exposing sensitive data is ever-increasing. Information must be protected in storage and transmission to reduce this risk, so only the data producer and the final consumer can access or modify it. In most cases, data producers are IIoT devices, limited in terms of processing and memory capabilities. End-to-end (E2E) security mechanisms have to address this challenge, and protect companies from data breaches resulting from value chain attacks. Moreover, value chain particularities must also be considered. Multiple entities are involved in dynamic environments like these, both in data generation and consumption. Hence, a flexible generation of access policies is required to ensure that they can be updated whenever needed. This paper presents a Ciphertext-Policy Attribute Based Encryption (CP-ABE) reliant data exchange system for value chains with E2E security. It considers the most relevant security and industrial requirements for value chains. The proposed solution can protect data according to access policies and update those policies without breaking E2E security or overloading field devices. The experimental evaluation has shown the proposed solution’s feasibility for IIoT platforms.

Keywords: CP-ABE · data exchange · end-to-end (E2E) security · IIoT · policy update · value chain

1 Introduction

Value chains are the evolution of traditional supply chains. Value chains, in addition to physical assets, also manage digital assets and production parameters. The exchange of this information between retailers, customers, and manufacturers gives companies a competitive advantage, increases efficiency, and reduces production costs \cite{15}. Integrating Industrial IoT (IIoT) devices into this infrastructure facilitates information management, but it also introduces new risks.
and vulnerabilities. For example, in 2016, over 200,000 industrial systems were exposed on Shodan [1]. This search engine exposes IP addresses, open services, and vulnerabilities [4]. In value chains, this information can be used to compromise one of the partners. Due to the interconnected nature of value chains, the consequences of an attack on one member can spread to the rest [28], giving attackers access to the infrastructures of other stakeholders. Building a system that ensures secure data exchange between partners is a security challenge that requires meticulous design and planning.

Value chain security is a growing concern for organizations reluctant to share sensitive data with partners who may be both collaborators and competitors. Protecting valuable information and controlling who has access to it are among the main security challenges for value chains [25]. The 2022 Data Breach Report by IBM [11] shows that 19% of companies’ data breaches are a result of supply chain attacks. Supply chain attacks harm companies’ reputations and cause significant economic damage. In fact, data breaches resulting from a supply chain compromise are more expensive for companies. On average, a data breach costs USD 4.46 million, while a data breach resulting from a supply chain compromise costs USD 4.35 million, 2.5% more than a standard data breach [11]. Furthermore, the cost of a data breach, in general, has risen a 12.7% since 2020 [10]. These staggering numbers make value chain security of utmost importance.

Ensuring the confidentiality of industrial data is essential to reduce the impact of data breaches. Protecting information during transmission and storage prevents attackers from obtaining sensitive information even if it is leaked. To do so, this protection must be end-to-end (E2E), i.e., only the generator and the receiver must have access to it. Protocols like TLS or DTLS are the dominant strategy to secure data in transit. The major drawback of these protocols is that their security ends at every middlebox, allowing attackers access to the transmitted information through these network elements. In addition, in environments where data created by one device can be consumed by multiple devices, TLS and DTLS present inefficiency issues. These environments benefit from one-to-many communication, and TLS/DTLS require encrypting information individually for each destination.

Regarding stored data, some cloud service providers integrate cryptographic mechanisms based on encryption protocols such as AES or RSA. However, this can lead to vendor lock-in [20], forcing every partner in the value chain to use the same service for information exchange to guarantee an end-to-end (E2E) secure exchange. Therefore, the challenge to design a secure and efficient data exchange architecture for value chains capable of meeting E2E confidentiality remains. Moreover, the system must be flexible and adaptable to changes, as this responsiveness is considered essential for value chains [2], as well as guarantee data integrity, which is crucial to achieve accurate decision-making in supply chains [9].

With these goals in mind, one-to-many encryption schemes are of great interest to achieve the desired E2E confidentiality in distributed environments. In particular, non-identity-dependent schemes, such as Ciphertext-Policy Attribute-
Based Encryption (CP-ABE) have shown promising results. CP-ABE is an encryption scheme that generates users’ secret keys based on attributes and protects messages according to access policies defined with those attributes. This scheme allows multiple users to access the same encrypted message as long as their attributes comply with the policy, which increases efficiency. However, CP-ABE lacks the required flexibility since it does not natively integrate a policy update system. In response to this situation, our proposal has the following contributions:

- We develop an efficient E2E secure information exchange system for value chains based on a one-to-many encryption scheme. Moreover, the proposal uses CP-ABE, but it is agnostic to a specific CP-ABE construction.
- We achieve the required flexibility by applying an access policy update scheme that neither breaks E2E security nor regenerates the symmetric key, nor interacts with field devices.
- Our solution allows data producers to control who has access to their information without prior knowledge of user identities. Therefore, we favor scalability by allowing the addition of new users without generating additional operations to the IIoT devices that produced the data.
- We prove the feasibility of our solution by deploying it on a resource-constrained device with ARMv6 architecture, emulating OT devices.

The rest of the paper is organized as follows: Section 2 analyses the State of the Art. Section 3 presents our scenario as well as the requirements defined for the system. Section 4 discusses the proposed system and Section 5 the used algorithms. We close the paper with an experimental evaluation in Section 6 and conclusions in Section 7.

2 State of the Art

Security is one of the critical issues of value chain management. In particular, information exchange vulnerabilities are considered the primary security concern for value chains. Real-world experiences show that such concerns are not unfounded: attacks to these infrastructures have been on the rise since 2020, exposing sensitive information and affecting critical industries. Value chain attacks are expected to grow in frequency and severity in the following years, which leads to an increased volume of data breaches, exposed information, and affected users. This has been analyzed by the Identity Theft Resource Center (ITRC). According to their Data Breach Analysis report, during the first quarter of 2021, attacks on value chains grew by 42% compared to the last quarter of the previous year. The attacks resulted in a rise of just 12% in data breaches, but the number of impacted users jumped from 8 million to 51, increasing 564%. As company interconnections grow, partners should upgrade their risk management strategies to include end-to-end security and protect themselves from compromised value chain members.
Value chain security must protect physical assets, digital products, and associated production parameters. Previous research combines cloud computing and a cryptographic envelope to protect product delivery. However, this approach is limited to transferring finished digital products and does not consider the exchange of manufacturing information. Researchers in combine Bloom filters and Oblivious Transfer to guarantee a private industrial parameters exchange. However, this solution reduces the control retained by data producers by allowing customers to retrieve data without the data producers knowing what has been transferred. Overall, there is a need for encryption schemes adaptable to Industrial IoT (IIoT) devices and capable of providing E2E security. This requirement is magnified in value chains dealing with industrial limitations and risks introduced by third-party services.

Managing data security by ensuring data confidentiality reduces the exposure of sensitive information and limits the impact of data breaches. However, industrial data encryption is a sensitive issue in manufacturing due to the large volume of data to be managed and exchanged. To address this issue, authors in combine Blockchain and symmetric encryption. The proposed system achieves the mentioned one-to-many encryption, but the identity of the receivers must be known in advance. This limitation hinders scalability, making it difficult to add new users, and can have an unpredictable impact on system efficiency.

Regarding logistics security, the authors of have developed a secure E2E sensing system for supply chains. Their solution focuses on ensuring that sensor readings are reliable and that each parameter is related to an existing physical event. Because the proposal is limited to sensor readings and does not consider other types of data, its direct application to digital assets in a value chain is not straightforward. Looking for E2E security, researchers in develop a security system for publish/subscribe communications in cyber-physical systems. However, this proposal is designed for the Operational Technology (OT) network, not a value chain.

In general, the different security proposals introduce interesting considerations. For example, the data exchange solution must ensure that data producers can determine who can access the information. Moreover, they must do so without knowing each recipient’s identity in advance. Similarly, the solution must be scalable, consider IIoT devices, and must not assume that every data exchange is tied to an event in the physical world.

Given the points mentioned in the previous paragraph, CP-ABE offers an optimal solution. It offers a one-to-many encryption system that provides the sought-after E2E confidentiality and allows Data Owners (DO)s to maintain control of their data. This control is achieved by protecting information with attribute-based access policies without binding decryption to a specific data requester. In addition, this system allows new users to access old information, promoting scalability.

Authors in combine CP-ABE with a symmetric cipher to incorporate encryption to attribute-based access control. However, they focus on protecting the RFID tags attached to the products. The requirement of RFID tags makes
it difficult to apply it to our scenario, which includes data and digital goods. Authors in [22] combine CP-ABE with Blockchain in international supply chains. They consider a product exchanged through different partners, but to which not all of them can access. Overall, applying CP-ABE to a trade infrastructure provides E2E security and allows one-to-many encryption. However, to guarantee the responsiveness and flexibility mentioned in the introduction, the policies used in CP-ABE should be updatable while preserving E2E security.

The difficulty of updating access policies is a known issue in CP-ABE. One of the works identifying it is [7], where authors solve it with a layered model allowing policy updates. However, their model requires knowing the information recipients beforehand. Another approach is [31], in which the authors focus on re-encrypting the symmetric ciphertext while DOs must produce a new ABE ciphertext with every update. However, the computational burden placed on DOs for updates makes this solution inadequate for IoT devices. Authors in [13] modify the linear secret sharing scheme used to define the access policy embedded in the encrypted message. This update, however, has to be performed by DOs, which can have an unpredictable computational cost for them. To reduce the burden on DOs, [3] proposes a hybrid system in which the ciphertext is sliced, and one of the slices is randomly chosen to be updated. Thus, nothing stops an attacker from collecting slices at different stages and then combining and decrypting them. Finally, authors in [29] combine CP-ABE with symmetric encryption. However, they use the same symmetric key for every message. Therefore, when the system updates the access policy, authors deem it necessary to update the symmetric key. This forces the DO to regenerate the symmetric key and re-encrypt it with CP-ABE.

Therefore, there appears to be no widely efficient data exchange method for value chains that support non-identity-based access to data with an efficient policy update mechanism. To address this, we set up a CP-ABE-based E2E secure data exchange that allows DOs to control who accesses their data without identifying users in advance. Since the information recipients do not have to be known beforehand, we favor scalability by allowing easy addition of users to the system. This also reduces the burden placed on DOs, who do not need to negotiate keys with every user in the system nor reencrypt ciphertext when new users are added. Finally, the policy update provides the system with resilience without needing intervention from DOs.

3 Scenario and Requirements

Value chains are complex distributed systems bounded by industrial requirements. Therefore, the companies participating in a value chain play roles associated with distributed information exchange systems. Thus, we can speak of information consumers, generators, and consumers-generators. Figure 1 presents a schematic of a generic value chain with companies, consumers, and transport companies.
As mentioned above, the different participants in the value chains fulfill existing roles in distributed information exchange systems. Thus, storage and transport companies are generators: they produce and store data related to the product’s transport and storage conditions. End users and after-sales services constitute pure information consumers. And finally, companies are consumer-generators. In Figure 1, information consumption is represented by a dotted line and information generation by a solid line.

Companies generate two data types: manufacturing parameters and digital products. Digital products are developed with high-performance equipment, but manufacturing parameters are generated by IIoT devices. Thus, the selected solution must be scalable to IIoT devices. Companies protect and store the information in a storage solution accessible to other chain members. In addition to being producers, companies are also consumers: they access digital products and production parameters generated by other companies. The data exchange platform must ensure that companies only have access to data they are authorized to obtain.

Regarding transportation companies, they are responsible for trading physical products. Physical product exchange and storage generates data of significant interest for the remaining members of the value chain. Examples of this are product geolocation, as well as parameters concerning transport and storage conditions, such as temperature or humidity. This role is limited to information generation and storage and does not consume shared data.

3.1 Design Requirements

The main goal is to develop a secure E2E data exchange for a value chain. To this end, this section defines the five requirements to be met by the developed solution. These requirements have been established taking into account the industrial constraints of value chains, as well as the needs identified in section 2. Table 1 analyzes, to the best of our knowledge, which requirements are met by the current state-of-the-art.

**R1. Heterogeneous Data Exchange.** We identify three information exchange cases, and consider that the final solution should be extensible to any of them. The cases are listed below.
Table 1. Defined requirement fulfillment level.

| Approach                        | R1       | R2 R3 R4 R5 |
|--------------------------------|----------|-------------|
| Vazquez-Martinez et al. [27]    | □ ■ ■ □  | □ ■ ■ □     |
| Pennekamp et al. [23]           | ■ □ □    | ■ □ ■ □     |
| Epiphaniou et al. [6]           | ■ □ □    | □ □ □ □     |
| Pennekamp et al. [21]           | □ □ ■    | □ □ □ □     |
| Dahlmanns et al. [5]            | ■ □ □    | ■ □ □ □     |
| Qi et al. [24]                  | □ □ ■    | ■ □ □ □     |
| Pennekamp et al. [22]           | □ □ ■    | □ □ □ □     |

R1.1 Production parameters exchange. This information exchange provides members of value chains with an advantage over their competitors. The system has to guarantee that sensitive data is managed securely.

R1.2 Digital product exchange. Digital products must be securely transferred to the final consumer, assuring confidentiality and integrity.

R1.3 Physical product exchange. The traditional exchange, linking the value chain with the conventional supply chain. The trade of physical products generates a multitude of sensitive data, which, if not protected, could be used by attackers and competitors.

R2. Computational Scalability. Data might be generated by IIoT devices. These devices have a limited computational capacity, and the solution must be scalable to achieve the required security operations.

R3. E2E data confidentiality and integrity. E2E security means that information must be secured before leaving the device that generated it. Therefore, data must be encrypted at the source by the device that generated it and maintain that encryption during transmission and storage.

R4. Non-Identity Based Access to Data. Access to sensitive information must be controlled. However, Section 2 showed that identity-based access control generates scalability and management issues in value chains. Thus, environments with many participants favor more scalable and flexible approaches. To this end, Role-Based Access Control (RBAC) or Attribute-Based Access Control (ABAC) provide fine-grained access to data and are easier to manage. Both support the definition of access policies unrelated to individual identities and instead use users’ roles in the system or attributes associated with them.

R5. System flexibility and responsiveness. The data protection system must be flexible and capable of evolving when the access policies change. Thus, to maximize the lifespan of the defined system, a policy update system should be in place. This system should consider both the case of a required policy update and any security event: from key renovations to security violations.

Achieving E2E security in a supply chain involves meeting various requirements. However, as shown in Table 1, none of the approaches studied in Section
Secure data exchange solutions must balance security, industrial availability, and system flexibility. Secure data sharing solutions must balance security, industrial availability, and system flexibility.

4 Proposed System

We define the proposed solution considering the requirements defined in Section 3.1. To this end, this Section explains the encryption cipher choice, defines the roles of the proposed system, and how they are mapped to an industrial high-level reference model.

4.1 Multi-Layered CP-ABE

As analyzed in Section 2, CP-ABE is a promising one-to-many encryption scheme that protects data by applying access policies—e.g., \( AP=(Mechanic \text{ AND Staff}) \). It also generates users’ secret keys using attributes—e.g., \( (Mechanic \ || \ Staff \ || Boss) \). Thus, the application of CP-ABE fulfills \( R4 \) by creating an Attribute-Based Access Control to Data. However, CP-ABE by itself only provides confidentiality. Thus, it has to be combined with symmetric ciphers that also provide integrity \( (R3) \). In this paper, the chosen symmetric cipher is AES-GCM.

Section 3 established that the data exchange system must be flexible and capable of handling a policy update. However, this requires managing existing encrypted data without breaking the E2E confidentiality or integrity. Thus, the proposed solution requires a CP-ABE system that accounts for this and manages policy updates on CP-ABE ciphertexts \( (CT_{ABE}) \) without overloading IIoT devices. To achieve this, we apply Multi-Layered CP-ABE \[18\], which combines CP-ABE with a symmetric cipher and policy update without violating the original message’s confidentiality or integrity.

Multi-Layered CP-ABE achieves policy updates through a layered encryption system, schematized in Figure 2. The original message \( (PT) \) is encrypted using symmetric encryption, e.g., AES. Then, the symmetric key \( (SK_{sym}) \) is encrypted using Multi-Layered CP-ABE. This implies iterative encryption of \( SK_{sym} \). The first layer \( (AP_1) \) is immutable and has CCA security, which protects the \( SK_{sym} \) against passive and active attackers. Then, the following layers \( (AP_2 \text{ through } AP_N) \) are added, containing the policies that can be updated.

The multilayer system requires a minimum of two layers, although developers can implement as many as desired. Users should note that fewer layers do not always lead to faster policy updates. The choice of the number of layers will depend on the device performing the update, the complexity of the policies contained in the layers, or the frequency with which they will be updated. Therefore, as suggested in \[18\], the outermost layers should be defined according to policies with the highest variability.

The layered system means that \( CT_{ABE} \) can be modified when an access policy is updated without exposing \( SK_{sym} \). This system ensures the confidentiality and integrity of the original message. Finally, Multi-Layered CP-ABE reduces the
computational burden on devices with more limited capabilities. This is because although the initial layer must be applied by the original device to guarantee E2E confidentiality, subsequent layers can be added by a more powerful device. These last layers can be updated and revoked as required by the system.

4.2 System Design

Multi-Layered CP-ABE provides both attribute-based access to data (R4) as well as policy update (R5). Figure 3 shows a conceptual representation of the E2E secure data exchange system. The developed system consists of eight roles, defined as follows:

- **Data Owners (DO)s.** These are typically IIoT devices that generate the original data. They use a symmetric algorithm, e.g., AES, to protect it. Then, they use CP-ABE to encrypt $SK_{sym}$. This way, only the original device, and the intended consumers know $SK_{sym}$ (R3). Data can be production parameters, digital products, tracking information, or any other sensitive information (R1). $SK_{sym}$ is protected by an immutable policy, as explained
in Section 4.1. DOs do not intervene again, reducing the interaction with the capacity-limited devices (R2).

- **Attribute Authority (AA).** During system setup, the AA generates the Master Secret Key (MSK) and Master Public Key (MPK) for CP-ABE. It stores and protects the MSK and sends the MPK to the DOs and CT engines. Finally, it generates the CP-ABE secret keys (SKs) based on consumers’ attributes and the timestamp indicating the key’s generation time.

- **System Manager.** It manages system access policies. When a policy is updated, it is in charge of sending it to the policy engine.

- **Policy Engine.** It pushes the new policies to the Policy Database. It also notifies the Internal CT Engine when a policy update occurs.

- **Internal CT engine.** It adds the encryption layers containing all the revocable and updatable policies. Once encrypted, it pushes them to the CT database. Whenever an access policy update occurs, it receives a notification from the Policy Engine and retrieves the old ciphertext from the CT database, updating and storing it again (R5). Note that the DO does not need to intervene in the policy update process (R2).

- **External CT engine.** Once system users obtain their CP-ABE key reflecting their attributes, they can use it to access all information whose access policy they comply with. However, there is always the risk of the keys being compromised. Therefore, it is necessary to have a system in place to ensure that consumers with old or compromised keys do not have access to the information. To this end, when a consumer requests a piece of data, the External CT Engine adds a new layer of CP-ABE encryption before sending it to the requesting consumer. This new layer defines an access policy that requires users to possess a key generated after the last security event in the system.

- **Policy Database.** It stores the access policies to be used for encryption.

- **CT database.** It stores the ciphertexts. The ideal solution is to set up a distributed storage solution. This way, the CTs are always accessible, even if one of the nodes goes down. Solutions like IPFS may be suitable since it distributes the storage, is immutable, and is tamper-resistant.

### 4.3 Industrial High-Level Reference Model

This section maps the roles shown in Figure 3 to a high-level industrial reference model. Industrial environments such as value chains benefit from defining the relationship between the architecture proposed in section 3 and existing reference models. The definition of the relationship between architecture and model reduces the proposal’s complexity and helps the stakeholders in the value chain define the structure to be used [16]. Thus, this mapping allows the different companies in the value chain to coordinate their elements and functions, identify common elements and share them.

Regarding high-level reference models, ENISA adapted the Purdue Model to smart manufacturing by establishing a five-layer model [19]. In this model, level
Based on the ENISA model, Figure 4 illustrates how the components of the proposed system are mapped to the high-level model. Data is generated and encrypted by the DOs, which can be IIoT devices located at level 1. The encrypted information is sent to the IIoT platform that the ENISA model defines at level 3. Finally, data reaches the engines and databases. The last element to be mapped in the model is the AA. The encryption system is based on the MPK and the MSK used by the authority to generate individual secret keys. The system presented has a single AA, shared by all members of the value chain and implemented through third-party services. In this context, the authority should be placed at level 5 of the ENISA model.

5 Policy Update and Revocation using Multi-Layered CP-ABE

The proposed CP-ABE scheme consists of four algorithms: system setup, key generation, encryption, and decryption. Policy addition and policy revocation are achieved by encryption and decryption algorithms.

- \textit{SystemSetup}(K) \rightarrow MPK, MSK
  This is the original CP-ABE setup algorithm, performed by the AA. After obtaining MPK and MSK, it sends the MPK to the DOs and the Engines.

- \textit{KeyGeneration}(MSK, \hat{\alpha}) \rightarrow SK
  Whenever users request a CP-ABE Secret Key (SK), the AA generates a timestamp for the request (T_{SK}). Then, the AA generates SK using the
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\( MSK \), according to an attribute set \( \mathcal{A} \) that contains the user’s attributes and \( T_{SK} : \mathcal{A} \leftarrow (\text{Att}_1 || \text{Att}_2 || \ldots || \text{Att}_n || T_{SK}) \).

The inclusion of \( T_{SK} \) in the policy makes sure that consumers with old \( SKs \) cannot access the system.

\(-\) Encryption(\( MPK, AP, PT \)) → \( CT_2 \)

![Diagram](image)

**Fig. 5.** Encryption message exchange

The message exchange between the DO and the internal CT engine during encryption is shown in Figure [5]. Note that generally, the DO is an IIoT device. The encryption process takes two significant steps. The first one generates \( CT_1 \) and is explained below.

1. The DO chooses a random AES-GCM key \( SK_{sym} \in \{0,1\}^n \) and nonce \( r \in \{0,1\}^n \). The DO generates a new \( SK_{sym} \) for every piece of data they create and encrypt.

2. The same device applies the Fujisaki-Okamoto transformation [8] combined with the Access Policy \( AP \) to create the nonce \( \text{u} \leftarrow H(r || SK_{sym} || AP) \).

3. To complete the Fujisaki-Okamoto transformation, the DO appends \( SK_{sym} \) to \( r \), resulting in \( M \leftarrow (SK_{sym} || r) \). Then, the first layer of CP-ABE encryption is applied to \( M \). This process of encrypting \( SK_{sym} \) is also known as encapsulation. This encryption process is summarized as follows: \( CT_{ABE_1} \leftarrow Enc_{ABE_{CP}}(MPK, AP, M, u) \). The performed Fujisaki-Okamoto transformation ensures the CCA Security, which, as mentioned in Section [4.1] protects \( SK_{sym} \) against passive and active attackers.

4. After encapsulating \( SK_{sym} \), the original message, \( PT \), is encrypted using AES-GCM. To guarantee the integrity of the encrypted \( SK_{sym} \), the authentication data is defined as \( AAD \leftarrow ExtractHeader(CT_{ABE_1}) \). \( PT \) is encrypted by running \( CT_{AES} \leftarrow Enc_{AES}(SK_{sym}, PT, AAD) \).

5. Finally, the devices send the resulting ciphertext \( CT_1 \leftarrow (CT_{AES}, CT_{ABE_1}) \) to the Internal CT Engine. With this, we finish the first exchange in Figure [5].

The second step of the encryption process generates \( CT_2 \). The internal CT engine adds the policy layers, which are applied so the innermost ones are...
less variable than the outermost ones. These layers contain the access policies that can be updated or revoked.

Algorithm 1: Policy Addition // Policy Update

Input: $CT_{ABE_1}, APs, MPK$
Output: $nLayers, CT_{ABE_2}$

1. for $i \leftarrow 0$ to $APs$ do
   2. if $i == 0$ then
      3. $C \leftarrow CT_{ABE_1}$
      4. $u \leftarrow H(C || AP_i)$
      5. $C_i \leftarrow Enc_{ABE_{CP}}(MPK, AP_i, C, u)$
      6. $nLayers + +$
      /* nLayers reflects the current amount of encryption layers. */
   7. else
      8. $u \leftarrow H(C_{i-1} || AP_i)$
      9. $C_i \leftarrow Enc_{ABE_{CP}}(MPK, AP, C_{i-1}, u)$
     10. $nLayers + +$

11. $CT_{ABE_2} \leftarrow C_i$

1. The Internal CT Engine requests the layered $APs$ to the Policy Database.
2. Then it performs the layered encryption over $CT_{ABE_1}$ to generate $CT_{ABE_2}$ by applying Algorithm 1. This same algorithm is the one used for Policy Update.
   (a) The Internal CT Engine takes the layered $APs$.
   (b) For the first iteration, it takes the inputed $CT_{ABE_1}$ and proceeds to rename it $C$.
   (c) Then, for each layer $AP_i$, it creates the random nonce $u \leftarrow H(C || AP_i)$.
   (d) With $u$ generated, the internal CT Engine applies the CP-ABE encryption resulting in $C_i$.
   (e) When $i = nLayers$, the iterations finish.
   (f) Finally, Algorithm 1 produces $CT_{ABE_2} \leftarrow C_i$.
3. The Internal CT Engine returns $CT_2 \leftarrow (CT_{AES}, CT_{ABE_2})$.
4. It finally sends $CT_2$ to the CT Database alongside information about the total number of layers, $nLayers$.

$Decryption(CT, SK, nLayers) \rightarrow PT$

In order to decrypt the $SK_{sym}$ encapsulated in $CT_2$, Supply chain consumers require a $SK$ provided by the AA. Consumers require $SKs$ to the AA whenever they log for the first time into the system or after a system security incident, which requires $SKs$ to be reissued.

Once the consumers have the $SK$, they can request $CT_2$ and try to decrypt it. To ensure that the keys have been issued after the last security incident, the External CT Engine performs a time-based encryption of $CT_2$. The result of
Algorithm 2: Layered Decryption // Policy Revocation

**Input:** $CT_{ABE_3}, nLayers, SK$

**Output:** $SK_{sym}', r', AAD, AP'$

1. $C ← CT_{ABE_3}$
2. for $i ← 0$ to $(nLayers - 1)$ do
   3. $C_i ← Dec_{ABECP}(MPK, SK, C_{i-1})$
   4. $CT_{ABE_i} ← C_i$
   5. $AAD ← ExtractHeader(CT_{ABE_i})$
   6. $\langle SK_{sym}'||r' \rangle ← Dec_{ABECP}(MPK, SK, CT_{ABE_1})$

This operation, $CT_3$, is sent back to the supply chain partner that requested it. The message exchange between the involved parties can be seen in Figure 6 and is explained below.

1. The engine defines a new access policy that requires the $SK$ to have been generated after the last security incident. For this purpose the policy takes the form of $AP_{time} ← (T_{SK} > T_{incident})$. In it, $T_{incident}$ is the timestamp of the last registered security incident in the system.
2. The External CT Engine generates the CP-ABE required random nonce computing $u ← H(CT_{ABE_2}||AP_{time})$.
3. The ciphertext is re-encrypted, generating $CT_{ABE_3} ← Enc_{ABECP}(MPK, AP_{time}, CT_{ABE_2}, u)$.
4. Finally, the engine sends the consumer the resulting ciphertext $CT_3 ← (CT_{AES}, CT_{ABE_3})$ and the amount of policies contained in it ($nLayers$).

With the obtained $CT_3$, the consumer tries to decrypt it.

1. The Consumer starts by applying Algorithm 2 to $CT_3$, which outputs $SK_{sym}', r', AAD, \text{ and } AP'$. This algorithm can be used for Policy Revocation of $i$ layers while $i < nLayers$.
   (a) The Supply Chain Partner takes $CT_{ABE_3}$ and loads it as $C_i$.
   (b) For every layer until $nLayers - 1$, it decrypts $C_i$ by using its $SK$.
   (c) For the layer $nLayers - 1$, the decryption of $C_i$ returns $CT_{ABE_1}$.

$CT_{ABE_1}$ was the original ciphertext produced by the DO, and thus contains the $SK_{sym}$ used to generate the corresponding $CT_{AES}$.

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**Fig. 6.** Decryption message exchange
(d) The user extracts the header from $CT_{ABE_1}$ and stores it to use as $AAD$.

(e) The partner performs the last CP-ABE decryption on $CT_{ABE_1}$, which returns $(SK'_\text{sym}||r')$.

(f) Finally, Algorithm 2 returns $AAD, SK'_\text{sym}$ and $r'$.

2. The Supply Chain Partner performs a security encryption for which the nonce is defined as $u' \leftarrow H(r'||AP'||SK'_\text{sym})$.

3. The security encryption is computed as: $CT'_{ABE_1} \leftarrow Enc_{\text{ABECP}} (MPK, AP', (r'||SK'_\text{sym}), u)$.

4. If $CT'_{ABE_1} == CT_{ABE_1}$, the consumer obtains $SK_{\text{sym}}$; if not, it obtains $\bot$.

5. With $SK_{\text{sym}}$, the consumer can obtain the original message $PT \leftarrow Dec_{\text{AES}}(SK_{\text{sym}}, CT_{AES}, AAD)$. Note that each $PT$ is generated with a different $SK_{\text{sym}}$, so the decryption process has to be performed in its entirety for each encrypted data in the system.

6 Experimental evaluation

To verify the requirement fulfillment analyzed in Section 4.2, we have created a setup simulating the roles of the proposed system. Subsection 6.1 describes the testbed setup. Section 6.2 discusses the designed experiments and the measured parameters.

Regarding the requirements established in section 3.1, “R1. Heterogeneous Data Exchange” is fulfilled by the message exchange system since it considers the three data types identified in Section 3.1, i.e., production parameters, digital products, and data related to physical product exchange. Meanwhile, the combination of CP-ABE and AES-GCM tackles “R3. E2E data confidentiality and integrity”. Moreover, CP-ABE also fulfills “R4. Non-Identity Based Access To Data” by creating an ABAC [30].

Thus, this section evaluates the fulfillment of “R2. Computational Scalability” and “R5. System flexibility and responsiveness”.

6.1 Testbed Setup

The main elements of the testbed designed for the experimental evaluation are:

- **DO**: The tasks assigned to this role are performed by Raspberry Pi Zero W (RPI0-W) with Raspbian Stretch. It has 512MB RAM, 1GHz, a single-core ARMv6, and Wi-Fi. It is thus a good representation of an IIoT device. The RPI0-W applies AES-GCM to messages and the first layer of CP-ABE Encryption to the $SK_{\text{sym}}$.

- **Internal CT Engine**: A Raspberry Pi 4 (RPI4) with 32 bits Ubuntu Server TLS. The RPI4 has a 8GB LPDDR4-3200 SDRAM and a Quad core Cortex-A72 (ARMv8). The RPI4 has to add the policy layers to the encrypted $SK_{\text{sym}}$. 
Consumer: This role is simulated using an Ubuntu Virtual Machine with an allocated RAM of 4GB within a host machine with an Intel Core i7-8850H CPU processor.

The used library is a modified version of OpenABE \cite{32} that implements the Multi-Layered CP-ABE. Further modifications have also been applied to compile the library for Raspbian, as well as ARMv6 and ARMv8 architectures.

6.2 Experiments definition

Regarding R5, its fulfillment is covered by the use of Multi-Layered CP-ABE, with the only constraint on its fulfillment being the system’s capability to accomplish the assigned tasks efficiently. Meanwhile, the system must perform encryption efficiently to be considered R2 compliant.

System DOs must encrypt two items. The original message, known as Plain-text (PT), and the symmetric key, SK\textsubscript{sym}. The PT encryption time is directly related to the size of the PT. Something similar happens with SK\textsubscript{sym} encryption, which also depends on its length. Therefore to study R2 compliance, the results focus on the time required for SK\textsubscript{sym} encryption. This is because the PT size is highly variable, while the chosen SK\textsubscript{sym} is always 256 bits.

We measure the encryption time required by DO (RPI0-W) to generate CT\textsubscript{ABE\textsubscript{1}}, and by the internal CT engine (RPI4) to generate CT\textsubscript{ABE\textsubscript{2}}. In addition, the result of this measurement is compared with the time required to create CT\textsubscript{ABE\textsubscript{2}} in the DO. The comparison illustrates the amount of work that has been offloaded to the internal CT engine.

To analyze how much the layers affect the Internal CT Engine, we measure the time required for the Internal CT Engine to generate CT\textsubscript{ABE\textsubscript{2}} if it were to apply all attributes in a single layer. In addition, the time needed to add policies represents the time it takes to update CT\textsubscript{ABE} since the update is performed by the same device using the same algorithm.

On the other hand, as already mentioned, SK\textsubscript{sym} is encrypted using CP-ABE. CP-ABE expands the original message when generating the CT, so this expansion has been studied as a function of the number of layers added. Furthermore, it has been compared with the result of encrypting a 160kBytes message to understand to what extent this growth of CT\textsubscript{ABE} affects the CT = (CT\textsubscript{AES}, CT\textsubscript{ABE}) obtained by consumers.

The measurements explained above have been obtained by performing the layered encryption 500 times and obtaining the average operation time. In addition, to correctly see the evolution of the results, we added up to 15 layers formed by three attributes. Thus, for the worst case, a total of 45 attributes are used.

6.3 Discussion of the Results

One of the main requirements of industrial scenarios is the availability of the system. Therefore, to fulfill R2, the IIoT devices have to encrypt information with an acceptable delay.
As mentioned, the proposed system combines AES-GCM and CP-ABE. Every encryption system causes an expansion of the message it encrypts. That is, the \( CT \) will always be larger than the corresponding \( PT \). However, the expansion generated by AES on the original message is practically negligible. In contrast, the expansion generated by CP-ABE cannot be disregarded. Therefore, we study how this increase in the \( CT \) size affects IIoT devices.

Figure 7 shows the time required to encrypt \( SK_{sym} \) on the y-axis, while the x-axis represents the total number of attributes contained in the policy. As mentioned above, the original message is encrypted with AES, so the layered encryption only affects the \( SK_{sym} \) encryption times. This proposal uses AES-256-GCM, so \( SK_{sym} \) is always 256 bits, regardless of the message size that AES encrypts. Therefore, Figure 7 only shows the time required for \( SK_{sym} \) encryption since it is the only value affected by the layered encryption. The encryption times in Figure 7 should be added to those resulting from symmetric encryption.

Figure 7 shows with red triangles the result of the DO applying the entire policy \( AP = (Att_1 \ AND \ Att_2 \ AND \ ... \ AND \ Att_n) \). Due to its limited capabilities, for 10 attributes, it takes 100% more time compared to the combined use case (in orange squares). In fact, for 40 attributes the difference goes from 750ms to 1.75s, increasing a 133%.

In the combined used case, the DO applies the first policy \( AP_1 = (Att_1 \ AND \ Att_2 \ AND \ Att_3) \). Then the Internal CT Engine applies the next layers by setting 3-attribute policies: \( AP_2 = (Att_4 \ AND \ Att_5 \ AND \ Att_6) \), \( AP_3 = (Att_7 \ AND \ Att_8 \ AND \ Att_9) \), up to \( AP_n \). The combined use of DO and Internal CT Engine demonstrates that even the worst-case encryption (45 attributes) takes 56% less time compared to the sole use of DO: 2s for the IIoT device and 0.84s for the combined case. It is also observed that the Internal CT Engine does not take much longer to add several layers (represented with orange squares) than it does to apply a single layer (represented with blue dots). It is also noteworthy
that the DO and Internal CT Engine combination achieves full key encryption in less than one second, even in the worst case.

Fig. 8. Total time required by the DO to generate $CT_{ABE_1}$ (orange) and the total time required for the Int. CT Engine to generate $CT_{ABE_2}$ (blue).

To better understand the combination of DO and External CT Engine and its correlation with encryption times, we present Figure 8. It provides a better understanding of the scenario represented with orange squares in Figure 7. DO protects the $SK_{sym}$ with a policy $AP_1 = (Att_1 AND Att_2 AND Att_3)$. Then, the Internal CT Engine adds layer-by-layer policies that maintain the same format. Figure 8 shows the total time required to create $CT_{ABE_1}$ and generate $CT_{ABE_2}$. This Figure depicts how time is distributed between the DO and the Internal CT Engine. The time consumed by the IIoT device in this scenario is constant, while the time consumed by the Internal CT Engine grows linearly as layers are added. This linear growth implies that the required time to add more layers is predictable and that encryption times do not escalate out of control.

Fig. 9. Sizes of the generated $CT_{ABE}$ and $CT_{AES}$

As discussed in Section 6.2, we analyze the size of $CT_{ABE_2}$. Figure 9 shows the total length of a $CT$ requested by a consumer for an original message of 160
kBytes. The figure compares the size in kBytes of the $CT$ with the total number of layers contained in $CT_{ABE}$. In the same figure, it can also be seen how the message size is divided between $CT_{AES}$ and $CT_{ABE}$. $CT_{ABE}$ has a significantly larger size than the original 256bits, but the expansion loses relevance compared to the size of the final $CT$. The reason for this is that $CT$ is influenced by the much larger size of $CT_{AES}$. Figure 9 shows that the proposed system achieves its maximum efficiency for large data packets, where the original message is much larger than the 256-bit AES key. Therefore, this result demonstrates the proposal’s suitability for the industrial environment. The DOs could send larger packets in longer intervals, which would reduce the interaction with the IIoT devices that constitute the DOs. In addition, the algorithm used to add policies is the same as the one used to update them, so it is proven that the update does not generate a $CT_{ABE}$ larger than $CT_{AES}$ for a reasonable number of attributes.

7 Conclusions

This paper proposes an E2E secure data exchange system for a value chain. E2E security protects members of the value chain from compromised partners and reduces the amount of sensitive data exposed due to data breaches. The proposed exchange system provides DOs in the value chain with control over who can access the information while allowing a straightforward definition of new value-chain partners. Having scalability to add new users favors system efficiency, flexibility, and management. The proposal is also mapped to ETSI’s High-Level Reference Model, facilitating the integration of the proposed system in an industrial environment.

The system is designed according to five requirements defined after studying the literature and considering security and industrial requirements. Our system fulfills “R1. Heterogeneous Data Exchange” because, as shown in the Results, even IIoT devices can perform the tasks assigned to DOs. IIoT devices are the ones that generate production parameters and data related to the exchange of physical products. This type of device has limited resources. Therefore, if they can protect the data they generate, the exchange of digital products is also protected since the devices that manage the latter have a higher computational capacity than IIoT devices.

Similarly, experiments also show the system is compliant with “R2. Computational Scalability” compliant. The IIoT devices can perform the designed tasks, and its combined use with a more powerful device yields efficient results. At any rate, the experiments also show that IIoT devices can protect the $SK_{AES}$, attaining E2E security. It also means that “R3. E2E data confidentiality and integrity” is fulfilled since only the DO and the consumer know $SK_{AES}$. Integrity is achieved by employing AES-GCM as symmetric cipher.

The system uses Multi-Layered CP-ABE to protect $SK_{AES}$, fulfilling “R4. Non-Identity Based Access Control to Data” by having a RBAC to data and “R5. Access Policy Update” by achieving policy update without break-
ing E2E Security. Besides, the IoT devices do not intervene in the policy update, which reinforces the compliance with R2.

Finally, the system also denies users using old $SK_{ABE}$ by generating an AP requiring a $SK_{ABE}$ generated after the last security event in the system.

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