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Time-Bound Hierarchical Key Assignment: An Overview*

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SUMMARY The access privileges in distributed systems can be effectively organized as a partial-order hierarchy that consists of distinct security classes, and the access rights are often designated with certain temporal restrictions. The time-bound hierarchical key assignment problem is to assign distinct cryptographic keys to distinct security classes according to their privileges so that users from a higher class can use their class key to derive the keys of lower classes, and these keys are time-variant with respect to sequentially allocated temporal units called time slots. In this paper, we present the involved principle, survey the state of the art, and particularly, look into two representative approaches to time-bound hierarchical key assignment for in-depth case studies.

key words: *information security, access control, time-bound hierarchical cryptographic key management*

1. Introduction

1.1 The Hierarchical Access Control Problem

With the rapid growth and pervasive deployment of information systems, sharing resources among multiple users over an open channel has become widespread. Access control on user permissions is a fundamental issue in any system that manages distributed resources. In this paper, we consider a *multilevel security* scenario, where users and data of an information system are organized into a hierarchy composed of disjoint *security classes*. Such a hierarchical structure arises from the fact that users in a distributed system may have distinct rights to access different parts or depths of the resources in the system, and some users may have higher privileges (in other terms, security levels or clearances) than others. In the real world there are many examples of this kind of hierarchy, such as in business administration, government departments, diplomatic corps, and the military. A *hierarchical* key assignment (KA) is to assign a distinct cryptographic key to each class so that users attached to any "base" class can also derive the keys of "lower" classes. As confidential data are classified into such security classes, they can be protected with respective encryption keys using a symmetric cipher, where the decryption operation asks a user for the same encryption key so as to recover the data.

Let there be m security classes C_ℓ, $1 \le \ell \le m$ in the hierarchy partially ordered according to a binary relation "$\preceq$". In this partial-order hierarchy $(C, \preceq)$, $C_j \prec C_i$ means the security level of class C_j is lower than that of class C_i (or, C_i dominates C_j), and $C_j \preceq C_i$ allows for the additional case of $j = i$. Formally, the hierarchical KA problem is to assign a key K_ℓ to each class C_ℓ, so that a user assigned to her base class C_i can use the issued K_i to derive any K_j (thus to recover the data in C_j), if and only if $C_j \preceq C_i$.

The partial-order hierarchy $(C, \preceq)$ can be mapped to a directed acyclic graph (DAG), where each class corresponds to a vertex and there is a directed edge from C_i to C_j if and only if $C_j \preceq C_i$. This graph can be simplified by eliminating all self-loops and edges which can be implied by the property of the transitive closure. Hence for such a refined DAG, an *edge* from C_i to class C_j implies that $C_j \prec C_i$ and there is no C_ℓ such that $C_j \prec C_\ell \prec C_i$. In this case, we say C_j is an immediate descendant of C_i, and C_i is an immediate ancestor of C_j. Accordingly, if $C_j \prec C_i$ but C_j is not an immediate descendant of C_i, there must be a directed *path* from C_i to class C_j connected by two or more directed edges. A class may have multiple immediate ancestors (e.g., in Fig. 1, C_6 has two immediate ancestors C_2 and C_3).

1.2 From Class Keys to Session Keys

In many commercial applications, there is an explicit temporal restriction so that a user is attached to her base class for only a limited period of time consisting of a contiguous set of time slots. Let the time dimension be discretized into even units (i.e., time slots or intervals) $t = 0, 1, \cdots, z$. Here the maximum index z should not be considered as a limitation of the access control, as the system lifetime may be arbitrarily large. For instance, if each time slot represents a second, $z = 3.156 \times 10^7$ denotes roughly 1 year; if each slot represents a week, $z = 5217$ denotes roughly 100 years.

Now, instead of with the previous K_i, let the data classified into C_i at time t be encrypted with a volatile key $k_{i,t}$. Such periodical update of the encryption key (i.e., employing a dynamic key instead of a static one) implies enhanced security against cryptanalysis, and thus is also beneficial to applications where there are no explicit temporal con-

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straints. Incorporating the temporal feature, we say the *class key* K_i is instantiated with a series of *session keys* $\{k_{i,t}\}$, by specifying:

- The static K_i for C_i is only used for generating session keys $\{k_{i,t}\}$ as well as deriving the time-invariant class key K_j of any lower class $C_j \prec C_i$, but never for actual data encryption.
- Only the time-based $k_{i,t}$ is employed by the aforementioned symmetric cipher for real data protection with respect to security class C_i, from session to session indexed by the time slot t.

A typical application of such time-bound hierarchical KA scheme is the digital pay TV system, where the service provider organizes the channels into several possible subscription packages for users' choices [1]. For example in Fig. 1 there are four independent TV channels C_5, C_6, C_7, and C_8, and subscription to package C_3 allows for the access to two of them (C_6 and C_8), while subscription to package C_1 allows for all. Another example is the electronic journal subscription system, where a user can subscribe to any combination of the available journals within a chosen period of time [2].

Assume a trusted central authority (CA) manages the key assignment. Upon registration, a user authorized to her base class C_i ($1 \le i \le m$) for time $[t_1 \cdots t_2]$ ($0 \le t_1 \le t_2 \le z$) is assigned by the CA certain *private primitive* denoted as $I(i, t_1, t_2)$. She should only be able to compute from $I(i, t_1, t_2)$ the session keys $\{k_{j,t}\}$ satisfying $C_j \le C_i$ and $t_1 \le t \le t_2$, thus only authorized to access the data stored in class C_j at time t. The session key derivation is constrained by both the class relation and the time bounds (t_1 and t_2), and the derived $k_{j,t}$ should equal the instance of the class key K_j at time t. The CA is active only at user registration. No private channel exists between the CA and the user after the issuance of the private primitive, i.e., the user should derive $k_{j,t}$ from only $I(i, t_1, t_2)$ and certain static public information, with no interaction with the CA.

In this paper, we refer interchangeably to time-based, time-bound, time-dependent, and time-variant. The rest of this paper is organized as follows. Section 2 surveys the literature. Sections 3 & 4 review and analyze two representative time-bound hierarchical KA schemes. Concluding remarks are in Sect. 5.

2. Time-Bound Hierarchical KA: A Survey

In the literature, the hierarchical cryptographic KA problem was first studied by Akl and Taylor [3] in 1983, where the temporal consideration was yet unavailable. A recent modification of the Akl-Taylor scheme [3] can be found in [1], where a technique termed "merging" is introduced so that a solution more efficient than the original one [3] is possible; even the multilevel security hierarchy itself may not need to be constructed.

In 2002, Tzeng proposed a time-dependent hierarchical KA scheme [4] as an extension of the Akl-Taylor approach [3] with an additional access control on the temporal dimension technically enabled with the Lucas sequence [5], which is similar to the RSA public-key cryptosystem [6]. The scheme has some interesting applications such as secure broadcasting and cryptographic key backup [4]. Bertino *et al.* immediately adopted Tzeng's scheme and showed that the scheme [4] is readily applicable to secure broadcasting of XML documents [7]. However, this first time-bound hierarchical KA scheme [4] was soon found to be vulnerable to the collusion attack. In [8], Yi and Ye showed that three users can conspire to infer some session keys that even a combination of them is not entitled to, but no security fix was proposed. We note that the identified security breach is irrelevant to the Lucas sequence [5] featured in Tzeng's scheme [4], although there are certain known weaknesses associated with the sequence [9].

In 2004, Chien proposed the second time-bound hierarchical KA scheme employing a tamper-resistant device [10], which is a direct extension to the time-invariant hierarchical KA scheme earlier proposed by him and Jan [11]. The time-dependent scheme [10] is quite different from Tzeng's [4] and greatly improves the computational performance. Interestingly, later Yi again showed that Chien's scheme is subject to the collusion attack, where again three users can conspire to acquire some unauthorized session keys [12], but in a manner not as sophisticated as in his previous collusion attack [8] against Tzeng's scheme [4]. Again Yi did not propose any security fix, though several very lightweight remedies are possible [13]. Although this time Bertino *et al.* took into consideration Yi's three-party collusion attack [12] and proposed in [14] a security fix, their approach requires that the tamper-resistant device additionally support elliptic-curve cryptography, and thus is far more complex and cost-expensive than straightforward improvements on Chien's scheme [10] such as those demonstrated by De Santis *et al.* [13]. Moreover, a complex solution does not always make for security [15], and the heavyweight security fix presented by Bertino *et al.* [14] was recently found to be still vulnerable to the collusion attack [16], where even only two conspirers are sufficient to break the fix.

In 2005, Yeh proposed a new time-bound hierarchical KA scheme [2] based on the RSA public-key cryptosystem [6], which is claimed to be resilient to collusion attacks. Unfortunately, Ateniese *et al.* soon identified that the scheme [2] is insecure against a two-party collusion attack [17], and the attack even affects a later work by Yeh published in 2008 [18]. There is also a scheme [19] very similar to Yeh's [2], and is found to be vulnerable to a two-party collusion attack [20] as well.

In 2006, Wang and Laih proposed an alternative implementation of the Akl-Taylor scheme [3] employing the so-called merging technique [1]. The technique not only is applicable to the spatial dimension (i.e., the partial-order hierarchy) but also can be extended to construct a time-bound KA scheme based on a two-dimensional "global hierarchy", which is the Cartesian product [4] of the security class hierarchy and the virtual *time hierarchy*. At the same

Table 1 Brief summary of time-bound hierarchical KA schemes in the literature.

Scheme	Security	Related	Notes
Akl-Taylor [3]	provable	[1], [4]	time-invariant; provably secure with the strong RSA assumption
Tzeng [4]	compromised [8]	[7]	Lucas sequence [5] has known weaknesses [9]; e_i generation defective [21]
Chien [10]	compromised [12]	[11], [13], [14]	fix with security proof available in full version of [16]
Bertino et al. [14]	compromised [16]		fix with security proof available in full version of [16]
Yeh [2]	compromised [17]	[18]	
Huang-Chang [19]	compromised [20]		
Wang-Laih [1]	no formal proof		
Tzeng [21]	no formal proof		e_i's become pairwise relatively prime (thus slightly different from [3], [4])
Ateniese et al. [17]	provable		contributes the first formal framework and two provably secure schemes
Atallah et al. [22]	provable	[23]	incorporates time-dependent capabilities to existent key management
Briscoe [24]	no formal proof	[25]	purely time-based, no security hierarchy

time, Tzeng proposed a secure data access system [21] based on an anonymous authentication scheme and his new time-based hierarchical KA scheme, the latter among which appears immune to collusion attacks. In the same year, the first result that provides a formal framework for time-bound hierarchical KA schemes was given by Ateniese *et al.* [17], where the notion of security for such KA schemes is formalized and two provably secure solutions are also proposed. It is worth noting that, both Tzeng's new time-bound KA scheme [21] and Ateniese *et al.*'s provably secure solutions [17] consider the spatial hierarchy and the temporal dimension in an integrated, transformed view like the "global hierarchy" [1]. Therefore, the underlying ideas of these three works [1], [17], [21] in 2006 bear certain similarities.

The study on time-dependent hierarchical key assignment originated from the time-invariant KA problem in a partial-order hierarchy [3], but recently the research on purely time-based KA has become a topic of interest, where the notion of security classes is absent, i.e., the considered multilevel security reduces to a setting with only a universal class. For example, Atallah *et al.* presented in 2007 a provably secure approach that can incorporate time-dependent capabilities to existent key management schemes [22]. If the time is regarded as a single dimension, their solution can be extended to higher dimensions, and a proof of concept with respect to two dimensions is presented in [23] in the geospatial setting. In 2008, Srivatsa *et al.* followed the same idea, and applied Briscoe's time-dependent KA scheme [24] to three dimensions, in a similar context of location-based broadcast services [25].

The topic of time-bound hierarchical KA has been widely discussed since 2002 [4]. A major problem observed is that, a proposed scheme may soon be found subject to certain collusion attacks (e.g., [8] against [4], both [12] and [13] against [10], [20] against [17], [19] against both [2] and [18], and the recent [16] against [14]), though sometimes a corresponding remedy may be available. Another problem is as follows. Typically, these schemes either involve public-key operations (modular exponentiations following the Akl-Taylor style [3]) or alike computations (the Lucas sequence in [4], and even bilinear maps in [17]), or require the protection by a tamper-resistant device (sometimes even both, as in Bertino *et al.*'s heavyweight security fix [14]). However, public-key (i.e., asymmetric) operations can be about a thousand times slower than symmetric ones [6], and commodity (particularly, low-cost) devices usually are not equipped with tamper-resistant casings. Hence, existent time-bound hierarchical KA schemes in general may not be very practical, and more research effort is needed before this security technique can be adopted in pervasive and emerging applications.

More recently proposed schemes [1], [17], [21] are believed to be resilient to collusion attacks, and may even achieve provable security. However, understanding the underlying constructions needs a heavy research background in cryptology, and they may not be easily implemented due to their intrinsic complexity (hence they are not topic of interest in the following sections). For example, in [1] the Akl-Taylor style [3] modular exponentiation is applied to the so termed "global hierarchy", which is the Cartesian product [4] of the original partial-order hierarchy and the conceived time hierarchy. Similar approach is adopted in [21]. These two schemes not only are computation-intensive, but also ask for a significant amount of public storage. In [17], two provably-secure time-bound hierarchical KA schemes were proposed, one based on symmetric encryption and the other based on bilinear maps. While the former scheme seems preferable in terms of processing cost, it asks for a prohibitively large public storage space scaling as $O(m^2z^3)$, where m is the number of security classes in the partial-order hierarchy and z denotes the system lifetime. Note that z^3 may be enormous (recall the examples in Sect. 1.2). In [22], Atallah *et al.* showed that it is possible to create a full-fledged hierarchical access control scheme with time-bound capabilities, but the proposed scheme also requires a formidable amount of public information.

We summarize the literature survey in Table 1. Next, we review two time-bound hierarchical KA schemes of interest proposed by Tzeng [4] and Chien [10], respectively. We provide a didactic viewpoint concerning not only their security but also pragmatic issues like practicality. We also present technical challenges and indicate possible directions for future research.

3. Tzeng's Scheme

3.1 Review of the Scheme

In 2002, Tzeng proposed the first time-bound hierarchical KA scheme [4] by introducing a time-based dimension to the Akl-Taylor scheme [3]. Following our notation, Tzeng's scheme can be considered as a generalization of previous ones where the private primitive $I(i, t_1, t_2)$ assigned by the CA to a user simply reduces to a single K_i, the time-invariant class key of his base class. Intuitively, the time-variant extension can be made by requiring each user to memorize $(t_2 - t_1 + 1)$ instances of each class key assigned to his base class C_i and all the classes lower down in the partial-order hierarchy. However, storing $O(t_2 - t_1)$ keys is not realistic as z may be arbitrarily large. Tzeng not only introduced the time-bound concept, but also showed that it is possible to find a solution far more elegant than the straightforward extension whose storage expense may be on the order of mz in the worst case. In Tzeng's scheme [4] the user private primitive $I(i, t_1, t_2)$ only consists of a very small quantity of information, whose size is independent of either the number of classes that the user can access (i.e., $|\{C_j | C_j \preceq C_i\}|$) or the number of authorized time slots (i.e., $(t_2 - t_1 + 1)$). However, the price is that, the derivation of the session key is very costly. Next, we look into its mathematical details.

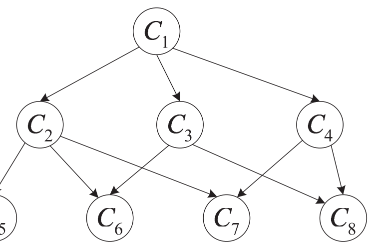
Initialization. Assume that a partial-order hierarchy consists of m disjoint classes C_i, $1 \le i \le m$ ordered by the binary relation "$\preceq$", for a lifetime numbered as slots 0 throughout z. The CA chooses two pairs of large strong primes (p_1, q_1) and (p_2, q_2), and computes $n_1 = p_1 q_1$ and $n_2 = p_2 q_2$. The CA also selects two random numbers a and b, $1 < a < n_1$ and $1 < b < n_2$. Numbers p_1, q_1, n_1, and a are for the partial-order hierarchy, while numbers p_2, q_2, n_2, and b are for the Lucas sequence [5] implementing the time-bound attribute.

- For the partial-order hierarchy, the CA randomly chooses $g_1, g_2, e_1, e_2, \cdots, e_m \in \mathbb{Z}^*_{\phi(n_1)}$, and computes $h_1, h_2, d_1, d_2, \cdots, d_m$ such that $g_1 h_1 \equiv g_2 h_2 \equiv e_i d_i \equiv 1 \pmod{\phi(n_1)}$ for $1 \le i \le m$.
- Concerning the time dimension, the CA randomly chooses f_1 and f_2, and associates with each $t \in [0 \cdots z]$ a $w_t = V_{f_1^{z-t} f_2^t}(b)$, which we call the *instance secret*. The Lucas sequence $\{V_\ell(x)\}_{\ell=0}^{\infty}$ regarding $x \in \mathbb{Z}^+$, is defined over $\mathbb{Z}_{n_2}$ as $V_\ell(x) = \ell V_{\ell-1}(x) - V_{\ell-2}(x) \bmod n_2$ for $\ell \ge 2$, with the initial conditions $V_0(x) = 2$ and $V_1(x) = x \bmod n_2$. One of its properties is $V_{\ell_1}(V_{\ell_2}(x)) = V_{\ell_1 \ell_2}(x)$.

Public information. A one-way hash function H and parameters $(n_1, g_1, g_2, e_1, e_2, \cdots, e_m)$, (n_2, f_1, f_2).

Class key. The CA computes $K_0 = a^{d_1 d_2 \cdots d_m} \bmod n_1$, and for $1 \le i \le m$, the class key of C_i is defined as $K_i = K_0^{\prod_{C_\ell \not\preceq C_i} e_\ell} \bmod n_1$. Figure 1 illustrates the class key assignment for a possible partial-order hierarchy.

Session key. The encryption key for class C_i (i.e., the instance of K_i) at time $t \in [0 \cdots z]$ is:



$$\begin{aligned}
K_1 &= K_0\ (= a^{d_1 d_2 \cdots d_8}) \\
K_2 &= K_0^{e_1 e_3 e_4 e_8} \\
K_3 &= K_0^{e_1 e_2 e_4 e_5 e_7} \\
K_4 &= K_0^{e_1 e_2 e_3 e_5 e_6} \\
K_5 &= K_0^{e_1 e_2 e_3 e_4 e_6 e_7 e_8} \\
K_6 &= K_0^{e_1 e_2 e_3 e_4 e_5 e_7 e_8} \\
K_7 &= K_0^{e_1 e_2 e_3 e_4 e_5 e_6 e_8} \\
K_8 &= K_0^{e_1 e_2 e_3 e_4 e_5 e_6 e_7}
\end{aligned}$$

Fig. 1 A partial-order hierarchy of $m = 8$ classes following the Akl-Taylor KA [3]. All keys are modulo an RSA modulus.

$$k_{i,t} = H(\gamma(i,t), w_t), \text{ where } \gamma(i,t) = K_i^{h_1^t h_2^{z-t}} \bmod n_1. \quad (1)$$

Private primitive. When a user is to be attached to the base class C_i for the period of time $[t_1 \cdots t_2]$, he is given $I(i, t_1, t_2) = (K_i^{h_1^{t_2} h_2^{z-t_1}} \bmod n_1, V_{f_1^{z-t_2} f_2^{t_1}}(b)) = (I_K, I_V)$, which is always of a constant size $(n_1 + n_2)$.

Key derivation. Given $I(i, t_1, t_2) = (I_K, I_V)$, the user can derive any $k(j, t)$ if $C_j \preceq C_i$ and $t_1 \le t \le t_2$. To do so, he first computes (including inferring K_j from K_i):

$$\begin{aligned}
&I_K^{g_1^{t_2-t} g_2^{t-t_1} \prod_{C_\ell \preceq C_i, C_\ell \not\preceq C_j} e_\ell} \bmod n_1 \\
&= (K_i^{\prod_{C_\ell \preceq C_i, C_\ell \not\preceq C_j} e_\ell})^{h_1^{t_2} h_2^{z-t_1} h_1^{t-t_2} h_2^{t_1-t}} \bmod n_1 \\
&= K_j^{h_1^t h_2^{z-t}} \bmod n_1 = \gamma(j,t), \text{ and} \\
&V_{f_1^{t_2-t} f_2^{t-t_1}}(I_V) = V_{f_1^{t_2-t} f_2^{t-t_1} f_1^{z-t_2} f_2^{t_1}}(b) = w_t.
\end{aligned}$$

Then, following (1) he can derive $k_{j,t} = H(\gamma(j,t), w_t)$.

3.2 Yi and Ye's Attack against the Scheme

In [8], Yi and Ye demonstrated a sophisticated collusion attack essentially against the time-bound property of Tzeng's scheme [4], while the partial-order property inherited from the Akl-Taylor scheme [3] is not challenged. The affected element in the user private primitive $I(i, t_1, t_2) = (I_K, I_V)$ is I_K, while I_V based on the Lucas sequence [5] appears to be not responsible for the identified security breach. Although cryptologists have warned against certain applications of the Lucas sequence [9], so far there is no reported weakness concerning its adoption in the time-bound KA scheme [4].

The collusion attack [8] can be generalized as follows. Assume there are three users A with $I(a, t_1, t_2)$, B with $I(b, t_3, t_4)$, and C with $I(c, t_5, t_6)$, where $t_5 \le t_2 \le t_3 \le t_6$. The security class of concern is any C_j satisfying $C_j \preceq C_a$, $C_j \preceq C_b$, but $C_j \not\preceq C_c$. Following [4], A can compute $\gamma(j, t_2)$ and B can compute $\gamma(j, t_3)$ (recall formula (1)). The point is that, it is feasible to infer $\gamma(j, t)$ for any $t \in [t_2 \cdots t_3]$, from $\gamma(j, t_2)$ and $\gamma(j, t_3)$ [8]. Therefore, with such $\gamma(j, t)$ offered by A and B, and the instance secret w_t computed by C (note that $[t_2 \cdots t_3] \subseteq [t_5 \cdots t_6]$), the three inner attackers can follow formula (1) to infer $k(j, t)$ for $t_2 \le t \le t_3$, which even a combination of them is not entitled to.

3.3 Discussions

Bertino *et al.* directly adopted Tzeng's scheme to build an access control mechanism for XML documents [7], and thus their mechanism is also subject to the above collusion attack. However, in [8] Yi and Ye did not provide any remedy to Tzeng's scheme. We note for the user private primitive $I(i, t_1, t_2) = (I_K, I_V)$, both I_K and I_V are time-bound, which seems unnecessary; actually, sometimes complexity impairs security [15]. Hence, a possible fix is to remove from the vulnerable I_K the time-dependent ingredient (the exponent $h_1^{t_2} h_2^{z-t_1}$), resulting in $I_K = K_i \bmod n_1$. This way I_K and I_V, the two building blocks respectively addressing spatial class designation and temporal restrictions, are decoupled, which corresponds to clear separation of duty. In a nutshell, formula (1) now becomes $k_{i,t} = H(K_i \bmod n_1, w_t)$. As we shall see later, Chien's scheme [10] exactly follows such a decoupled structure.

The above approach, however, is still subject to the following two-party collusion attack: if user A with $I(a, t_1, t_2)$ offers the class key $K_a \bmod n_1$ while user B with $I(b, t_3, t_4)$ offers the instance secret w_t for $t_3 \le t \le t_4$, they can easily conspire to compute $k(a, t)$ for $t_3 \le t \le t_4$ (also $k(b, t)$ for $t_1 \le t \le t_2$). Such collusion, which we call the *interweaving* attack, violates the security policy. This can be eliminated by introducing a tamper-resistant device. It computes $k(j, t) = H(K_j \bmod n_1, w_t)$ for $C_j \le C_i$ and $t_1 \le t \le t_2$, from $I(i, t_1, t_2) = (I_K, I_V) = (K_i \bmod n_1, V_{f_1^{z-t_2} f_2^{t_1}}(b))$ stored in the device and some public information either stored locally or available online, in such a secure manner that any stored secret (e.g., I_K or I_V) will not be revealed even to the device owner. This way I_K and I_V are *fully* decoupled, as any interweaving is impossible. We also note that, in cases where the multilevel hierarchical characteristic is not needed (i.e., the considered setting reduces to only a single security class), the instance secret w_t, in the absence of the tamper-resistant device, can play the role of a time-bound session key.

As long as there is no weakness found regarding the usage of the Lucas sequence, the above remedy seems feasible. However, in practice the tamper-resistant device may not always be available. Besides the collusion attack, Tzeng's scheme has the disadvantage that the key derivation is very expensive. Inherited from the Akl-Taylor time-invariant hierarchical KA scheme [3], computing K_j from K_i for $C_j \prec C_i$ involves expensive public-key operation (modular exponentiation). At the same time, computing the Lucas sequence proves to be likewise expensive. Although there are fast algorithms [5], each Lucas operation is roughly equivalently expensive as a modular exponentiation [4]. Therefore, the overall algorithm is computation-intensive. Although Tzeng's scheme [4] is efficient in terms of storage and communication, the heavy computational loads and implementation costs may limit its actual deployment.

Recall that Yi and Ye's three-party collusion attack [8] is only against the time-bound property of Tzeng's scheme [4], while the partial-order property is not challenged. However, we observe that there is some slight difference between the original Akl-Taylor scheme [3] and its adoption in Tzeng's scheme [4]. In Tzeng's scheme, the class keys are computed in the RSA setting [6], with the modulus $n_1 = p_1 q_1$ and the random exponents $e_i \in \mathbb{Z}^*_{\phi(n_1)}$, $e_i d_i \equiv 1 \pmod{\phi(n_1)}$ for $1 \le i \le m$. Consequently, in [4] $K_0 = a^{d_1 d_2 \cdots d_m} \bmod n_1$, and $K_i = K_0^{\prod_{C_\ell \not\le C_i} e_\ell} \bmod n_1$ for $1 \le i \le m$. In the Akl-Taylor scheme [3], however, K_0 is randomly chosen (i.e., information-theoretic), while each class C_i is associated with a distinct prime e_i. Although K_i is computed from K_0 in the same manner, Tzeng's modification complicates the generation of K_0, as all the d_i's in [4] are actually unnecessary. Moreover, a subtle security breach may arise regarding the selection of e_i's. Next, we discuss this problem separately.

We begin with a very simple partial-order hierarchy containing only three security classes C_1, C_2, and C_3, where C_2 and C_3 are both immediate descendants of C_1 (hence C_2 and C_3 are independent of each other). Since $C_2 \le C_1$ and $C_3 \le C_1$, we have $K_2 = K_0^{e_1 e_3} \bmod n_1$ and $K_3 = K_0^{e_1 e_2} \bmod n_1$. In most cases, randomly selecting $e_i \in \mathbb{Z}^*_{\phi(n_1)}$ as in [4] does not lead to a problem. However, if one of e_2 and e_3 happens to be a divisor of the other (which can be easily checked as all e_i's are public), say $e_2 | e_3$, then users in C_3 can trivially compute the class key of an irrelevant security class C_2 by $K_2 = K_3^{\frac{e_3}{e_2}} \bmod n_1$. The problem may also occur in a more complicated (and possibly more realistic) hierarchy. One can take Fig. 1 for example, where K_5, K_6, K_7, and K_8 are four independent class keys; there might be a similar security breach if the exponents e_5, e_6, e_7, and e_8 are chosen without care. Therefore, although e_i's do not necessarily need to be primes (but specified in the original Akl-Taylor scheme [3] and derivatives like [1]), any of them should not be a divisor of any else. This observation can be attributed to Tang and Mitchell [20], though the actual target of their attack is Huang and Chang's scheme [19].

It is also worth noting that, later in Tzeng's new time-bound hierarchical KA scheme [21], K_0 becomes information-theoretic (thus no d_i's), while (according to a footnote in [21] but without any explanation) e_i's should be pairwise relatively prime; the rest remains the same, say $K_i = K_0^{\prod_{C_\ell \not\le C_i} e_\ell} \bmod n_1$, and thus $K_j = K_i^{\prod_{C_\ell \le C_i, C_\ell \not\le C_j} e_\ell} \bmod n_1$ for $C_j \le C_i$. Although looser than originally specified by Akl and Taylor [3], the unexplained requirement on e_i's may still seem to be an overkill; that any of them is not a divisor of any else seems sufficient for security. However, we show the requirement is necessary by again considering the example in Fig. 1. Suppose $\gcd(e_6, e_4 e_7 e_8) = 1$. Then a user in C_4 knowing $K_4 = K_0^{e_1 e_2 e_3 e_5 \cdot e_6} \bmod n_1$, and a user in C_6 knowing $K_6 = K_0^{e_1 e_2 e_3 e_5 \cdot e_4 e_7 e_8} \bmod n_1$, can conspire to infer $K_0^{e_1 e_2 e_3 e_5} \bmod n_1$ following the merging idea [1], essentially by employing the common modulus attack [6]. Assume $e_3 | e_4 e_7$, say $e_3 = 15$, $e_4 = 9$, and $e_7 = 25$. Then, $K_3 = K_0^{e_1 e_2 e_5 \cdot e_4 e_7} \bmod n_1$ can be easily derived from $K_0^{e_1 e_2 e_5 \cdot e_3} \bmod n_1$, which is the class key of C_3 but not intended for even the coalition of C_4 and C_6. It is enough to deter such collusion attack by requiring the e_i's to be pairwise relatively prime.

4. Chien's Scheme

4.1 Review of the Scheme

In 2004, Chien proposed the second time-bound hierarchical KA scheme [10] involving no expensive operations like modular exponentiation or Lucas sequence. It actually extends his time-invariant KA protocol [11] featuring a reference table instead of following the Akl-Taylor style [3] with a tamper-resistant device performing mainly one-way hash functions. From [11] to [10], the introduced instance secret w_t is computed by the tamper-resistant device with a technique that can be termed as the dual directional hash chains, which serves as the building block for the temporal restrictions.

Let $H^{\ell}(x)$ be the result of applying a one-way hash function H for ℓ times to x. Then $x, H(x), H^2(x) \cdots$ forms a forward hash chain. Chien's scheme [10] employs two hash chains (a forward one and a reverse one), and is far more efficient than Tzeng's scheme [4]. However, the computation of the instance secret w_t needs the protection by a tamper-resistant device. Otherwise, two users may conspire to share the "earlier" one of their forward chains and the "later" one of their reverse chains to infer unauthorized instance secrets. Note the Lucas sequence in [4] is not subject to such a collusion. Therefore, compared with Tzeng's scheme, Chien additionally introduced a tamper-resistant device.

Next, we look into the nuts and bolts of Chien's scheme [10]. We follow the previous notation.

Initialization. The CA randomly selects a server secret key X, two secret values a and b, and m keys $K_i, 1 \leq i \leq m$. The security class C_i, identified by ID_i, is assigned the class key $K_i, 1 \leq i \leq m$.

Public information. For each directed edge $C_j \prec C_i$ in the hierarchy, the CA publishes a reference $r_{ij} = H(X\|ID_i\|ID_j\|K_i) \oplus K_j$ on a public board, resulting in the public reference table $\{r_{ij} \mid C_j \prec C_i, 1 \leq i, j \leq m\}$.

Session key. Compute w_t with the dual hash chains. Then the data in class C_i at time t is encrypted with:

$$k_{i,t} = H(K_i \oplus w_t), \text{ where } w_t = H^t(a) \oplus H^{z-t}(b). \qquad (2)$$

Private primitive. When a user is assigned to his base class C_i for a period of time $[t_1 \cdots t_2]$, the CA distributes K_i to the user through a secure channel. The CA also issues the user a tamper-resistant device, in which X, $H^{t_1}(a)$, and $H^{z-t_2}(b)$ are secretly stored (even inaccessible to the device owner). The device also contains non-confidential (but readonly) information ID_i and H. Therefore, $I(i, t_1, t_2) = (K_i, H^{t_1}(a), H^{z-t_2}(b))$ is the user-specific private primitive (of a constant size, similar to Tzeng's scheme [4]).

Key derivation. With the tamper-resistant device, the user entitled to $I(i, t_1, t_2)$ can derive any $k(j, t)$ for $C_j \preceq C_i$ and $t_1 \leq t \leq t_2$. For example, if $C_j = C_i$, the user simply enters K_i into the device, which yields $k_{i,t} = H(K_i \oplus H^{t-t_1}(H^{t_1}(a)) \oplus H^{t_2-t}(H^{z-t_2}(b)))$ complying with (2). Generally, assume the path from C_i $(= C_{\ell_\theta}, \theta \geq 2)$ to C_j $(= C_{\ell_1})$ is $C_{\ell_1} \prec C_{\ell_2} \prec \cdots \prec C_{\ell_\theta}$, where C_{ℓ_d} is an immediate descent of $C_{\ell_{d+1}}, 1 \leq d \leq \theta - 1$. The user enters $r_{\ell_\theta \ell_{\theta-1}}, r_{\ell_{\theta-1}\ell_{\theta-2}}, \cdots, r_{\ell_2\ell_1}$, $ID_{\ell_\theta}(= ID_i), ID_{\ell_{\theta-1}}, \cdots, ID_{\ell_2}, ID_{\ell_1}(= ID_j)$, and $K_{\ell_\theta} = K_i$ into the device, which sequentially computes:

$$\begin{aligned} K_{\ell_{\theta-1}} &= r_{\ell_\theta\ell_{\theta-1}} \oplus H(X\|ID_{\ell_\theta}\|ID_{\ell_{\theta-1}}\|K_{\ell_\theta}), \\ K_{\ell_{\theta-2}} &= r_{\ell_{\theta-1}\ell_{\theta-2}} \oplus H(X\|ID_{\ell_{\theta-1}}\|ID_{\ell_{\theta-2}}\|K_{\ell_{\theta-1}}), \cdots \\ K_j = K_{\ell_1} &= r_{\ell_2\ell_1} \oplus H(X\|ID_{\ell_2}\|ID_{\ell_1}\|K_{\ell_2}), \\ w_t &= H^{t-t_1}(H^{t_1}(a)) \oplus H^{t_2-t}(H^{z-t_2}(b)), \end{aligned}$$

and $k_{j,t} = H(K_j \oplus w_t)$ following (2).

4.2 Yi's Attack against the Scheme

In [12], Yi again demonstrated a three-party collusion attack, which is against Chien's scheme [10] and is generalized as follows. Assume there are three users A with $I(a, t_1, t_2)$, B with $I(b, t_3, t_4)$, and C with $I(c, t_5, t_6)$, where C_c is an immediate descendant of C_b but $C_a \npreceq C_b$. At first, with the public reference $r_{bc} = H(X\|ID_b\|ID_c\|K_b) \oplus K_c$, C knowing K_c can infer $H(X\|ID_b\|ID_c\|K_b) = r_{bc} \oplus K_c$ and forward it to B. Suppose A also forwards K_a to B. Then B, as if going to derive $k_{c,t}$ for $t_3 \leq t \leq t_4$, can enter into his tamper-resistant device the correct class identifier ID_c, his base class key K_b, but a crafted $r'_{bc} = H(X\|ID_b\|ID_c\|K_b) \oplus K_a$. The device is then misled into computing $K'_c = r'_{bc} \oplus H(X\|ID_b\|ID_c\|K_b) = (H(X\|ID_b\|ID_c\|K_b) \oplus K_a) \oplus H(X\|ID_b\|ID_c\|K_b) = K_a$, which appears to be still within the combined knowledge of the three conspiring users A, B, and C. However, the point is that, B's device can also compute w_t for $t_3 \leq t \leq t_4$, and thus can yield corresponding $k_{a,t}$ following (2). Obviously, such collusion violates the intended security policy (unless $[t_3 \cdots t_4] \subseteq [t_1 \cdots t_2]$). In other words, it is easy for the three users to acquire K_a's instances beyond A's authorized time period $[t_1 \cdots t_2]$.

4.3 Discussions

This time, different from the previous one [8], Yi's attack [12] against Chien's scheme [10] actually targets the partial-order property, while the time-bound property based on the dual hash chains is not challenged. Note that without the protection of the tamper-resistant device, a user with $I(i, 0, t_1)$ and another user with $I(i, t_2, z)$ can collude to acquire w_t for any t in the entire system lifetime (and thus any $k_{i,t}$ for $0 \leq t \leq z$). This explains why the dual hash chains should only be employed in a tamper-resistant device so as to compose a secure solution to time-bound key management. On the other hand, interestingly, Yi's attack does not affect the time-invariant version [11] of Chien's KA scheme, as in that case the conspiring users cannot gain any more than the combination of their respective privileges. However, when another dimension is introduced, as from [11] to

[10], Yi exploited the partial-order property to launch an interweaving attack (recall Sect. 3.3). Therefore, it seems that, the combination of respectively secure building blocks does not always result in an integration that is overall secure. This is the lesson we learn from Chien's scheme [10].

In Sect. 3.3 when proposing a possible security fix to Tzeng's scheme [4], we have pointed out that, the decoupled structure $k_{i,t} = H(K_i \bmod n_1, w_t)$ should be implemented in a tamper-resistant device such that $I_K = K_i \bmod n_1$ will not be revealed even to the device owner. In Chien's scheme [10], $k_{i,t} = H(K_i \oplus w_t)$ follows the decoupled structure and the tamper-resistant device is also assumed, but K_i is distributed in the clear to the user upon registration. This observation helps understand Yi's attack. Although in [12] Yi again did not propose any remedy, a security fix can be made in a straightforward manner, also based on the above observation. That is, during the registration of a user entitled to $I(i, t_1, t_2)$, K_i should also be securely embedded in the issued tamper-resistant device, just like the way X, $H^{t_1}(a)$, or $H^{z-t_2}(b)$ is stored. Such a slight modification to distributing the base class key makes the security difference, as this way K_i and w_t in (2) are fully decoupled. It also makes the time-bound hierarchical KA scheme more user-friendly, as the device owner no longer needs to input K_i for session key derivation. Note that it is prohibitively difficult for human beings to bear in mind a cryptographic key (randomly generated by the CA according to [10]).

Essentially, Yi's collusion attack [12] lies in the misuse of the tamper-resistant device, which is deceived into believing that the derived class key is always of a lower security class than the device owner's base class. Hence alternatively, Chien's scheme [10] can be repaired by preventing users from entering crafted references like the r'_{bc} in Sect. 4.2. For example, if r_{ij} on the public board is changed to an encrypted form, say $E_X(r_{ij} \| ID_i)$, the tamper-resistant device can employ the server secret key X and the readonly public identifier ID_i to reliably retrieve an authenticated r_{ij}. Three similar lightweight remedies have been presented in [13]. However, securely embedding K_i (along with other secrets) into the tamper-resistant device should be the most convenient, as it incurs the slightest modification and user-friendliness as a bonus.

Recently, a heavyweight remedy to Chien's scheme [10] was proposed by Bertino *et al.* [14], where the tamper-resistant device is additionally required to support elliptic-curve cryptography so as to defend against Yi's three-party collusion attack [12]. Essentially, the scheme by Bertino *et al.* [14] is a rewritten (the elliptic-curve edition) of Chien's scheme [10], where each of the public references r_{ij} is generated and then employed using the elliptic-curve public-key cryptography instead of the cost-efficient one-way hash function. Unfortunately, recently Sun *et al.* [16] showed that, aside from the increased computational overhead, the rewritten scheme [14] appears to be even more vulnerable than the original one [10]; merely two conspirators are enough to misuse the tamper-resistant device to infer unauthorized session keys. Simple fix to the rewritten scheme is also suggested in [16], which still reduces to the authentication on r_{ij} and thus directly applies to the original Chien's scheme [10] (without necessarily involving the expensive elliptic-curve cryptography).

Finally, compared with Tzeng's scheme [4], Chien's scheme [10] seems more promising, as expensive computations like modular exponentiation and the Lucas sequence have both been replaced with cost-efficient operations (mainly one-way hash functions). Chien's scheme is also efficient in terms of storage and communication; the user private primitive incurs constant storage cost, and the needed public parameters $\{r_{ij}\}$ are of the same size with the number of direct edges in the DAG representing the partial-order hierarchy. Note that such $|\{r_{ij}\}|$ usually scales as $O(m)$ (e.g., $|\{r_{ij}\}| = 10$ in Fig. 1, where $m = 8$), and thus is comparable to Tzeng's scheme [4]. In case m is not large, it is possible to store all these public parameters on the user's device. The only issue seems to be that, Chien's scheme is based on a tamper-resistant device (in which the user base class key K_i should be securely embedded). However, note that the remedy for Tzeng's scheme [4] to thwart the collusion attack [8] also asks for the protection by a tamper-resistant device (recall Sect. 3.3). Therefore, for real adoption, Chien's scheme [10] is more promising than Tzeng's [4].

5. Conclusions

In this paper the topic of time-bound hierarchical key assignment is concerned. We surveyed the recent literature and looked into two representative schemes by Tzeng [4] and Chien [10] as case studies. Collusion attacks have shown to be a major threat to time-bound hierarchical KA schemes. Secure building blocks do not always lead to an integration that is overall secure, and complexity may not necessarily help with security.

Both schemes [4], [10] can be remedied to withstand known collusion attacks. The point is to follow a decoupled structure $k_{i,t} = H(K_i, w_t)$ on a tamper-resistant user device, where K_i and w_t should be inaccessible to even the device owner so as to prevent interweaving attacks. Moreover, in Tzeng's [4] and other schemes that follow the Akl-Taylor style key assignment [3], the assigned exponents do not necessarily need to be primes, but they should be pairwise relatively prime.

Due to cost considerations, existent time-bound hierarchical KA schemes may not be readily applicable to commodity (particularly, low-cost) devices that neither afford heavy computation nor have tamper-resistant casing. More studies are needed in order to find efficient and practical KA solutions.

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