A Robust Time-Bound Hierarchical Key Assignment Scheme

Yu-Li Lin, Chien-Lung Hsu, and Yu-Hao Chuang

Abstract—Recently, Chien proposed a time-bound hierarchical key assignment scheme based on tamper-resistant devices, which improves the performance in terms of the computational efforts and the implementation costs. Later, Santis et al. demonstrated a collusion attack on Chien’s scheme to show that collusive malicious insiders can cooperatively derive some encryption keys and further proposed an improvement to eliminate the security flaws inherent in Chien’s scheme. In this paper, we will prove that Santis et al.’s key derivation is incorrect and their claimed security requirements cannot be achieved. On the other hand, we will further propose a new key derivation to improve the weakness in Santis et al., scheme.

Index Terms—Access control, cryptography, hierarchical key assignment.

I. INTRODUCTION

In the real world, there are several examples of hierarchies such as military, government units, business companies, and etc. All users in such a system form a user hierarchy and can be assigned into a number of disjoint sets of security classes, say $C = \{C_1, C_2, \ldots, C_n\}$, which is partially ordered by a binary relation “≤”. The symbol “$C_j \leq C_i$” means that the security level of class $C_j$ is lower than or equal to that of the class $C_i$. It also implies that the users in the security class $C_j$ can access to the information held by those in the class $C_j$, while the opposite is not allowed. For instance, a business company can be regarded as a partially ordered hierarchy. All users in a business company are assigned to the different security classes according to their responsibilities such as top management, divisions, and departments. There are several projects in a department. Members of a project team can have access rights to their project, but are unable to access information about other projects. A manager of a division is authorized to access information in all departments and information about other projects. A manager of a division is responsible for the access control problems. MacKinnon et al. [2] presented an optimal algorithm, called the canonical algorithm, to reduce the number of public parameters as compared with Akl and Taylor’s scheme [1]. Sandhu [3] addressed a novel cryptographic solution to access control problem for the special case of a rooted tree hierarchy. The keys for security classes are iteratively generated by using one-way functions. This approach is easier for implementation.

In 2002, Tzeng [8] proposed a time-bound cryptographic key assignment scheme in which the cryptographic keys of a class is distinct for each time period. Tzeng’s scheme can be applied to broadcast encrypted data to authorized users through a broadcast channel and to construct a flexible cryptographic key backup system. However, Tzeng’s scheme is insecure against the collusion attack demonstrated by Yi and Ye [9]. A coalition of classes with distinct time periods can cooperate to compute unauthorized keys that they should not be able to learn. To improve Tzeng’s scheme, Chien [10] later proposed a new time-bound hierarchical key assignment scheme that employed a low-cost tamper-resistant device to perform simple arithmetic operations. Chien’s scheme reduces the implementation costs and the computational loads. Santis, Ferrara, and Masucci [11] recently showed that Chien’s scheme is still vulnerable to collusion attack which is contrary to his claimed security requirements. That is, some malicious users can collusively to extend the time period of their secret keys. Santis, Ferrara, and Masucci [12] further proposed an improvement to eliminate the security flaws inherent in Chien’s scheme. This paper, however, will demonstrate the incorrectness of Santis et al.’s scheme. That is, the key derivation will fail in Santis et al.’s scheme, which implies their scheme cannot achieve the claimed security requirements. We finally will propose an improved scheme to correct Santis et al., scheme.

Rest of this paper is sketched as follows. In Section II, we will review Santis et al., scheme [12]. In Section III, we will demonstrate the incorrectness of Santis et al., scheme and
propose an improvement. Finally, we give conclusions in Section IV.

II. REVIEW OF SANTIS ET AL.’S SCHEME

Santis et al.’s scheme [12] consists of the initialization, the user registration, the key generation, and the key derivation phases. In the initialization phase, a trusted agent (TA) determines all system parameters. In the user registration phase, a user can join the system and be assigned a secret key according to his security class. In the key generation phase, TA will determine a secret key for encrypting data belonging to each class at each time period. In the key derivation phase, the legal user can use his own secret key to derive the encrypting key for his class or lower class at some time period.

Suppose the system has \( n \) disjoint classes, \( \{C_1, C_2, \ldots, C_n\} \), and the time is divided into \( z \) periods, starting at time period 1. Let \( ID_j \) be the identity of the class \( C_j \). A user belonging to class \( C_i \) from time period \( t_1 \) to \( t_2 \) is able to derive the secret key \( K_{j,t} \) of the intended class \( C_j \) at time period \( t \), where \( C_j \leq C_i \) and \( t_1 \leq t \leq t_2 \). Detailed descriptions of these phases are given below.

**Initialization.** Initially, the trusted agent TA determines his own secret key \( X \) and a secure one-way hash function \( h \), and randomly chooses two secret values, \( a \) and \( b \), as the time-bound seeds for time periods. TA determines a secret key \( k_i \) for each class \( C_i \) (for \( i = 1, 2, \ldots, n \)) and a public value

\[
r_{ij} = h(X \parallel ID_i \parallel ID_j \parallel k_i) \oplus h(X \parallel k_j)
\]

(1)

For the relationship between \( C_i \) and \( C_j \) where \( C_j \leq C_i \) and there is no class \( C_i \) such that \( C_j \leq C_i \leq C_j \). Note that the symbol \( \parallel \) denotes the string concatenation and \( \oplus \) denotes the bit-wise XOR operation. Finally, TA publishes \( X \), \( ID_i \)'s, and all \( r_{ij} \)'s on an authenticated public board.

**User registration.** When a user joins the system and is assigned to a class \( C_i \) in the time interval \([t_1, t_2]\), TA transmits \( C_i \)'s secret key \( k_i \) to him via a secure channel and gives him a tamper-resistant device containing \( ID_i \), TA’s secret key \( X \), and two hash values \( (h^a(a), h^{z-t_2}(b)) \). Note that no one can access the tamper-resistant device to obtain the stored information.

**Key generation.** Assume a user \( U_j \) belonging to the class \( C_j \) during the time period \( t \) \((t_1 \leq t \leq t_2)\) can encrypt the data by the key \( K_{i,t} \). The key \( K_{i,t} \) is defined as

\[
K_{i,t} = h(X \parallel k_i) \oplus h^a(a) \oplus h^{z-t}(b).
\]

**Key derivation.** When a user \( U_i \) belonging to class \( C_i \) in time interval \([t_1, t_2]\) wants to decrypt the encrypted data of the class \( C_j \) at time period \( t \), where \( C_j \leq C_i \), there is no class \( C_i \) such that \( C_j \leq C_i \leq C_j \), and \( t_1 \leq t \leq t_2 \). The user \( U_i \) inputs the public value \( r_{ij} \), the identity \( ID_i \), and the secret key \( k_i \) to the tamper-resistant device. The device performs the following steps to derive the decryption key \( K_{j,t} \):

Step 1. Use the public information \( r_{ij} \) and \( C_j \)'s secret key \( k_j \) to compute \( C_j \)'s secret information \( h(X \parallel k_j) \) by

\[
h(X \parallel k_j) = r_{ij} \oplus h(X \parallel ID_i \parallel ID_j \parallel k_i)
\]

(2)

Step 2. Compute \( h'(a) \) and \( h^{z-t}(b) \) as

\[
h'(a) = h^{t-t_1}(h^a(a)) \quad \text{and} \quad h^{z-t}(b) = h^{t_2-t_1}(h^{z-t_2}(b))\]

Step 3. Derive \( C_j \)'s secret key \( K_{j,t} \) by

\[
K_{j,t} = h(X \parallel k_j) \oplus h'(a) \oplus h^{z-t}(b).
\]

If there exists some class(es) between \( C_i \) and \( C_j \), the user \( U_j \) can use above method to iteratively derive the secret key(s) of \( C_i \)’s, where \( C_j \leq C_i \leq C_j \) in time interval \([t_1, t_2]\).

All above steps will be performed iteratively by the same way.

III. INCORRECTNESS AND IMPROVEMENT OF SANTIS ET AL., SCHEME

In this section, we will show the incorrectness of Santis et al., scheme and then propose the improvement to correct Santis et al., scheme.

A. Incorrectness of Santis et al.’s scheme

According to Santis et al.’s scheme, each class \( C_i \) has the secret key \( k_i \) and the tamper-resistant device after the initialization phase. Consider the situation that a user \( U_j \) belonging to \( C_j \) wants to access the information held by some user \( U_j \) of \( C_j \), where \( C_j \leq C_i \) and there is no class \( C_i \) such that \( C_j \leq C_i \leq C_j \), \( U_j \) can input public information \((r_{ij}, ID_i, ID_j)\) and his secret key \( k_i \) into his tamper-resistant device to obtain \( h(X \parallel k_j) \). The device uses \( h(X \parallel k_j) \) to derive \( U_j \)'s secret key \( K_{j,t} \) at time period \( t \). Finally, \( U_j \) can decrypt \( U_j \)'s information with the derived secret key \( K_{j,t} \).

Consider the another situation that a user \( U_j \) in \( C_i \) wants to decrypt the encrypted data held by some user in \( C_j \) from the path \( C_i \) to \( C_j \) in a user hierarchy, where \( C_j \leq C_i \leq \cdots \leq C_{l_2} \leq C_{l_1} \leq C_j \), \( U_j \) has to perform the computations iteratively by the following equations:

\[
h(X \parallel k_{l_1}) = r_{l_1} \oplus h(X \parallel ID_i \parallel ID_j \parallel k_i)
\]

(3)

\[
h(X \parallel k_{l_2}) = r_{l_2} \oplus h(X \parallel ID_i \parallel ID_j \parallel k_{l_1}), \ldots,
\]

(4)

\[
h(X \parallel k_j) = r_j \oplus h(X \parallel ID_j \parallel ID_j \parallel k_{l_1})
\]

From Eq. (3), we can precisely know that \( h(X \parallel k_{l_1}) \)
consists of TA’s secret key X and U_i’s secret key k_i. If we want to carry out Eq. (4) to derive the secret value h(X || k_i), we must first obtain secret key k_i from h(X || k_i) and then feed it to the right-hand side of Eq. (4). Unfortunately, U_i cannot derive the next secret value h(X || k_2) = r_{t2} @ h(X || ID_i || ID_2 || k_1) since k_1 is protected by the one-way hash function. Based on the intractability of reversing the one-way hash function, it can be seen that the user U_i cannot derive the secret keys, k_1,k_2,⋯,k_l, from h(X || k_1),h(X || k_2),⋯,h(X || k_l).

For example, the set of classes is organized as a user hierarchy such as Fig. 1. The users belonging to C_1, C_2, and C_4 are associated with time intervals [t_1,t_6], [t_2,t_5], and [t_3,t_4], respectively, where 1 ≤ t_1 < t_2 < t_3 < t_4 < t_5 < t_6 ≤ z. As shown in Fig. 1, the users belonging to C_1 have access rights to the information held by those belonging to C_4. When the users in C_1 wants to derive C_4’s secret key K_{A,t} in the time period t (t_2 ≤ t ≤ t_5), they have to input the public value r_{t2}, the identity ID_1, and the secret key k_1 into his tamper-resistant device to compute h(X || k_2) = r_{t2} @ h(X || ID_1 || ID_2 || k_1). If the users belonging to C_1 has the ability to reverse the one-way hash function h, he can derive k_2 from the derived value h(X || k_2). Then, they can further derive the secret key by the following equations:

\[
h(X || k_4) = r_{t4} @ h(X || ID_2 || ID_4 || k_2) \\
h'(a) = h^{-t_2}(h^{t_2}(a)), \quad h^{z-t_2}(b) = h^{t_5-t_2}(h^{z-t_5}(b)) \quad K_{A,t} = h(h(X || k_4) @ h'(a) @ h^{z-t_2}(b))
\]

Since the security of Santis et al.’s scheme is primarily assumed based on the intractability of reversing the one-way hash function h, the users in C_1 cannot derive k_2 from h(X || k_2).

\[
r_{ij} = h(ID_i || ID_j || h(X || k_i) @ h(X || k_j)) \\
h(X || k_j) = r_{ij} @ h(ID_i || ID_j || h(X || k_j))
\]

When a user U_i belonging to class C_i in time interval [t_1,t_2] wants to decrypt the encrypted data of the class C_j at time period t, where C_j ≤ C_i, there is no class C_l such that C_j ≤ C_l ≤ C_i, and t_1 ≤ t ≤ t_2. The user U_i inputs the public value r_j, the identity ID_i, and his own secret key k_i to the temper-resistant device. The device performs the following steps to derive the decryption key K_{j,t}:

Step 1. Use the public information r_j and C_j’s secret key k_i to compute C_j’s secret information h(X || k_j) by h(X || k_j) = r_{ij} @ h(ID_i || ID_j || h(X || k_j)).

Step 2. Compute h'(a) and h^{z-t_2}(b) as

\[
h'(a) = h^{-t_2}(h^{t_2}(a)) \quad h^{z-t_2}(b) = h^{t_5-t_2}(h^{z-t_5}(b))
\]

Step 3. Derive C_j’s secret key K_{j,t} by

\[
K_{j,t} = h(h(X || k_j) @ h'(a) @ h^{z-t_2}(b))
\]

If there exists some class(es) between C_i and C_j, the user U_i can use above method to iteratively derive the secret key(s) of C_i’s, where C_j ≤ C_i ≤ C_l in time interval [t_1,t_2].

All above steps will be performed iteratively by the same way.

From Eqs. (1*) and (2*), we can see that the value h(X || k_j) can be easily derived by h(X || k_j) = r_{ij} @ h(ID_i || ID_j || h(X || k_j)) with the knowledge of h(X || k_j).

Hence, incorrectness of Santis et al.’s scheme is corrected in the proposed improvement. The security analysis of our proposed scheme is similar to that of Santis et al.’s scheme based on the same cryptographic assumptions. The interested readers are encouraged to refer [12].

### IV. CONCLUSIONS

We have demonstrated the incorrectness of Santis et al.’s scheme, which implies their scheme cannot achieve the claimed security requirements. That is, Santis et al.’s key derivation only allows the users to derive the secret key for the direct successor of the intended class. The secret keys for all immediate successors of the intended class however cannot be derived, which is contrary to their claimed security requirements. We finally propose an improvement to fix the pointed out problem.

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![Fig. 1. A small partially ordered hierarchy example.](image-url)
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REFERENCES


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