A new key assignment scheme for enforcing complicated access control policies in hierarchy

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Abstract

In a traditional key assignment scheme, an access control policy is used to solve the access control problem in a hierarchy. A higher security class can access lower security classes, but the opposite is not allowed. However, in some cases, this can be troublesome because of the lack of flexibility. In this paper, we shall propose a secure key assignment scheme which can be performed not only in a hierarchy but also in more complicated policies with anti-symmetrical and transitive exceptions.

Keywords: Access control; Cryptography; Data security; Key assignment; Multilevel security

1. Introduction

In the past decade, many key assignment schemes have been proposed in the literature to control access in a hierarchy \cite{1–12}. In a hierarchic access control policy, all users are allocated into a number of disjoint sets of security classes $C_1, C_2, \ldots, C_m$. According to the partially ordered hierarchy, a user in security class $C_j$ can derive the secret keys of the users in any security class $C_i$ that is in the same security level as $C_j$ or lower, but the opposite is not allowed. In other words, the users in $C_j$ can access the information held by the users in $C_i$. The relation can be expressed as $C_i \leq C_j$.

In real-life situations, many organizations are in partially ordered hierarchies. However, the hierarchy structure is not suitable for all the organization in the societies. For example, there is a more flexible organization structure in Fig. 1. A user in the top level user class $C_1$ possesses the authority to access information items of classes $C_2$ and $C_4$, but access to the information items of $C_3$ is not allowed; a user in $C_2$ can access information items of $C_3$ and $C_4$; a user in $C_4$ can access information items of $C_2$. It is difficult to meet the relationships by using the traditional key assignment scheme in hierarchy.

Recently, Yeh et al. \cite{14} proposed a more flexible key assignment scheme (named, the YCN scheme) for enforcing access control policy in a user matrix model. The user matrix model cannot only enforce the access control policies in the user hierarchy model...
Fig. 1. An example access control policy in a hierarchy structure with explicit anti-symmetric and transitive exceptions.

but also enforce the two extension policies: transitive exceptions and anti-symmetrical arrangements.

The key assignment scheme in the hierarchy structure with an explicit transitive exception policy goes that

- \( C_i \) can access \( C_j \) and \( C_j \) can access \( C_k \), but \( C_i \) cannot access \( C_k \). For example, \( C_1 \) can access \( C_2 \) and \( C_2 \) can access \( C_3 \), but \( C_1 \) cannot access \( C_3 \) as Fig. 1 shows.

The key assignment scheme in the hierarchy structure with an anti-symmetrical policy is that \( C_i \) can access \( C_j \) and \( C_j \) can access \( C_i \), but \( C_i \) and \( C_j \) are two different user classes. For example, \( C_2 \) can access \( C_4 \) and \( C_4 \) can access \( C_2 \), but \( C_2 \) and \( C_4 \) are two different user classes as Fig. 1 shows. Therefore, the YCN scheme is more flexible than the schemes in the user hierarchy model in solving the access control problem. The scheme has opened a brand new research area for key assignment in a hierarchy. However, the YCN scheme is not secure. Hwang presented counter-evidence to point out the YCN scheme is not secure [9]. In some cases, several user classes in YCN scheme can collaborate to derive the derivation and encryption keys. To amend the problem in security, we shall propose a secure key assignment scheme which can also enforce the complicated access control policies. Besides, our proposed scheme does not require large amount of storage for storing the public parameters.

The organization of the paper is as follows. In the next section, we shall briefly review related work on key assignment schemes in a hierarchy. Following the review, we shall propose our new key assignment scheme for enforcing more flexible access control policies in Section 3. In Section 4, we shall give a simple example to illustrate our scheme. The security of our proposed scheme and the required storage and computations are analyzed thereafter. Finally, our conclusion will be presented in the last section of this paper.

2. Related work

In this section, we shall introduce some related work on key assignment schemes in a hierarchy. One of the simplest methods to control access in a hierarchy is to make only the authorized users hold all the users’ secret keys of the successor security classes. In this simple method, each user must hold and manage a set of subordinate keys. Such an arrangement raises the key management problem of multilevel security [1].

To solve this problem, one of the workable ways is to use a super-key instead of many subordinate keys. The concept of the super-key was first introduced by Akl and Taylor in [1]. Since then, many schemes have been proposed for solving the problem based on the concept of the super-key. Akl and Taylor designed the key assignment scheme using the top–down approach. In their scheme, a central authority (CA) assigns to each user class a prime, a secret key, and a public parameter. If \( C_j \) has a security clearance higher than \( C_i \), the users in \( C_j \) can easily derive the secret key of \( C_i \) with their own secret key and the public parameters of \( C_i \) and \( C_j \). Thus, the scheme can solve the key management problem. However, the values of public parameters are very large. Since the public parameter of the user class \( C_i \) in the Akl–Taylor scheme is the product of the primes of \( C_i \) which is not a descendant of \( C_i \), the scheme requires a large amount of storage to store the public parameters.

In 1985, Mackinnon et al. [11] proposed an algorithm to reduce the values of public parameters in Akl and Taylor’s scheme. The method is called canonical assignment. However, the scheme also requires a large amount of storage to store the public parameters [2,12]. Moreover, the optimal canonical algorithm is difficult to find.

In 1990, Harn and Lin [3] proposed a cryptography-based hierarchy scheme. This scheme is similar to the Akl–Taylor scheme, but the Harn–Lin scheme used a bottom–up approach instead of the top–down approach employed in the Akl–Taylor scheme. More-
3. A new key assignment scheme

In this section, we shall propose a new key assignment scheme for access control in a more flexible hierarchy structure. We design the scheme using the bottom-up approach. The security of our scheme is based on the difficulty of factoring a product of two large primes.

There is a CA in our scheme. It is a trust third party. The responsibility of this CA is to generate and distribute keys. Initially, CA assigns each user class two keys: a secret key and a derivation key. The secret key is used to encipher and decipher documents in a symmetric cryptosystem such as DES, IDEAL, or AES (advanced encryption standard) [13]. The derivation key is used to derive the secret key of other user classes which are allowed to access. The details of the new key assignment scheme are described as follows.

Step 1 CA randomly chooses two large primes: \( p \) and \( q \). Both of \( p \) and \( q \) need to be kept secret. Next, CA calculates \( n \) such that \( n = p \times q \), where \( n \) is public.

Step 2 CA chooses another parameter, \( g \), which is relatively prime to \( n \) and in the range between 2 and \( n - 1 \).

Step 3 CA chooses a set of distinct primes \( \{ e_1, e_2, \ldots, e_m \} \) for all user classes \( \{ C_1, C_2, \ldots, C_m \} \), where \( e_i \) has to relatively prime to \( \phi(n) \), i.e., \( \gcd(\phi(n), e_i) = 1 \) and \( 1 < e_i < \phi(n) \). Then, CA publishes the parameters \( \{ e_1, e_2, \ldots, e_m \} \) and \( n \).

Step 4 CA calculates \( \{ d_1, d_2, \ldots, d_m \} \), where each \( d_i \) is the multiplicative inverse of \( e_i \), i.e., \( e_i \times d_i \equiv 1 \mod \phi(n) \), where \( \phi(n) \) denotes the Euler’s totient function of \( n \).

Step 5 CA generates the derivation keys \( \{ DK_1, DK_2, \ldots, DK_m \} \) and the secret keys \( \{ SK_1, SK_2, \ldots, SK_m \} \) for all user classes \( \{ C_1, C_2, \ldots, C_m \} \) as follows:

\[
DK_i = g \prod_{C_j < C_i, k} (d_k) \mod n, \quad (1)
\]

\[
SK_i = g^{d_i} \mod n. \quad (2)
\]

\( C_j < C_i \) means that the user class \( C_j \) possesses the authority to access the information items of \( C_m \). Next, CA delivers \( SK_i \) and \( DK_i \) to each user in the user class \( C_i \) through a secure channel. Each user has to keep \( SK_i \) and \( DK_i \) secret.

Step 6 If the user classes keep the relation \( C_j < C_i \), an user class \( C_j \) can derive the secret key of class \( C_j \) with the derivation key \( DK_i \) as follows:

\[
SK_j = DK_i \prod_{C_k < C_j, \forall \phi(ek)} (e_k) \mod n \]

\[
= (g \prod_{C_k < C_j, \forall \phi(ek)} (d_k)) \prod_{C_k < C_j, \forall \phi(ek)} (e_k) \mod n \]

\[
= g^{d_j} \mod n. \quad (3)
\]

The public parameters in the Akl–Tayor scheme [1] are the products of the primes associated with non-authority classes. If there are many user classes in the system, the values of public parameters will be very large. Therefore, their scheme requires a large amount of storage to store the public parameters. In contrast, the public parameter \( e_i \) of user class \( C_i \) is a single prime in our proposed scheme. Thus, our scheme requires only small storage to store the public parameters.
4. An example

In the following example, we apply the proposed scheme to the structure of an organization in Fig. 1. The users in $C_1$ possess the greatest authority; they can derive the secret keys of the users in $C_2$ and $C_4$, but they cannot derive the secret key of the users in $C_3$ because it is restricted by the transitive exceptions policy. The users in $C_2$ have the authority to derive the secret keys of the users in $C_3$ and $C_4$. Furthermore, the anti-symmetrical policy allows that the users in $C_4$ can derive the secret key of the users in $C_2$. Finally, the users in $C_3$ have the least authority; they can only access information held by the users in the same class as themselves.

Initially, CA chooses the public parameters $e_1, e_2, e_3, e_4$ for all user classes $C_1, C_2, C_3, C_4$ and calculates the public modular $n$. According to Eq. (1), CA can calculate the derivation keys $DK_1 = g^{d_2 \times d_4} \mod n, DK_2 = g^{d_3 \times d_4} \mod n, DK_3 = n, and DK_4 = g^{d_4} \mod n$ for the users in $C_1, C_2, C_3, and C_4$, respectively. Obviously, the secret keys $SK_1 = g^{d_4} \mod n, SK_2 = g^{d_2} \mod n, SK_3 = g^{d_3} \mod n, and SK_4 = g^{d_4} \mod n$ for the users in $C_1, C_2, C_3, and C_4$, respectively, can also be calculated by CA using Eq. (2).

Using the derivation keys and the public parameters, the users in $C_1$ can derive the secret keys $SK_2$ and $SK_4$ following the equations $SK_2 = DK_2^{e_1} \mod n$ and $SK_4 = DK_4^{e_1} \mod n$, but they cannot obtain the secret key of $C_3$. Similarly, the users in $C_2$ can also use their own derivation key to derive the secret keys $SK_3$ and $SK_4$ following the equations $SK_3 = DK_3^{e_2} \mod n$ and $SK_4 = DK_4^{e_2} \mod n$. The users in $C_3$ cannot derive any secret key. The secret key of $C_3$ can also be derived by the users in $C_4$ with the equation $SK_2 = DK_4^{e_1} \mod n$. With the secret key, users can decipher the plaintext and access the information they want. The scheme is simple, and the access policies are more flexible than traditional hierarchy structures.

5. Discussions

In this section, we shall examine the security of our proposed key assignment scheme. In addition, we shall also discuss the required storage and computational complexity in our proposed scheme.

5.1. Security analysis

The security features of our proposed scheme are described as follows.

1. Difficulty for factoring the modular $n$. From the public parameter $e_i$ and the modular $n$, no one can derive the multiplicative inverse $d_i$. The security is similar to that of the RSA cryptosystem [13]; it is based on the difficulty of factoring the modular $n$. Any adversary who wants to derive the multiplicative inverse $d_i$ from the public parameter $e_i$ and the modulus $n$ has to factor $n$ into its two prime factors. Currently, there are many factoring algorithms, but they are all time-consuming. Furthermore, if an adversary tries all possible corresponding multiplicative inverses, $d_i$, until he/she finds the correct one, it is in fact not more efficient than trying to factor $n$ [13].

2. Preventing the unauthorized users to access. Without the authority to access the information in $C_j$, the users in $C_i$ cannot derive the secret key of the users in $C_j$. If the users in $C_i$ has the authority to access the information in $C_j$, the derivation key $DK_i$ has a hidden multiplicative inverse $d_j$. Therefore, the secret key $SK_j$ will be able to be derived by Eq. (3). However, if users are not authorized, the derivation key $DK_i$ will not reveal about $C_j$, and there will be no way for the users to derive the secret key $SK_j$ from the derivation key $DK_i$ or the other public parameters.

3. Resisting common modulus attack. If everyone is given the same modulus $n$, but different values for the exponents $d_i$ and $e_i$, the RSA cryptosystem is not secure. The problem occurs when the same message is encrypted by two different exponents (both having the same modulus), and the two exponents are relatively prime, then the message can be recovered without using the private key $d_i$ [13]. The attack is called common modulus attack. For example, a message $m$ is encrypted by using the keys $e_1$ and $e_2$. The two ciphertexts are

$$c_1 = m^{e_1} \mod n, \quad c_2 = m^{e_2} \mod n.$$  

Since the $e_1$ and $e_2$ are relatively prime, we can derive $r$ and $s$ using Euclidean algorithm, such that

$$re_1 + se_2 = 1.$$
Thus, the plaintext $m$ can be recovered by using the following equation without the private key $d$:

$$(c_1)^r \times (c_2)^s \equiv m \mod n.$$  

In our scheme, even though all user classes use the same modulus and different values for the exponents $e$ and $d$, our system will not reveal any information under the common modulus attack. Since $SK_i = g^{e_i} \mod n$ must be kept secret by the users in class $C_i$, no public parameters are calculated by power of $e_i$ modular $n$. Even though several users reveal their secret keys $SK_i$ in different user classes $C_i$, only the parameter $g$ can be derived by using the common modulus attack. However, revealing the parameter $g$ does not harm the security of our scheme, because the multiplicative inverses $d_i$ are unknown.

4. Resisting collaborate attack. In collaborate attack, several user classes may reveal their derivation keys and secret keys to try to derive the derivation keys and secret keys of the unauthorized classes. Using the common modulus attack with the revealed secret keys, only the parameter $g$ can be derived. Furthermore, the exponential of $DK_i = \prod_{C_j < C_i} (d_j) \mod n$ only contains the multiplicative inverses $d_i$ of the authorized classes. Therefore, the collaboration is not helpful to derive the derivation keys and secret keys of the unauthorized classes. The key pointer is that the multiplicative inverses $d_i$ are unknown, they are kept secret by CA.

5.2. Required storage and computational complexity

Assume that there are $m$ user classes in the hierarchy. From the algorithm of our proposed scheme, the public parameters $\{e_1, e_2, \ldots, e_m\}$ and $n = m + 1$ integers, where the binary value of $\{e_1, e_2, \ldots, e_m\}$ are between 1 and $\phi(n)$. That is, the size of the public parameters must be less than or equal to $\log_2(n)$. Let the size of each public parameter is $k$ bits, where $2^{k-1} < n < 2^k$. Generally, the length of $k$ in the range of 512–1024 bits is secure [13]. Therefore, the amount of the required storage for storing the public parameters is $(m+1) \left[ \log_2(n) \right]$ bits, i.e. $(m+1)k$ bits. Recalling the Akl–Taylor scheme, the public parameter of the user class $C_i$ is a product of the primes dedicated to the user classes which are not the descendants of $C_i$. Obviously, the amount of the required storage in our scheme is much less than the Akl–Taylor scheme, especially when the number of user classes in the hierarchy is large.

The computational complexity of our scheme is also simple. When a user in class $C_i$ and the relationship $C_j < C_i$ holds, the user can derive the secret key of class $C_j$ with the derivation key $DK_j$ from Eq. (3). It requires $r$ multiplications and 1 modular exponential computations, where $r$ is the number of immediate successors of the processed user class. Therefore, our scheme is efficient to implement.

6. Conclusions

We have proposed a secure key assignment scheme for solving the multilevel access control problem in complicated access control policies. The main contribution of our scheme is that it can be used in more flexible applications than that of the scheme proposed before. In this scheme, the access control policy not only able to be enforced in a hierarchy but also able to be employed for more complicated policies with anti-symmetrical arrangements and transitive exceptions. Furthermore, our scheme does not require large amount of storage for storing public parameters.

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References

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