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Efficient key management for cryptographically enforced access control

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ABSTRACT

Cryptographic enforcement of access control mechanisms relies on encrypting protected data with the keys stored by authorized users. This approach poses the problem of the distribution of secret keys. In this paper, a key management scheme is presented where each user stores a single key and is capable of efficiently calculating appropriate keys needed to access requested data. The proposed scheme does not require encryption of the same data (key) multiple times with the keys of different users or groups of users. It is designed especially for the purpose of access control. Thanks to that, the space needed for storing public parameters is significantly reduced. Furthermore, the proposed method supports flexible updates when user's access rights change.

1. Introduction

Advances in information and communication technologies bring with numerous benefits also concerns with respect to security issues. The data no longer resides on mainframes physically isolated within an organization, where physical security measures can be taken to safeguard the data and the system. Modern solutions are evolving towards open, interconnected environment where storage outsourcing and operations on untrusted servers happen frequently. Open access data storage standards pose new challenges on security technologies. The old server-centric protection model locks data in a database server and uses a traditional access control model to permit access to data. To facilitate current developments, a data-centric protection model is required, where data is cryptographically protected and allowed to be outsourced or even freely float on the network. In many cases there is a need to replicate the data and send it to the clients. Examples are distributed databases, grid computing, enterprise rights management systems and peer-to-peer data management systems in general. Consider for example the development of Electronic Health Records (EHRs). It aims at increased availability and sharing of patient records. Records are shared among different healthcare providers, external wellness services and relatives. As the healthcare data is very sensitive, privacy and security have to be taken care of. Today this often means that access to EHRs is restricted to a controlled environment of care institutions. This limitation can be overcome by the more flexible data-centric protection.

In this paper, we address the key management problem of the data-centric protection model. Namely, when the data is encrypted, the access control policies have to be taken into account so that control is maintained regarding which users can access what data. In a standard access control model, the policies are defined using one of the standard model/languages, such as Lightweight Directory Access Protocol (LDAP) [19], ANSI/INCITS Role Based Access Control [6], Security Assertion Markup Language standards [9] or OASIS Extensible Access Control Markup Language [10]. However, when a data-centric protection model is used these policies have to be mapped into a proper key management scheme, which is the problem this paper deals with.

The remainder of this paper is organized as follows. Section 2 describes the problem and surveys the related work. Our key management solution is presented in Section 3. Section 4 is devoted to the problem of updates of access rights. Section 5 discusses the advantages of the proposed solution compared to the state-of-the-art. Finally, Section 6 summarizes our contributions and proposes several directions for the future work.

2. Related work and problem description

A straightforward solution to enforce access control with cryptography is to encrypt the data with a data key, which is consequently encrypted with the keys of users that should be able to access this data. The drawback of such approach is that each data key is stored in multiple copies encrypted with different user keys. The number of copies of a single data key can reach the number of users (or roles or user groups) in the system. For large systems that allow fine granularity of access to data, this number can by far exceed the size of the protected data itself. Another problem is updating encrypted data keys when the access control policies change. Thus, we search for a method to assign the keys to the data and the users in a more efficient manner, supporting flexible updates.

There are a number of different definitions of the key management problem in the literature. We propose here a generalized problem statement. To the best of our knowledge our definition covers all the approaches presented in the literature.

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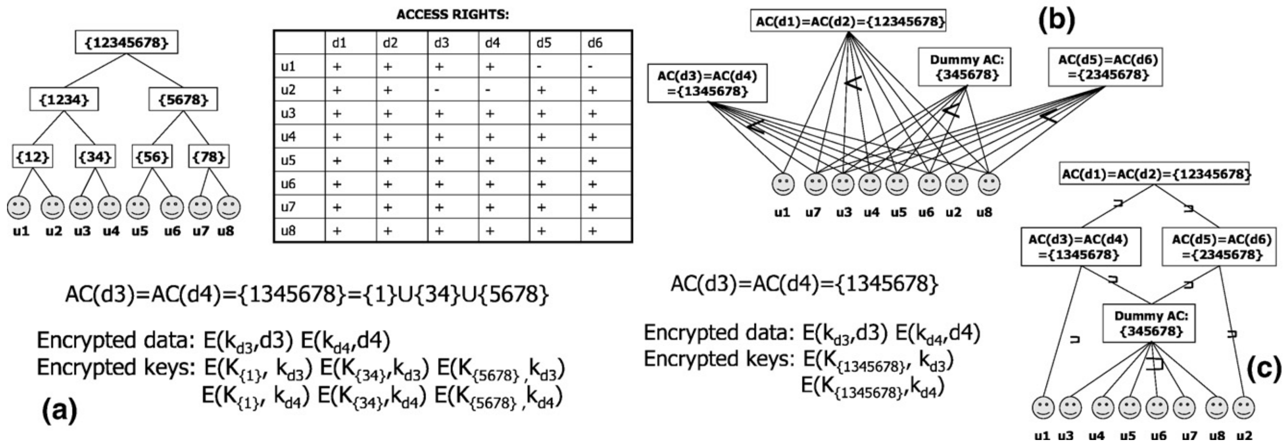
ACCESS RIGHTS:

	d1	d2	d3	d4	d5	d6
u1	+	+	+	+	-	-
u2	+	+	-	-	+	+
u3	+	+	+	+	+	+
u4	+	+	+	+	+	+
u5	+	+	+	+	+	+
u6	+	+	+	+	+	+
u7	+	+	+	+	+	+
u8	+	+	+	+	+	+

Fig. 1. Example of an access table and orders on access configurations from this table.

2.1. Generalized key management problem

Let $\mathcal{U}$ be the set of users of the system (users can represent individuals, roles or groups of individuals), and let $\mathcal{D}$ be the set of data records. Any set of users is an access configuration. The set of users allowed to access data record $d \in \mathcal{D}$ is an access configuration associated with d, denoted as AC (d). The access configurations are partially ordered in a natural way via subset inclusion $\subset$ (see Fig. 1c).

The inclusion partial order is used to assign the keys to groups of users. This partial order satisfies more conditions than necessary and therefore wastes opportunities. By relaxing these, and defining a weaker order relation, we allow partial orders that in turn allow for more efficient key management.

The necessary conditions for the partial order (P, $<$) on access configurations are as follows. For each user u access configuration $\{u\}$ belongs to $P : \forall_{u \in \mathcal{U}} \{u\} \in P$. There may be however some additional access configurations in P, for example AC (d) for $d \in \mathcal{D}$. The order relation $<$ on elements of P satisfies (order conditions):

$$\begin{cases} AC_1 \supset AC_2, |AC_2| = 1 \Rightarrow AC_1 < AC_2 \\ AC_1 < AC_2 \Rightarrow AC_1 \supset AC_2 \end{cases}. \quad (1)$$

This definition ensures, that if $u \in$ AC, then $\{u\} >$ AC, and requires as few other order relations as possible. Intuitively, we want to model that the data accessible by the whole group AC is also accessible by any user $u \in$ AC. Examples of orders that satisfy our definition are presented in Fig. 1.

The task of the key management scheme is to (i) design an efficient [1] partial order P satisfying order conditions (1) and (ii) assign to each access configuration AC in P on or more secret keys K_{AC}, such that based on $K_{\{u\}}$ each user u can obtain K_{AC} for every AC$<\{u\}$. The data records $d \in \mathcal{D}$ are encrypted with the data key k_d, that in turn is encrypted with the keys of groups of users AC$_i$ in such a way, that AC(d)$=\cup_i$ AC$_i$. Thus, all the authorized users can access their data. The examples are shown in Fig. 1. In case of broadcast encryption order (Fig. 1a), the data keys k_{d_3} and k_{d_4} are encrypted three times each with the keys of access configurations that sum up to AC (d_3)=AC (d_4). In the two other partial orders in Fig. 1b and c, AC (d) for each data record $d \in \mathcal{D}$ is included in the order, thus each data key is encrypted only once.

Various solutions were proposed to address this problem [11,17,22,16,25,12]. Practical approaches designed for cryptographically enforced access control are mostly based on broadcast encryption [16]. In the basic approach, the users are represented by the leafs and the access configurations are represented by the interior nodes of a binary tree. This binary tree represents the partial order on access configurations, as shown in Fig. 1a. The user is required to store all the keys on the path from the corresponding leaf to the root of the tree. She can decrypt all the necessary data with the keys she stores. This strategy only partially reduces the redundancy described previously, as there are still multiple copies of data keys. Furthermore, each user stores the number of keys that is of order of the logarithm of the number of subjects, instead of just a single key as in the straightforward solution.

A number of improvements of this basic method were proposed. Most of them [25,12] consider users as stateless receivers, and are referred in the literature as revocation schemes. The improvements are achieved by introducing more groups, more complex orderings of these groups, and sophisticated key assignment methods.

Another popular approach constitutes of the key generation schemes [11,17,22]. Essentially, the partial order is given, and the task of the scheme is to assign the keys to the elements (access configurations) of the given order. In the access control settings, that means that given the key of AC$_1$ and some public information one can compute the key of AC$_2$ if and only if AC$_2 <$ AC$_1$. Support for an arbitrary number of groups allows the complete elimination of the multiple copies of data keys while, thanks to key generation mechanism, each user has only one secret key. However, the price to be paid is the public information that is stored on a public server, used by the users to derive keys. Especially in the case of access control, it is very important to minimize the public space, as the size of the partial orders of access configurations can be exponential in the number of users. We discuss the key generation schemes applied to access control (as done in [13]) and compare them with our approach in Section 5.

3. Key management solution

In this section we propose an efficient solution for the key management problem stated above. In Section 3.1, we present an algorithm for constructing the partial order on access configurations (AC) satisfying Eq. (1). We represent this partial order by an acyclic and transitively reduced directed graph, where nodes are access configurations, and arcs (directed edges) connect comparable elements, from greater to smaller. In the literature, such a graph is called a Hasse diagram of a partial order. We denote the presence of an arc from x to y by $x \rightarrow y$, and a directed path as $x \twoheadrightarrow y$. The constructed graph has two additional properties referred to as V-conditions:

$$\begin{cases} \text{The number of arcs coming into a node is either 2 or 0} \\ \text{For any two nodes, at most one node has arcs into both of them.} \end{cases} \quad (2)$$

[1] By efficient we mean with minimal number of configurations and relations on them, but avoiding multiple copies of data keys.

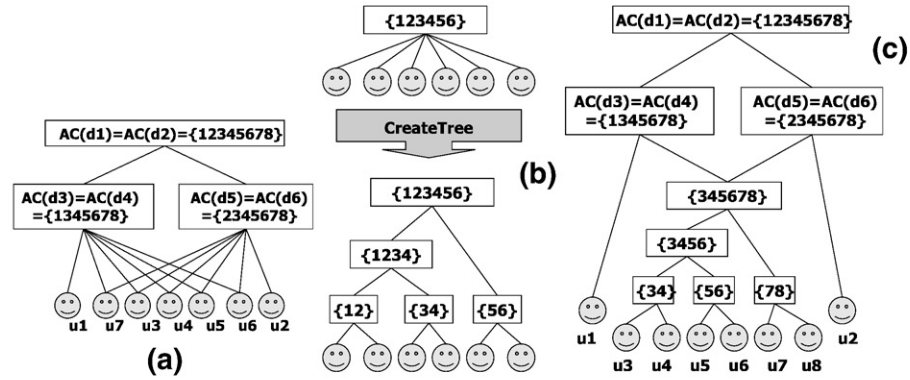

Fig. 2. (a) Graph obtained after the first phase applied to table in Fig. 1; (b) transformation. CreateTree applied in the third phase; (c) the final result of the algorithm applied to the table in Fig. 1.

A graph satisfying Eq. (2) is a *V-graph*. Examples of a non V-graph (a) and a V-graph (c) are shown in Fig. 2. We refer to a transitively reduced acyclic digraph satisfying Eq. (2) and representing an order satisfying Eq. (1) as *access control graph*. The V-form of the graph allows us to apply the Diffie–Hellman (DH) based key generation scheme presented in Section 3.2. The DH scheme assigns public and private keys to the nodes. Each user receives a single private key and using this key he is able to derive the keys needed to decrypt the data he has right to access.

3.1. Hierarchy construction algorithm

In this section we present the construction of a partial order on access configurations. The *CreateHierarchy(Access Table ACCESS)* algorithm presented in this section takes as input an access table (as in Fig. 1a) and builds an access control graph on access configurations (shown in Fig. 2c). Appendices A and B provide the code and the correctness proof respectively.

The input access table *ACCESS* is a boolean matrix representing access rights given to the users. The rows correspond to the users and the columns to the data records. The value ACCESS[u, d] = true(+) if and only if user u is allowed to access data d. Each column represents an access configuration of the corresponding data object. The access table from Fig. 1a could represent access rights of eight roles of health care professionals: u1-u8 related to six categories of documents in patients electronic health records: d1–d6. According to the hospital and patient policy, some roles do not have access to some document categories (such as u1 to d5 and d6 and u2 to d3 and d4). The rest is accessible by all care professional roles.

The algorithm consists of the initial phase and the three construction phases described below. In the initial phase, the *CreateHierarchy* algorithm obtains access configurations of all $d \in \mathcal{D}$ from corresponding columns and stores them in the priority queue Q, with the priority of AC set to its size |AC|. Smaller configurations are extracted earlier. Additionally, all access configurations containing a single user are inserted to initially empty graph G.

Let In(x) for $x \in G$ denote the set of directed edges (arcs) pointing to x. In the next phases, the algorithm adds access configurations and edges to the graph. Some of these adds may cause previously added edges to be removed. The aim of these transformations is to obtain a graph satisfying the conditions from Table 1.

In the first phase, the algorithm constructs graph G satisfying conditions ($a-b'$). Queue Q stores the configurations that still need to be added to G. As before smaller configurations are extracted earlier. For each extracted configuration AC the algorithm:

1. inserts AC to graph G
2. finds in G the minimal set cover of AC, that is a minimal set of configurations AC_i already in G, such that $AC = \cup AC_i$
3. inserts an edge $AC_i \rightarrow AC$ for each AC_i from the found cover until Q is empty (see Appendix A, procedure *InsertCoveredMin(AC)*). Trivially, (a–b') are satisfied after completing this phase. For the example access table from Fig. 1, the graph obtained after this phase is shown in Fig. 2a.

In the second phase, the algorithm transforms the graph to preserve conditions (a–b'), and reduce the number of incoming edges to at most two per node. Queue Q stores configurations that need to be processed by the algorithm, that is those with more than two incoming edges. The algorithm extracts the configurations with a greater number of incoming edges first. For each extracted configuration AC, the algorithm looks at configurations AC′ in Q, and considers their intersection AC∩AC′ with AC. For each AC′, AC∩AC′ is a potential new configuration to be added to graph G. Note, that if $X \subset AC \cap AC' \subset AC$, then adding configuration AC∩ AC′ and edges $X \rightarrow AC \cap AC'$, $AC \cap AC' \rightarrow AC$, makes edge $X \rightarrow AC$ unnecessary by transitivity. The algorithm chooses AC′ in a way, that adding configuration AC∩AC′ allows to reduce the maximal number of edges coming into AC. It repeats this step, until no more edges in In(AC) can be reduced in this manner. During these transformations, the numbers of incoming edges of configurations AC′ are reduced as well. The configurations, whose incoming edges were reduced to at most two are removed from Q. After completing the loop described above, the graph for our running example is shown in Fig. 1c. Condition (d) is satisfied trivially after the termination of the second phase (see Appendix B).

In the third phase, if after the second phase there are AC in G such that |In(AC)| > 2, then the algorithm reduces |In(AC)| by substituting In(AC) with a binary tree rooted in AC (see Appendix A procedure *CreateTree(*AC*)*), as shown in Fig. 2b. The leafs are the nodes connected to AC with arcs In(AC). After this step, |In(AC)| = 2 and AC can be removed from Q. The algorithm continues the third phase until Q is empty.

Note, that |In(AC)| = 1 cannot hold for any AC. At the end of the third phase, all ($a-d$) are satisfied (see Appendix B), and the algorithm

Table 1
Conditions specifying access control graph and their informal description

	Description	Condition
a.	Access configurations of all single users belong to G	$\{u\} \in G$ for each $u \in \mathcal{U}$
a′.	Access configurations of all data records belong to G	$AC(d) \in G$ for each $d \in \mathcal{D}$
b.	A user is connected via directed paths with all the configurations she belongs to (first order condition)	$u \in AC \Rightarrow \{u\} \twoheadrightarrow AC$
b′.	Second order condition	$AC_1 \twoheadrightarrow AC_2 \Rightarrow AC_1 \subseteq AC_2$
c.	First V-condition	$\lvert In(AC)\rvert = 0$ or $\lvert In(AC)\rvert = 2$ for any $AC \in G$
d.	Second V-condition	$\lvert In(AC_1) \cap In(AC_2)\rvert \le 1$ for any $AC_1, AC_2 \in G$

Data Object \ Access Configuration	New Steps: Inserting Access Configuration AC	Existing Steps: Not needed
New Steps: Adding Data Object DO	A new data object is assigned a new access configuration Steps: Insert AC, Add DO.	A new data object is assigned to an existing access configuration Steps: Add DO.
Existing Steps: Rekeying Data Object DO	A new access configuration is assigned to an existing data object Steps: Insert AC, Rekey DO.	An existing object changes the assigned access configuration into another existing one Steps: Rekey DO.

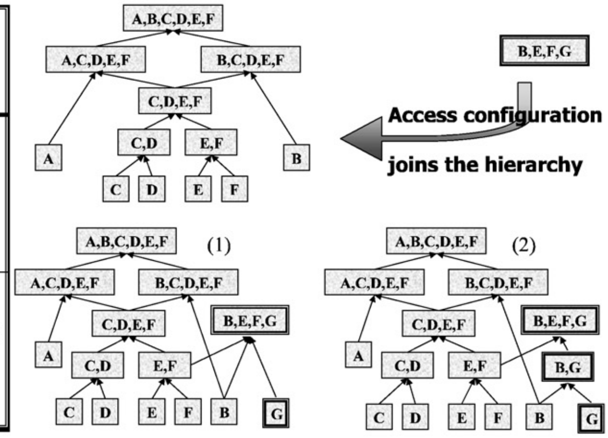

Fig. 3. Update scenarios and example.

terminates. The final result of the algorithm for the running example is shown in Fig. 2c.

3.2. Diffie–Hellman based key generation scheme

In this section, we describe a key generation scheme for an access control graph returned by algorithm *CreateHierarchy(Access Table ACCESS)*, which was presented in Section 3.1. The security of the scheme follows directly from the security of the DH key exchange protocol. The Diffie–Hellman key exchange protocol is standardized by RSA Laboratories as the Diffie–Hellman Key Agreement standard [8]. It is used in a number of standards such as ISO/IEC 11770-3:1999, the part three of the Key Management standard (mechanisms using asymmetric techniques) [4], IEEE P1363 Public Key Standard [3], as well as in a number of components of Transport Layer Security (TLS) [5] and its predecessor Secure Socket Layer (SSL).

Let *LeftParent(AC)* and *RightParent(AC)* be the nodes of In(AC). We assign private and public keys to the nodes of *G*, according to the Diffie–Hellman key exchange protocol. If In(AC) is empty then the secret key of AC is a randomly chosen number. Otherwise the secret key of AC is a shared key obtained by applying Diffie–Hellman protocol on the private and public keys of *LeftParent(*AC*)* and *RightParent(*AC*)*, treating them as the key exchanging parties. The public key of AC is obtained from its private key according to the Diffie–Hellman protocol. Thus, each AC is labeled with its private key *S*AC and its public key *P*AC as follows:

$$\begin{cases} S_{AC} = g^{S_{\text{LeftParent(AC)}} \cdot S_{\text{RightParent(AC)}}} \bmod p \\ P_{AC} := g^{S_{AC}} \bmod p \end{cases} . \quad (3)$$

To derive the key of a descendant node, a node needs its own secret key, as well as the public keys of the "other" parents in the path to the target node. It recursively derives child keys along the path to the target, by calculating $S_{\text{child}} = (P_{\text{other parent}})^{S_{\text{parent}}}$.

4. Updates

This section shows how to efficiently deal with the updates of the access control policies. The updates to the policies can be categorized according the amount of change they cause in the database. Each category requires different steps to be taken to re-encrypt the necessary data. The table in Fig. 3 presents four categories covering all possible scenarios of access control policy update. According to the nature of the introduced update, we apply a combination of three basic steps as presented in the table. Below we describe these basic steps and their effects on the database.

The *Insert Access Configuration (Insert AC)* step is needed when new access control policies imply a new access configuration AC_{new}, which is not an element of the current hierarchy (represented by an access control graph). This is the only step, in which the hierarchy must be updated. We proceed as follows. The new node is created in the hierarchy for AC_{new}. It is not assigned any children. If it were, then the set $\{X \in G: \exists_{Z \in G} AC_{\text{new}} \twoheadrightarrow Z \text{ and } X \twoheadrightarrow X\}$ must be assigned new keys. This could require the re-encryption of the whole hierarchy. Thus, to insert AC_{new}, we apply the operations *G.InsertCoverMin*(AC_{new}) and *G.CreateTree*(AC_{new}) (see Section 3.1). After these two steps conditions [a–d] from Section Table 1 remain satisfied and we can generate new keys for new nodes using the DH scheme. No rekeying is required whatsoever. Frequent updates of the hierarchy influence the performance and public space. Therefore after a certain number of updates the whole hierarchy is rebuilt and rekeyed. If the access configuration in the hierarchy does not correspond to any data object, it is not removed until the hierarchy is rebuilt, and remains as a virtual node. Applying updates to an example hierarchy is shown in Fig. 3.

The *Add Data Object (Add DO)* step is required when a new data object is assigned an existing access configuration. In this case, a new secret key for the new data object is created, the object is encrypted with the new key, and the new key is encrypted with the key of the (existing) access configuration assigned to the object.

The *Rekey Data Object (Rekey DO)* step is performed, when an access configuration AC_{old} assigned before to a data object $d \in \mathcal{D}$ is changed into another existing access configuration AC_{new}. Assume $K(d)$ is the data encryption key assigned to d, $K(AC_{\text{new}})$ and $K(AC_{\text{old}})$ are the key encryption keys corresponding to these access configurations. There are two possible cases:

1. $AC_{\text{old}} \subset AC_{\text{new}}$: in this case the users gain access rights and$K(d)$ is re-encrypted with $K(AC_{\text{new}})$.
2. otherwise: in this case the users loose rights and $K(d)$ must be changed into $K_{\text{new}}(d)$, d is re-encrypted with $K_{\text{new}}(d)$, $K_{\text{new}}(d)$ is encrypted with $K(AC_{\text{new}})$ and stored.

5. Discussion

In this section, we compare our scheme to the schemes described in Section 2. Compared to broadcast encryption methods, which are used in a number of copy protection standards [2], the solution we propose eliminates the need for multiple copies of data keys and reduces to a single key the storage required per user. Therefore, we

[2] Such as Content Scrambling System (CSS) [26], Video Content Protection System (VCPS) [7], Content Protection for Recordable Media (CPRM) [2], and Advanced Access Content Systems (AACS) for HD-DVD [1].

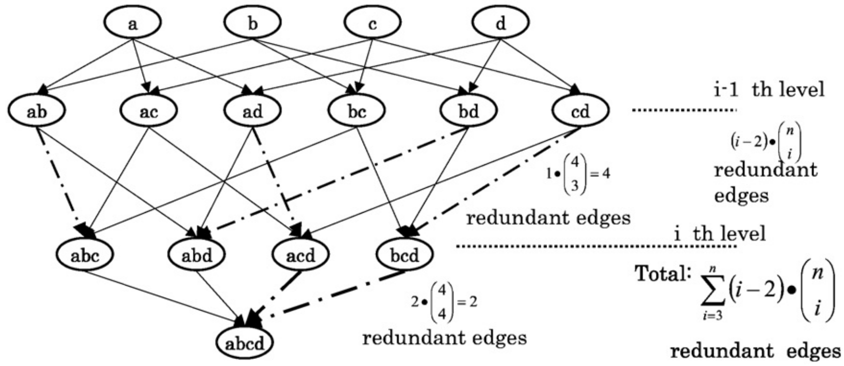

Fig. 4. Full access control hierarchy.

focus in this section on the comparison of our scheme with the key generation schemes. For the sake of a clear comparison we divide them into two groups: PKC (Public Key Cryptography) based schemes and SKC (Symmetric Key Cryptography) based schemes.

Let n be the size of a partial order to which a PKC scheme is applied. The PKC based solutions are essentially extensions of two basic approaches. The first approach requires storing large public keys proportional to the product of first n primes: $p_1 \cdot \dots \cdot p_n$ [11,27,20]. The upper bound for the product of n primes is $(n \log n)^n$, so the size in bits required to store it is $\log (n \log n)^n = n \log(n \log n)$. Each key derivation step requires a single operation, but computation on numbers of that size implies the time needed for the key derivation proportional to n. In the second approach, the number of modular exponentiations needed for computing the private keys is proportional to n [17,18,24]. This is applicable for reasonably small partial orders, for instance hierarchies inside a company or an institute. However in our settings, assuming that N is the number of users, the number n of possible access configurations can reach 2^N. Therefore the direct application of these schemes for partial order on access configurations results in a key derivation time that is exponential in N.

In the scheme we propose, all the private and public keys are bounded from above by a large prime number p. To ensure that the keys are unique, p must be of order n^α for some constant α. Therefore the size of a public key is bounded from above by $\alpha \log n$. It is in the worst case proportional to N. The key derivation time in the proposed scheme is proportional to the height of the partial order. Since the height of a partial order on access configurations cannot exceed N, the derivation time is bounded from above by N. An additional advantage of our scheme is the support for flexible updates, which are poorly supported in the PKC based schemes.

The SKC based schemes [17,14,23,22] are more efficient, however some successful attacks against them have been proposed [21]. Furthermore, we argue below that in terms of storage space our scheme is more efficient than any of these schemes applied directly to an inclusion partial order on access configurations.

Essentially, the SKC based schemes assign the private keys to the nodes and public keys to the edges of the given partial order. When the nodes are access configurations, this order is naturally given by set inclusion. It is represented by a directed graph with n nodes (access configurations) and e edges. An SKC based scheme assigns $O(n)$ private and $O(e)$ public keys. As emphasized in the problem statement given in Section 2, inclusion order gives many redundant edges, which in turn give many redundant public parameters. Intuitively, our partial order construction aims at minimizing the number of edges.

A perceptive reader spots immediately that our scheme assigns both private and public keys to the nodes of the partial order we construct. However, for each node AC except for N singletons $\{u\}$ we have $|\mathrm{In(AC)}| = 2$ (V-condition). Therefore, the number of nodes is equal to $\frac{|\mathrm{edges}|}{2} + N$, and this is the number of public keys issued by our scheme[3].

[3] |X | denotes the number of elements of set X.

This does not complete the analysis, because the number of edges in the order we construct is different than in the inclusion order. Let n and e be the number of nodes and edges in the inclusion order given on access configurations $\{u\}_{u \in \mathcal{U}}$ and $\mathrm{AC}(d)_{d \in \mathcal{D}}$. Let n_t' and e_t' be the number of nodes and edges in our construction after the t th phase of the algorithm. After the first phase, the following conditions are satisfied: $e_1' \leq e$ and $n_1' = n$. This is due to the weaker order conditions defined in Section 2. When constructing the order, we insert only necessary edges that connect users with access configurations they belong to, thus for many inclusions $\mathrm{AC}_1 \subset \mathrm{AC}_2$ there is no relation (edge) in the constructed order. An example is shown in Fig. 4.

After the second phase, the number of edges decreases even more: $e_2' \leq e_1'$. Each inserted dummy access configuration D decreases $|\mathrm{In(AC}_i)|$ by $\alpha \geq 2$ configurations. The precise number of edges after inserting D changes from e_1' to $e_1' - (\alpha - 1) \cdot |\mathrm{In}(D)| + \alpha$ as shown in Fig. 5a.

After the third phase, $e_3' \leq 2e_2' - 1$, so the number of edges at most doubles. This is due to the transformations made by function CreateTree(AC), which transforms AC with In(AC) into a binary tree with AC as a root and In(AC) as leaves (see Fig. 5b). Each call of *CreateTree*(*AG*) adds $|\mathrm{In(AC)}| - 1$ edges.

Thus, in the end we have $e \geq e_1' \geq e_2' \geq \frac{e_3'}{2}$ and $n_3' = \frac{e_3'}{2} + N$ is the number of public parameters in our scheme. This in practice means that in the worst case, when all the reductions of edges do not bring any result, we use at most $(e+N)$ public parameters, whereas SKC based schemes use at least e. However, when dealing with a few or many intersecting access configurations we expect an improvement, as shown in the figures. The number of private parameters remains the same for both SKC based schemes and our scheme and is equal to $n = n_1'$, since we do not have to store the private keys for dummy access configurations.

The support for updates of the access control policies is another advantage of our scheme. We provide methods to efficiently handle all possible changes in access rights granted to the users. If the hierarchy is expanded with new access configurations, only the currently inserted extension and the corresponding data keys need to change. Concluding this comparison, it is worth mentioning that the security of our scheme is guaranteed by the security of well-known DH key-exchange protocol.

6. Conclusions and future work

In this paper, we proposed an efficient method to design a partial order on access configurations. We provided a scheme to assign and derive secret keys for the proposed partial order.

Compared to broadcast encryption methods, our solution eliminates the need for multiple copies of data keys and reduces to a single key the storage required per user. This improvement is achieved by applying the proposed key generation scheme. Compared to key generation schemes adapted for access control purposes, our solution reduces the required size of public information. This is achieved

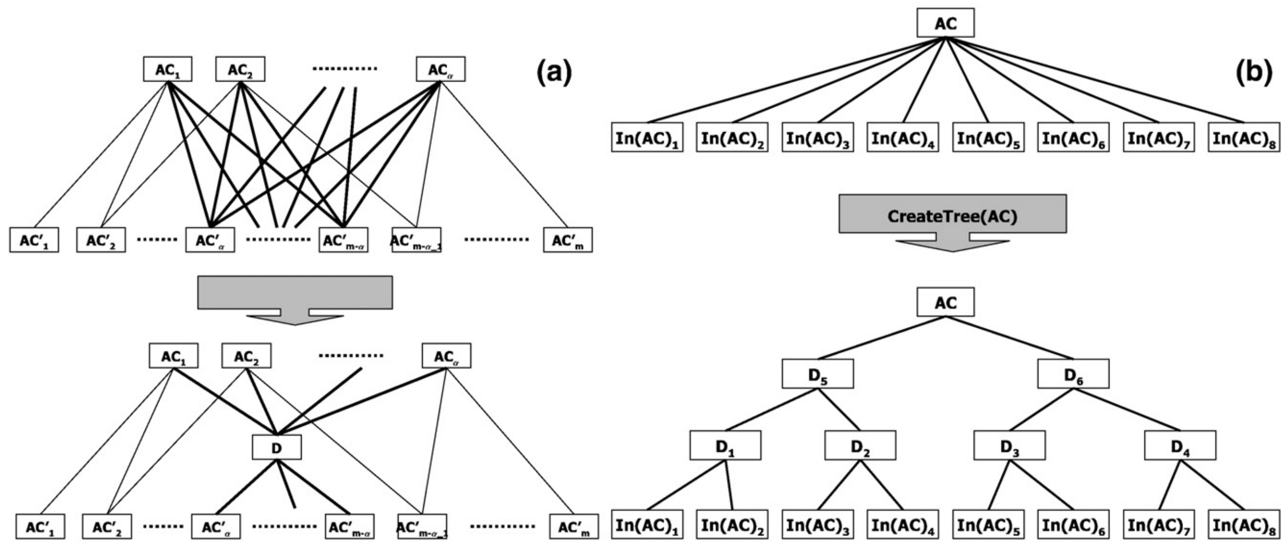

Fig. 5. Insertion of a dummy access configuration *D* and tree transformation.

thanks to the special properties of the hierarchy we propose, designed especially for the access control purpose. To the best of our knowledge, and as reported in [15], nobody has yet proposed a key generation solution that takes advantage of constructing the hierarchy especially for the access control settings. Finally, since access control systems are very dynamic, the issue of changing access rights cannot be neglected. Our solution supports flexible updates of access rights granted to the users.

The work presented in this paper suggests some interesting directions for future research. First of all, we want to apply the proposed key generation method to the application of broadcasting secret messages to stateless receivers. We want to consider specifically scenarios where secure storage or communication overhead is expensive and should be minimized. In these scenarios, the goal is to decrease the need for the private storage to one key per receiver, and minimize the size of the message to and the time needed for deriving a key.

Another important direction is to find an assignment of public parameters such that the users can generate them efficiently on-the-fly. This would allow releasing the public space requirement on our scheme.

Finally, in this paper we have not discussed if the proposed algorithm for hierarchy creation is optimal. It will be worthwhile to look at this optimization problem.

Appendix A. The algorithm

The output of the CreateHierarchy(Access Table ACCESS) algorithm is the directed graph $G=(V, E(V))$ in a V-form, where the node set $V \supseteq \{AC(d)|d \in \mathcal{D}\}$. The algorithm uses an abstract data structure Digraph *G* to represent the order on access configurations it constructs. The standard available operations are: New(), Cover (Node *A*), InsertNode(Node *A*), InsertEdge(Node *A*, Node *B*), Remove-Node(Node *A*) and RemoveEdge(Node *A*, Node *B*). We assume that the graph does not allow duplicate nodes (if the node to be inserted already exists, than the insertion procedure terminates). Similarly, no multiple arcs are allowed between two nodes. The algorithm CreateHierarchy(Access Table ACCESS) uses the priority queue *Q*. A priority queue is an abstract data type to efficiently support finding the item with the highest priority across a series of operations. The basic operations are: New(), Insert(Item, Priority), ExtractMax(), ExtractMin(), FindMax(), FindMin() and Remove(Item). The items of *Q* are the access configurations. The algorithm calls two additional procedures: InsertCoverMin(Node AC) and CreateTree(Node AC), which are presented in Section A.1. The number of elements in data structure *X* is denoted as #*X*. For data structures *X* and *Y* we denote their set difference (the elements in *X* but not in *Y*) as $X-Y$, and their intersection as $X*Y$.

A.1. Subprocedures codes

```
algorithm InsertCoveredMin(Node AC)
begin
   (1) G.InsertNode(AC) ;
   (2) Node X:=AC;
   (3) while (#X>0) do
     begin
     (4) Node Y:=maximal Z in G, s.t. X contains Z;
     (5) G.InsertEdge(Y,X);
     (6) X:=X−Y;
    end
end.
```

```
algorithm CreateTree(Node AC)
begin
   (1) pos:=0;
   (2) for each (X in G s.t. X ->> AC) do
      begin
        Q. Insert (X, pos++);
     (3) while (#Q>2) do
         begin
         (4) AC_1:=Q.ExtractMin(); AC_2:=Q.ExtractMin();
         (5) Node Y:=AC_1+AC_2; (6) G.InsertNode(Y);
         (7) G.InsertEdge(AC_1,Y); G.InsertEdge(AC_2,Y);
         (8) G.RemoveEdge(AC_1,AC); G.RemoveEdge (AC_2, AC);
         (9) G.InsertEdge (Y,AC); (10) Q.Insert (Y, position++);
         end
      end
end.
```

A.2. The main code

```
algorithm CreateHierarchy(Access Table ACCESS)
begin
   (1) Digraph G:=New (); PriorityQueue Q:=New();
   (2) for each (u in U) do G.InsertNode({u});
```

```
    (3) for each (d in D) do Q.Insert(AC(d),#AC(d));
    (4) while (Q.size()>0) do
          begin
          (5) AC:=Q.ExtractMin();
          (6) G.InsertCoveredMin(AC);
          end
  (7) for each (AC in G s.t. #In (AC)>2) do Q.Insert (AC, #In (AC));
    (8) repeat
      (9) Node AC:=Q.FindMax (); MAX_CUT:=empty set;
      (10) for each (AC_k in Q) do
           begin
            (11) CUT:=AC*AC_k;
            (12) if ( #{X in G s.t. X-≫ AC, CUT contains X}
                   >#{X in G s.t. X-≫ AC, MAX_CUT contains X}
                  AND
                 there are X,Y in G
                 s.t. X!=Y, X,Y-≫ AC, CUT contains X*Y
                 AND
                 there are X,Y in G
                 s.t. X!=Y, X,Y-≫ AC_k, CUT contains X*Y
      (13) then MAX_CUT:=CUT;
    end // for each
  (14) if (MAX_CUT not empty) //if MAX_CUT found
  (15) then
        begin
      (16) G.InsertCoveredMin(MAX_CUT);
      (17) for each (X in Q) do
          begin
          (18) if (X contains strictly MAX_CUT
                AND
                there are Y,Z in G s.t. Y!=Z,
                  Y,Z-≫ X, MAX_CUT contains X*Z)
          (19) then
                begin
                (20) G.InsertEdge (MAX_CUT,X);
                (21) for each (Y in G s.t. Y-≫ X, MAX_CUT
                       contains Y) do
                         G. RemoveEdge(Y,X);
                (22) if (#In(X)<=2) then Q.Remove(X),
          end // if
        end // for each
      (23) if (#In(MAX_CUT)>2)
      (24) then Q.Insert (MAX_CUT,#In(MAX_CUT));
       end // if
  (25)else G.CreateTree(AC); Q.Remove(AC);
  (26)until Q is empty; // repeat
end.
```

Appendix B. Correctness proof

Lemma 1. *After the termination of the algorithm* CreateHierarchy, *the output graph G=(V, E(V)) satisfies the following five conditions:*

(a) $\forall_{u \in \mathcal{U}} \{u\} \in V$
(a') $\forall_{d \in \mathcal{D}} AC(d) \in V$
(b) $u \in AC \Rightarrow \{u\} \twoheadrightarrow AC$
(b') $AC_l \twoheadrightarrow AC_2 \Rightarrow AC_l \subseteq AC_2$
(c) $\forall_{AC \in V}$ $|In(AC)|=0$ or $|In(AC)|=2$
(d) $\forall_{AC_1, AC2 \in V} |\{AC \in V : AC \rightarrow AC_l, AC \rightarrow AC_2\}| \leq 1.$

Proof. In the first phase (1–6), the algorithm constructs the hierarchy, which satisfies (*a*), (*a*'), (*b*) and (*b*'). Since the arcs are added only between such two configurations, that one contains the other, (*b*') remains trivially satisfied until the termination. After addition of singletons (2) *G* satisfies (*a*), and after addition of existing access configurations (3–6), *G* satisfies (*a*') as well. Both (*a*) and (*a*') are not affected by the algorithm anymore and remain satisfied until termination. After line (2) *G* satisfies (b) trivially because *V* is the set of singletons. (b) remains satisfied after each step of the main algorithm until line (21), because the procedures *InsertCoveredMin* and *CreateTree* preserve (b), and only in line (21) the edges are removed so (b) has a chance to be affected.

In the second phase, from line (7), additional access configurations are inserted to reduce the number of edges and satisfy the condition (c). Beginning at line (7) until the termination, *Q* stores the nodes AC∈*V* for which |In(AC)|>2 and thus they still need to be processed. The priorities of the items on *Q* determine the order of processing the nodes of *G*. The priority of an item AC is |In(AC)|. The nodes with larger In(AC) are processed first. The main loop REPEAT (8-26) is terminated when *Q* is empty, so all the nodes have at most two incoming edges. In (9) node AC, with the maximal number of incoming edges, is extracted from *Q* to reduce |In(AC)|. After current iteration of the main loop, the size |In(AC)| is reduced, and therefore each iteration reduces the number of incoming edges of a node, with the maximal number of incoming edges in *G*. Thus, at some point the maximal number of incoming edges in *G* must reach 2. This guarantees that the loop terminates. In lines (10–13), the algorithm searches for the dummy access configuration *MAX_CUT*, which insertion reduces |In(AC)| maximally, under the assumption that it also reduces $|In(AC_k)|$ for some other access configuration AC_k still stored on *Q*. If (14) *MAX_CUT* was found, then (15) it is inserted into *G* (16), and for each node *X* on *Q* (17) the algorithm checks (18) whether |In(*X*)| can be reduced using *MAX_CUT*. If the condition from line (18) is satisfied, then *MAX_CUT* → *X* is added to |In(*X*)| (20), but then based on (18) at least two edges in In(*X*) are removed in (21), and therefore |In(*X*)| decreases at least by one. AC satisfies (18), thus one of the iterations of loop for each (17–24) reduces In(AC) for a node AC with the maximal number of incoming edges in *G*. In(*MAX_CUT*) does not increase back the maximal number of incoming edges in *G*, because |In(*MAX_CUT*)|<|In(AC)|. Based on (18), (b) is preserved after each execution of line (21). In (23) the algorithm enqueues *MAX_CUT* if it needs to be processed. If (25) *MAX_CUT* was not found, then |In (AC)| is reduced to 2 by inserting to *G* a binary tree rooted in AC with configurations *X*: *X*→AC as leaves. The result of the algorithm is the *V-graph* satisfying (a–d).

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