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Using AVL Trees for Fault Tolerant Group Key Management

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Abstract In this paper we describe an efficient algorithm for the management of group-keys for Group Communication Systems. Our algorithm is based on the notion of *key-graphs*, previously used for managing keys in large IP-multicast groups.

The standard protocol requires a centralized key-server that has knowledge of the full key-graph. Our protocol does not delegate this role to any one process. Rather, members enlist in a collaborative effort to create the group key-graph. The key-graph contains n keys, of which each member learns $\log_2 n$.

We show how to balance the key-graph, a result that is applicable to the centralized protocol. We also show how to optimize our distributed protocol and provide a performance study of its capabilities.

Key words Logical Key Hierarchy – Group Communication – Security

1 Introduction

This paper describes an efficient algorithm for key-management in Group Communication Systems (GCSs).

Use of GCSs is now common in industry when clustering technology is required. The SP2, and other IBM clustering systems use the Phoenix

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system [10], IBM AS/400 clusters use the Clue system [15], and Microsoft Wolfpack clusters use Group Communication technology at the core of their system [40]. GCSs are used for other purposes as well. The first industrial strength GCS, Isis [6], has been used for air-traffic control, large-scale simulations, in the New-York and Swiss stock exchanges and more. Some of these projects are described in [7]. Adding security to Group Communication Systems will enable industry to use this technology were it was not possible before, in unprotected wide area networks.

In our work we use the *fortress* security model. The "good guys" are protected by a castle from the hordes of barbarians outside. In the real world this maps to a situation where the "good guys" are the organization's machines, which need protection from hackers lurking outside.

In the context of a Group Communication System, the basic entity is a process (member). The set of honest processes requires protection from the adversary. Since the honest members are distributed across the network, they cannot be protected by a firewall. An alternative vehicle for protection is a shared secret key. Assuming all members agree on the same key, all group messages can be MAC-ed[1] and encrypted. Assuming the adversary has no way of retrieving the group-key, the members are protected.

The group-key needs special handling as it must be distributed *only* to authenticated and authorized group members. This raises two issues: merge and rekey.

- Merge: How do we allow new members into an existing group? More generally, how do we merge two existing group components, each using a different group-key?
- Rekey: How do we switch the secret key, without relying on the old key?

Here, we confine ourselves to describing an efficient rekey algorithm. For a discussion on merge-related issues see [36]. Other work on GCS key architectures and security has been performed in Spread [2], Antigone [24], Rampart [29], and Totem [22]. We postpone discussion of related work until Section 7.

Our contributions are:

- A completely distributed version of the well-known Logical Key Hierarchy (LKH) [42,41], named dLKH.
- LKH requires a key-server that has knowledge of all group keys. If the group contains n clients, then the server maintains $n-1$ sub-group keys, and n point-to-point keys. In dLKH each member maintains $log_2(n)$ sub-group keys, and a variable number of point-to-point keys.
- A novel rebalancing scheme applicable also to LKH. Previous work on balancing has been very limited [26]. The challenge is in performing a rebalance operation without incurring the costs of tree reconstruction.

[1] MAC is a Message Authentication Code algorithm. In practice, the group-key is composed of two disjoint pieces. A separate key for encryption, and a separate key for MAC-ing.

– Support for arbitrary group partition and merge scenarios.
– Performance that is on par with the centralized solution.

dLKH has been completely implemented the Ensemble [18] group communication system. The software is open-source and free for public use. A short version of this work was published in [35].

2 Model

Consider a universe that consists of a finite group $\mathcal{U}$ of n processes. Processes communicate with each other by passing messages through a network of channels. The system is asynchronous: clock drifts are unbounded and messages may be arbitrarily delayed or lost in the network. We do not consider Byzantine failures.

Processes may get *partitioned* from each other. A partition occurs when $\mathcal{U}$ is split into a set $\{P_1, \ldots, P_k\}$ of disjoint subgroups. Each process in P_i can communicate only with processes in P_i. The subsets P_i are sometimes called *network-components*. We shall consider *dynamic partitions*, where in network-components dynamically merge and split. The partition model is more general than the more common "crash failure" model since crash failures may be modeled as partitions, but not the converse.

A GCS creates process groups in which reliable ordered multicast and point-to-point messaging is supported. Processes may dynamically join and leave a group. Groups may dynamically partition into many *components* due to network failures/partitions; when network partitions are healed group components remerge through the GCS protocols. Information about groups is provided to group members in the form of *view* notifications. For a particular process p a view contains the list of processes currently alive and connected to p. When a membership change occurs due to a partition or a group merge, the GCS goes through a (short) phase of reconfiguration. It then delivers a new view to the applications reflecting the (new) set of connected members.

In what follows p, q, and s denote Ensemble processes and V, V_1, V_2 denote views. The generic group is denoted by G. G's members are numbered from p_1 to p_n.

In this paper, all group-messages are delivered in the order they were sent: "fifo" or "sender-ordered" property. This is the basic guarantee provided by the system.

Ensemble follows the Virtual Synchrony (VS) model. This model describes the relative ordering of message deliveries and view notifications. It is useful in simplifying complex failure and message loss scenarios that may occur in distributed environments. For example, a system adhering to VS ensures "atomic failure". If process q in view V fails then all the members in $V \setminus \{q\}$ observe this event at the "same time".

In particular, virtual synchrony is a strong enough model to support replicated data and consistency in a distributed environment [21,14]. Our

protocols (described later) employ these guarantees to consistently replicate complex data structures. Furthermore, our algorithms strongly depend on the guarantee that views are agreed. This is important in choosing agreed group leaders. The VS guarantee is used to agree an all-or-nothing property whereby either all group members receive the new group key, or none of them do.

To achieve fault-tolerance, GCSs require members to actively participate in failure-detection, membership, flow-control, and reliability protocols. Therefore, such systems have inherently limited scalability. We have managed to scale Ensemble, the GCS with which the work reported here was undertaken, to a hundred members per group, but no more. For a detailed study of this problem, the interested reader is refered to [8,7,34]. In this paper, we do not discuss configurations of more than a hundred members. However, given a GCS capable of supporting larger groups our algorithms are intended to scale at least as well.

We assume processes in a group have access to trusted authentication and authorization services, as well as to a local key-generation facility. We also assume that the authentication service allows processes to sign messages. Our system ([36]) currently uses the PGP [43] authentication system. Kerberos [28] is also supported, though our interface is out of date.

As noted earlier, in a secure group, protection is afforded to group members through a shared key, with which all group messages are MAC-ed and encrypted. Accordingly, a secure group should support:

- Authorization and access control. Only trusted and authorized members are allowed into the group.
- The system should support Forward Confidentiality (FCY) with respect to the group key. Briefly, this means that past members cannot obtain keys used in the future. The dual requirement that current members cannot obtain keys used in the past is termed Backward Confidentiality (BCY). This requirement is also known as resistance to *known key attacks*.
- Compromising long-term secrets should not reveal group keys (*Perfect Forward Secrecy*).

To support FCY, the group key must be switched every time members join and leave. This may incur high cost, therefore, we would like to relax this requirement without breaching security. Other researchers have also noted that rekeying is a costly operation, and have tried to perform periodic rekeying [38,27], or to tie it with the ACL mechanisms [24]. Our approach is three pronged:

- Fast rekeying algorithms are included in the system.
- The system rekeys itself every 24 hours
- Rekeying becomes a user initiated action. Hence, the user can trade off security against performance.

The main goal of this paper is the improvement of rekeying performance, allowing a better tradeoff for the user.

2.1 Secure Groups

Henceforth, we assume that the system creates only secure groups where:

- All members are trusted and authorized
- All members have the same group-key.
- No outside member can eavesdrop, or tamper with group messaging.

In the remainder of this paper, we make extensive use of secure point-to-point communication. Although public keys can be used for this purpose, their poor performance motivates us to employ symmetric point-to-point keys where such communication may occur repeatedly. Accordingly, we introduce a *secure channel* abstraction. A secure channel allows two members to exchange private information, it is set up using a Diffie-Hellman [12] exchange. This exchange is protected from man-in-the-middle attacks using the current group-key. The initial exchange sets up an agreed symmetric key with which subsequent communication is encrypted. The set of secure channels at member p is managed using a simple caching scheme: (1) only connections to present group members are kept. (2) the cache is flushed every 24 hours[2] to prevent cryptanalysis.

Integer module exponentiations, needed for a Diffie-Hellman exchange, are expensive. We used a 500Mhz PentiumIII with 256Mbytes of memory, running the Linux OS, kernel version 2.2, for speed measurements. An exponentiation with a 1024bit key [3] using the OpenSSL [11] cryptographic library was clocked at 40 milliseconds. Setting up a secure channel requires two messages containing 1024bit long integers. Hence, we view the establishment of secure channels as expensive, in terms of both bandwidth and CPU. Our caching scheme efficiently manages channels, but in what follows, an important goal will be to minimize the need of their use.

2.2 Liveness and Safety

Ideally, one would hope that distributed protocols can be proven *live* and *safe*. Key management protocols must also provide *agreement* and *authenticity* properties. Here these properties are defined, and the degree to which our protocols satisfy them is discussed.

Liveness: We say that a protocol is live if, for all possible runs of the protocol, progress occurs. In our work, progress would involve the installation of new membership views with associated group keys, and the successful rekeying of groups.

Safety: We say that a protocol is safe if it does not reveal the group key to unauthorized members.

[2] This is a settable parameter.

[3] Group size is of size 1024bit, subgroups of Z_p* were not used here to speed up the computation.

Agreement: the protocol should guarantee that all group-members decide on the same group-key. Note that this is slightly different than the definition of the Handbook of Applied Cryptography [25] for key-agreement. The point here is that in a distributed system subject to failures, members agree on the same key; in the Handbook, the definition stresses the contributory nature of the key.

Authenticity: An authentic group-key is one chosen by the group-leader.

To show how a rekeying protocol can comply with the above four requirements, we introduce a simplistic rekeying protocol, $\mathcal{P}$.

Protocol $\mathcal{P}$:

1) The group leader chooses a new key.
2) The leader uses secure channels to send the key securely to the members.
3) Each group member, once it receives the group-key from the leader, sends an acknowledgment (in the clear) to the leader.
4) The leader, once it receives acknowledgments from all group members, multicasts a *ProtoDone* message.
5) A member that receives a *ProtoDone* message knows that the protocol has terminated and the new key can now be used.

$\mathcal{P}$ is safe since it uses secure channels to group members, all of which are trusted. It satisfies agreement because a single agreed member acts as leader. It satisfies authenticity because only a trusted authorized member can become the leader, and only the leader can choose a new key.

However, $\mathcal{P}$ is not live. Notice that the protocol requires all processes to receive the new-key and send acknowledgments. If some member fails and never recovers during the execution, protocol $\mathcal{P}$ blocks.

To make the protocol fault-tolerant it is restarted in case of a view change. Note that restarting is not enough to guarantee liveness. In fact, no protocol solving this class of problems can guarantee liveness in an asynchronous networking environment (see FLP [13]). However, our protocol is able to make progress "most of the time". The scenarios under which the protocol would fail to make progress are extremely improbable, involving an endless sequence of network partitioning and remerge events, or of timing failures that mimic process crashes. Theoretically, such things can happen, but in any real network, these sequences of events would not occur, hence our protocol should make progress. It is stressed that the protocol can continue operation in the face of any *finite* sequence of partition and merge events.

This short exposition has shown that the four requirements listed above, while fundamental for a rekeying protocol, are easily satisfied (to the degree possible) for a protocol using the services of a group communication system. The critical ingredients are the ack-collection stage, and restarting. Such

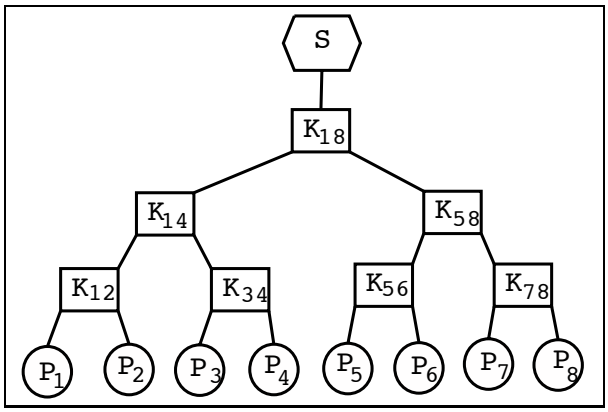


Fig. 1 A key-graph for a group of eight members.

stages can be added to *any* rekeying protocol. Hence, in the more complex protocols described later on in sections 4, and 5 we omit these stages.

3 The centralized solution ($\mathcal{C}$)

Here a protocol created by Wong et al. [42], and Wallner et al. [41] is described. Improvements were later suggested in [5,9]. The general idea is termed a *Logical Key Hierarchy* (LKH), and it uses the notion of *key-graphs*. Key-graphs have been put to use in other security protocols, for example, Cliques [23].

In its basic form LKH is used to switch the group key every time a member joins or leaves the group. When LKH is used to manage keys for large groups, where the rate of join and leave operations is high, it becomes prohibitively expensive to rekey every membership change. Hence, rekeying is performed periodically, or using some user defined policy [38,27,24].

A key-graph is defined as a directed tree where the leafs are the group members and the nodes are keys. A member knows all the keys on the way from itself to the root. The keys are chosen and distributed by a key-server. While the general notion of a key-graph is somewhat more general, we focus on binary-trees. In Figure 1 we see a typical key-graph for a group of eight members. This will serve as our running example.

Each member p_i shares a key with the server, K_i, using a secret channel. This key is the secure-channel key used for private communication between p_i and the server. It is called the *basic-key*. Each member also knows all the keys on the path from itself to the root. The root key is the group key. In the example, member p_1 knows keys $K_1, K_{12}, K_{14}, K_{18}$. It shares K_1 with the server, K_{12} with p_2, K_{14} with $\{p_2, p_3, p_4\}$, and K_{18} with members $\{p_2, \ldots p_8\}$. In what follows we denote by $\{M\}_{K_1,K_2}$ a tuple consisting of message M encrypted once with key K_1, and a second time with K_2.

The key server uses the basic keys to build the higher level keys. For example, the key-graph in the figure can be built using a single multicast message comprised of three parts:

- Part I: $\{K_{12}\}_{K_1,K_2}$, $\{K_{34}\}_{K_3,K_4}$, $\{K_{56}\}_{K_5,K_6}$, $\{K_{78}\}_{K_7,K_8}$
- Part II: $\{K_{14}\}_{K_{12},K_{34}}$, $\{K_{58}\}_{K_{56},K_{78}}$
- Part III: $\{K_{18}\}_{K_{14},K_{58}}$

All group members receive this multicast, and they can retrieve the exact set of keys on the route to the root. For example, member p_6 can decrypt from the first part (only) K_{56}. Using K_{56}, it can retrieve K_{58} from the second part. Using K_{58} it can retrieve K_{18} from the third part. This completes the set K_{56}, K_{58}, K_{18}. In general, it is possible to construct any key-graph using a single multicast message.

The group key needs to be replaced if some member joins or leaves. This is performed through key-tree operations.

Join: Assume member p_9 joins the group. S picks a new (random) group-key K_{19} and multicasts: $\{K_{19}\}_{K_{18},K_9}$. Member p_9 can retrieve K_{19} using K_9, the rest of the members can use K_{18} to do so.

Leave: Assume member p_1 leaves, then the server needs to replace keys K_{12}, K_{14}, and K_{18}. It chooses new keys K_{24}, and K_{28} and multicasts a two part message:
- Part I: $\{K_{24}\}_{K_2,K_{34}}$
- Part II: $\{K_{28}\}_{K_{24},K_{58}}$.

The first part establishes the new key K_{24} as the subtree-key for members p_2, p_3, p_4. The second part establishes K_{28} as the group key.

In this scheme each member stores $\log_2 n$ keys, while the server keeps a total of $2n$ keys (n of which are secure channel keys). The protocol costs exactly one multicast message (acknowledgments are not discussed here). The message size, as a multiply of the size of a key ℓ, is as follows:

Construction	Leave	Join
$2\ell n$	$2\ell \log_2 n$	2ℓ

Trees become imbalanced after many additions and deletions, and it becomes necessary to rebalance them. A simple rebalancing technique is described in [26]. However, their scheme is rather rudimentary. For example, in some full binary key-tree T, if most of the right hand members leave, the tree becomes extremely unbalanced. The simple scheme does not handle this well. Our scheme can handle such extreme cases.

3.1 Tree balancing

This section describes an efficient tree balancing scheme that can be used by the centralized algorithm. The challenge in efficient rebalancing is the maximal reuse of existing tree-parts. In the standard algorithm, a key-tree

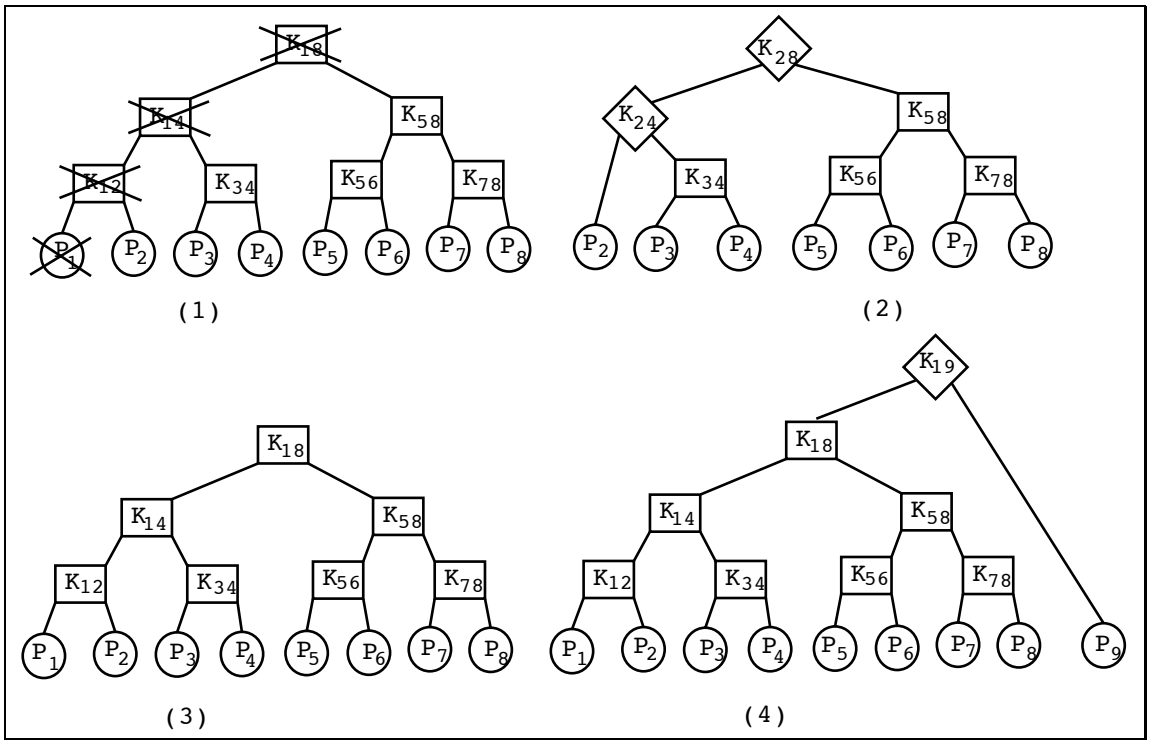


Fig. 2 Examples for join/leave cases. Examples one and two depict a scenario where member p_1 leaves. Examples three and four depict a scenario where member p_9 joins. New keys are marked by diamonds.

is initially created fully balanced. However, certain join and leave scenarios can cause it to become unbalanced, and leave operations can then incur cost significantly more than $log_2(n)$.

After multiple leaves, a key-graph is composed of a disjoint set of sub-key-graphs. More generally, setting up the distributed version of the protocol, we shall be interested in merging different key-graphs. For example, in Figure 3(1), one can see two key graphs, T_1 that includes members $\{p_1, \ldots, p_5\}$, and T_2 that includes members $\{p_6, p_7\}$. The naive approach in merging T_1 and T_2 together is to add members $\{p_6, p_7\}$ one by one to T_1. However, as we can see in Figure 3(2) this yields a rather unbalanced graph. Instead, we create a new key K_{57} and put T_2 under it.

Merging two trees in this fashion can be performed using one message sent by the key-server. The message includes two parts:

- Part I: The new key, K_{57} encrypted for both of its children: $\{K_{57}\}_{K_{67},K_5}$
- Part II: All keys above T_2 encrypted with K_{67}: $\{K_{15}\}_{K_{67}}$

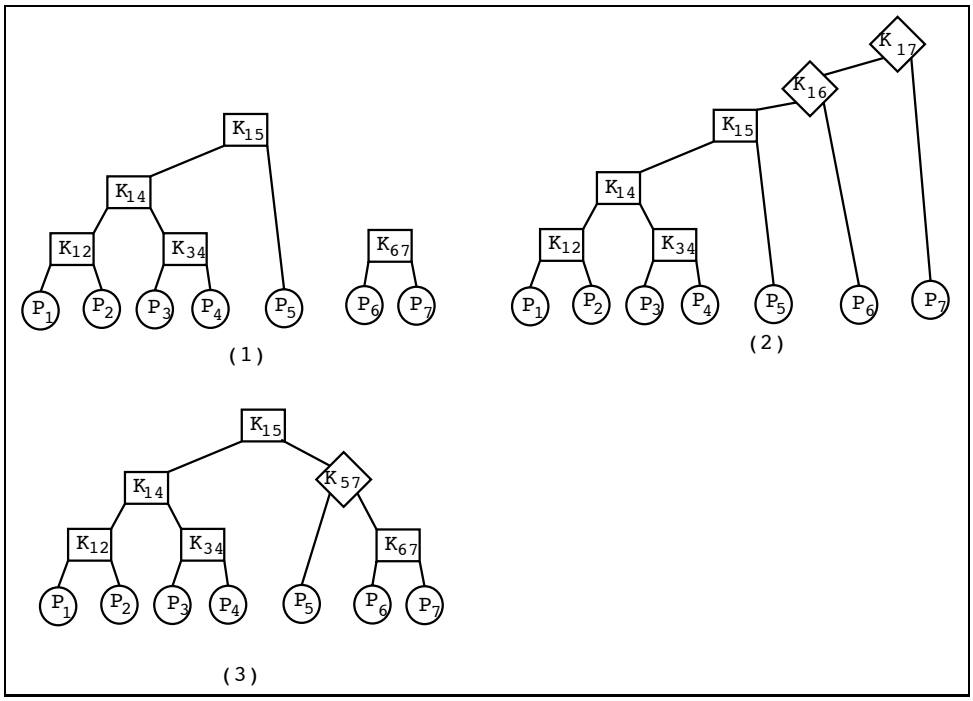


Fig. 3 Balancing example.

The example can be generalized to a *balanced merge* (Bal_Merge) procedure. In what follows we denote by $h(T)$ the height of tree T. To describe the structure of a tree we use a recursive data structure that contains nodes of two kinds:

- $Br(L, K, R)$: An inner-node with left subtree L, right subtree R, and key K.
- $Leaf(p_i)$: A leaf node with member p_i.

The simplest tree contains a single member, $Leaf(p_x)$. A single member tree does not have a key, since a single member can communication with itself alone. Such communication does not need protection. The height of a tree $Leaf(p_x)$ is 1.

Assume that L and R are two subtrees that we wish to merge. W.l.o.g we can assume that $h(L) \geq h(R)$. Bal_Merge will find a subtree L' of L such that $1 \geq h(R) - h(L') \geq 0$, and create a new tree T where L' is replaced by $Br(L', K_{new}, R)$. The merge procedure is performed at the key-server, that has complete knowledge of all keys and the structure of existing key-trees. The local computation is a simple tree recursion. The message size required to notify the group is of size $O(\log_2 n)$. This is because R's members must know all keys above K_{new}.

In a general key-graph, there is no bound on depth as a function of the number of leaves. If a member that is situated very deep in the tree is removed, then the tree is split into many disconnected fragments. Therefore, it is desirable to have balanced trees. We propose using AVL [1] trees for this purpose. Assume that T_1 and T_2 are AVL trees. We shall show that the merged tree is also AVL. First, we state more carefully the Bal_Merge algorithm, in the form of pseudo-code.

Algorithm Balanced Merge(T_1, T_2):

if $h(T_1) == h(T_2)$ then {
  choose a new key K_{new}
  return $Br(T_1, K_{new}, T_2)$
}
if $h(T_1) > h(T_2)$ then {
  assume $T_1 = Br(L, K_{T_1}, R)$
  if $h(L) < h(R)$ then return $(Br(merge(L, T_2), K_{T_1}, R))$
  else return $Br(L, K_{T_1}, merge(T_2, R))$
}
if $h(T_1) < h(T_2)$ then {
  the same as above, reversing the names T_1, T_2.
}

Claim : Merging two AVL trees T_1 and T_2 results in an AVL tree whose height is at most $1 + \max(h(T_1), h(T_2))$.

Proof: The proof is performed by induction on the difference in height: $h(T_1) - h(T_2)$.

- Base Case: If $h(T_1) = h(T_2)$ then the merged tree is $T = Br(T_1, K_{new}, T_2)$. The depth of the T is $h(T_1) + 1$.
- Induction: We assume that if $h(T_1) - h(T_2) < k$ then the theorem holds. W.l.o.g $h(T_1) > h(T_2)$. If $h(T_1) - h(T_2) = k$ then T_1 is of height at least two, and $T_1 = Br(L, key, R)$. There are two cases:
  - $h(L) < h(R)$: The result will be, $T = Br(merge(T_2, L), key, R)$ By induction we have that $merge(T_2, L)$ is AVL, and that its height is at most $h(R) + 1$.
    Hence, the difference in height between the left and right children of T is no more than 1, and T's height conforms to $h(T) \leq h(R) + 2 = 1 + max(h(T_1), h(T_2))$
    $h(L) \geq h(R)$: The result will be $T = Br(L, key, merge(T_2, R))$. By induction we have that $merge(T_2, R)$ is of height that is at most $h(L) + 1$.
    Hence, the difference in height between the left and right children of T is no more than 1, and T's height conforms to $h(T) \leq h(L) + 2 = 1 + max(h(T_1), h(T_2))$

□

Two AVL trees can be merged into a single AVL tree at low cost. This can be generalized to merging a set of trees. Sets of trees are interesting since they occur naturally in leave operations. For example, if a member leaves an AVL tree T, then T is split into a set of $\log_2 n$ subtrees. These subtrees, in turn, are AVL and they can be merged into a new AVL tree.

The cost of a merge operation is measured by the size of the required multicast message. We are interested in the price of merging m AVL trees, with n members. First, we shall use a naive but imprecise argument to show that the price is bounded by $2K(m-1) + K(max\{h(T_i)\} - min\{h(T_i)\})$. Then we shall provide a proof showing this to be in fact $3K(m-1) + K(max\{h(T_i)\} - min\{h(T_i)\})$.

We sort the trees by height into a set $\{T_1, T_2, \ldots, T_m\}$. They are merged two at a time: first the smallest two into T_{12}, then T_{12} and T_3 into T_{13} etc. The price for merging two trees is $2K + K||h(T_1) - h(T_2)||$. Assuming naively that $h(\mathsf{Bal\_Merge}(T_x, T_y)) = \max(h(T_x), h(T_y))$ then the total price is the height difference between the deepest tree, and the shallowest one. Hence, the total price is: $2K(m-1) + K(max\{h(T_i)\} - min\{h(T_i)\})$.

The naive argument fails to take into account the fact that merged trees conform to $h(\mathsf{Bal\_Merge}(T_x, T_y)) \leq 1 + \max(h(T_x), h(T_y))$. Therefore, we insert the trees into a heap. Iteratively, the smallest two trees are popped from the heap, merged together, and put back into the heap.

Claim : The cost of a balanced merge of m trees $\mathcal{T}_m = \{T_1, \ldots, T_m\}$ is bounded by $3K(m-1) + K(max\{h(T_i)\} - min\{h(T_i)\})$.

Proof: The proof is by induction. For two trees T_1 and T_2 , the price is simply $2K + K||h(T_1) - h(T_2)||$.

Assume the claim is true for up to $m-1$ trees. We shall show for m. We proceed according to the heap discipline and merge the two smallest trees, T_1 and T_2 into $T_{1 \uplus 2}$. We get a heap with trees $\mathcal{T}_{m-1} = \{T_{1 \uplus 2}, T_3, \ldots, T_m\}$.

The cost for merging the trees in $\mathcal{T}_{m-1}$ is, by induction, $3K(m-2) + K(max\{h(T_i)\}_{\mathcal{T}_{m-1}} - min\{h(T_i)\}_{\mathcal{T}_{m-1}})$. The cost for merging T_1 and T_2 is $K||h(T_1) - h(T_2)|| + 2K$.

We know that:

1) $max\{h(T_i)\}_{\mathcal{T}_{m-1}}$ is bounded by $max\{h(T_i)\}_{\mathcal{T}_m} + 1$.
2) $min\{h(T_i)\}_{\mathcal{T}_{m-1}} \geq min\{h(T_i)\}_{\mathcal{T}_m} + ||h(T_1) - h(T_2)||$

Hence, the sum:

$K(max\{h(T_i)\}_{\mathcal{T}_{m-1}} - min\{h(T_i)\}_{\mathcal{T}_{m-1}}) + 3K(m-2) + 2K + K||h(T_1) - h(T_2)||$

is bounded by:

$K((max\{h(T_i)\}_{\mathcal{T}_m} - min\{h(T_i)\}_{\mathcal{T}_m}) + 1) + 3K(m-2) + 2K =$

$= \quad K(max\{h(T_i)\}_{\mathcal{T}_m} - min\{h(T_i)\}_{\mathcal{T}_m}) + 3K(m-1)$

□

In Figure 4 we can see a balanced tree, after a join.

The table below lists the costs of balanced join and leave events. This shows that AVL trees do not cost significantly more than standard key-graphs. We shall use them henceforth.

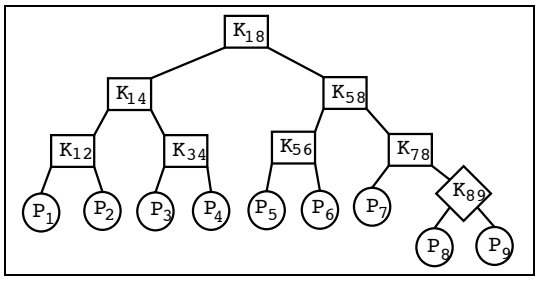


Fig. 4 Balancing the join case.

Construction	Leave	Join
$2\ell n$	$2\ell \log_2 n$	$\ell \log_2 n$

Note that the technique described so far does not maintain Backward Confidentiality (BCY). For example, in the join case, member p_9 learns the set of keys used before by members $\{p_1, \ldots p_8\}$. To guaranty BCY, we must replace all keys on the path from the joiner to the root with fresh keys.

Currently, we do not address the issue of BCY in full. However, we allow the application to determine a time period after which the whole tree is discarded and built from scratch. By default this timer is set to 24 hours. Hence, BCY is guaranteed up to 24 hours.

4 The basic ($\mathcal{B}$) distributed protocol

The centralized solution $\mathcal{C}$ does not satisfy our objectives because it relies on a centralized server which has knowledge of the complete key-graph. We require a completely distributed solution, without a single point of failure. While our algorithm is based on $\mathcal{C}$, each member keeps only $\log_2 n$ keys and members play symmetric roles. The algorithm presented here is called Basic ($\mathcal{B}$) since it is rather simple and inefficient. We optimize it in the next sections.

It is stressed that rekeying is not performed every leave or join event, rather, it is a user initiated action, invoked whenever the user wishes to increase group security.

A group of members G has key-graph T if: (1) the set of leaf-nodes that T contains is equal to G (2) each member of G possesses exactly the set of keys on the route from itself to the root of T (3) members agree on the tree structure. The leader of T, denoted C_T, is the leaf that is the left-most in the tree. Since members agree on the tree structure, each member knows if it is a leader or not. $M(T)$ denotes the members of T, and K_T denotes the top key of T (if one exists).

Observe that members in G must have routes in the tree that "match", i.e., when pulled together they make a tree that is the same as a tree ob-

tained by the centralized algorithm. To perform this "magic" in a distributed environment we rely on Virtual Synchrony (see more below 4.1).

To motivate the general algorithm, a naive protocol that establishes key-trees for groups of size 2^n is described. The notion of subtrees *agreeing* on a mutual key is employed. Informally, this means that the members of two subtrees L and R, securely agree on a mutual encryption key. The protocol used to agree on a mutual key is as follows:

Agree(L, R):

1. C_L chooses a new key K_{LR}, and sends it to C_R using a secure channel.
2. C_L encrypts K_{LR} with K_L and multicasts it to L; C_R encrypts K_{LR} with K_R and multicasts to R.
3. All members of $L \cup R$ securely receive the new key.

The *agree* primitive costs one point-to-point and two multicast messages. Its effect is to create the key-graph $Br(L, K_{LR}, R)$ for the members of $M(L) \cup M(R)$.

Below is an example for the creation of a key-tree for a group of 8 members (see Figure 5):

1. Members 1 and 2 agree on mutual key K_{12}
   Members 3 and 4 agree on mutual key K_{34}
   Members 5 and 6 agree on mutual key K_{56}
   Members 7 and 8 agree on mutual key K_{78}
2. Members 1,2 and 3,4 agree on mutual key K_{14}
   Members 5,6 and 7,8 agree on mutual key K_{58}
3. Members 1,2,3,4 and 5,6,7,8 agree on mutual key K_{18}

Each round's steps occur concurrently. In this case, the algorithm takes 3 rounds, and each member stores 3 keys. This protocol can be generalized to any number of members.

Base case: If the group contains 0 or 1 members, then we are done.
Recursive step ($n = 2^{k+1}$): Split the group into two subgroups, M_L and M_R, containing each 2^k members. Apply the algorithm recursively to M_L and M_R. Now, subgroup M_L possesses key-tree L, and subgroup M_R posseses key-tree R. Apply the agreement primitive to L and R such that they agree on a group key.

This protocol takes $\log_2 n$ rounds to complete. Each member stores $\log_2 n$ keys.

Clearly, the naive protocol builds key-graphs for groups of members of size 2^n. Note that no member holds more than $\log_2 n$ keys, and the total number of keys is n.

In the lifetime of the group members join, and leave, the group partitions and merges with other group components. For example, when member p_1

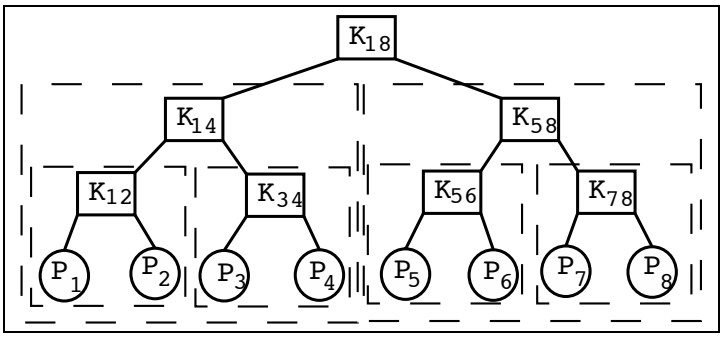


Fig. 5 The naive protocol for a group of eight members. Groups that agree on a key are surrounded by a dashed rectangle.

leaves, the key-graph is split into three pieces. When p_9 joins, the new key-tree is a merging of the key-graphs containing $\{p_1,\ldots,p_8\}$, and $\{p_9\}$. To handle these events efficiently, the computation of the new key-tree, as a function of existing subtrees, is performed by the group leader. After a view-change, the leader requests subtree *layouts* from subleaders. A tree *layout* is a symbolic description of a key-tree. The leader combines the subtree layouts and multicasts a new complete layout, coupled with a schedule describing how to merge subtrees together.

Note that the leader is not allowed to learn the actual keys used by other members. This is the reason for using symbolic representations.

We now extend *agree* to conform to the merge step described in the previous section. If L and R are two subtrees that should be merged together then, assuming $h(L) \geq h(R)$, the leader finds a subtree L' of L such that $1 \geq h(R) - h(L') \geq 0$. The protocol is as follows. $C_{L'}$ denotes the leader within L', C_R the leader within R, C_T the tree leader. The algorithm as a whole is initiated by C_T.

Extended Agree(L, R):

1. C_T initiates the protocol by multicasting the new layout and schedule.
2. $C_{L'}$ chooses a new key $K_{L'R}$, and sends it to C_R using a secure channel.
3. $C_{L'}$ encrypts $K_{L'R}$ with $K_{L'}$ and multicasts it.
   $C_{L'}$ encrypts all keys above $K_{L'R}$ with $K_{L'R}$ and multicasts them.
   C_R encrypts $K_{L'R}$ with K_R and multicasts it.
4. All members of $L \cup R$ securely receive the new key.

Below are two examples, the first is a leave scenario, the second is a join scenario. Both reference Figure 2.

In figures (1) and (2), member p_1 fails. All members receive a view-change notification, and locally erase from their key-trees all keys of which p_1

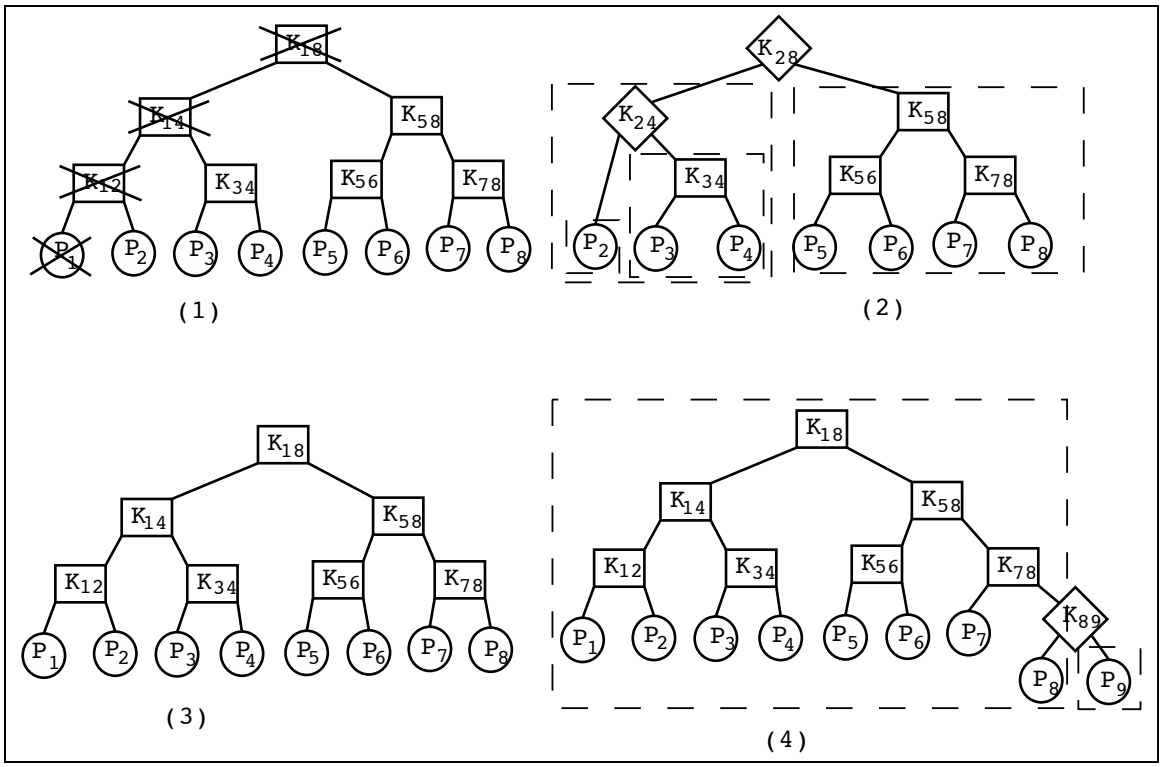


Fig. 6 Single member join/leave cases. Examples (1) and (2) show the actions performed when member p_1 leaves the group. Examples (3) and (4) show the actions performed when member p_9 joins.

had knowledge. The key-graph has now been split into three pieces T_1, T_2, T_3 containing: $\{p_2\}, \{p_3, p_4\}, \{p_5, p_6, p_7, p_8\}$ respectively. The leader collects the structures of T_1, T_2, and T_3 from the subleaders p_2, p_3, and p_5. It decides that the merged tree will have the layout described in Figure 6(2). It multicasts this structure to the group, with instructions for T_1 to merge with T_2 into T_{12}, and later for T_{12} to merge with T_3.

In figures (3) and (4) member p_9 joins the group. All members receive a view-change that includes member p_9. The key-graph is now comprised of two disjoint components: T_1 containing: $\{p_1, \ldots, p_8\}$, and T_2 containing $\{p_9\}$. The leader collects the structures of T_1 and T_2 from the subleaders p_1 and p_9. It decides that the merge tree will have the layout described in Figure 6(4). It multicasts this structure to the group with instructions for T_1 to merge with T_2.

Protocol $\mathcal{B}$ takes 2 stages in case of join, $\log_2 n$ stages in case of leave, and $\log_2 n$ in case of tree construction. In general, the number of rounds required is the maximal depth of the set of new levels in the tree that must be constructed. The optimized protocol improves this result to two

communication rounds, regardless of the number of levels that must be constructed.

4.1 Virtual Synchrony

Protocol $\mathcal{B}$ makes use of the GCS guarantees on message delivery, and view agreement. All point-to-point and multicast messages are reliable, and sender-ordered. Furthermore, they arrive in the view they are sent, hence, an instance of the protocol is run in a single view. If the view changes, due to members leaving or joining, then the protocol is restarted.

The guarantee that members agree on the view is crucial. It allows members to know what role they play in the protocol, be it leader, sub-leader, or no-role.

Although the protocol is multi-phased, we can guarantee an *all-or-nothing* property. Either all members receive the new key-tree, and the new group-key, or the protocol fails (and all members agree on this). To see this, examine the last step of the protocol, where $\mathcal{B}$ has been completed, and acknowledgments are collected by the leader. Once acknowledgment collection is complete, a *ProtoDone* message is multicast by the leader. Members that receive *ProtoDone* know that the protocol is over, and that other members also possess the same key-tree.

Should failures occur prior to the last multicast, then the protocol is restarted with the previous sub-trees. If a failure occurs afterwards, then remaining members agree on the key-tree and group-key. Failed members will be removed in the next view, and the protocol will be restarted.

This description is also valid for the optimized solution described in the next section.

4.2 Liveness and Safety

Here we show that $\mathcal{B}$ adheres to the four Liveness and Safety requirements (Section 2.2).

Liveness: Since the protocol is restarted if membership events occur, and since the GCS is live, the protocol is live.

Safety: The GCS creates only groups with trusted authenticated members. The protocol permits only communication between current group members, and all such communication is performed using pair-wise secret keys. Hence, the group key is not revealed to unauthorized members.

Agreement: The protocol completes successfully only in the event that a complete tree has been built, and ack-collection has been performed.

Authenticity: As in *Safety*, since the group leader is authenticated and agreed then the group key is authentic. Many members choose sub-group keys, however, they have all passed group authentication and access control barriers.

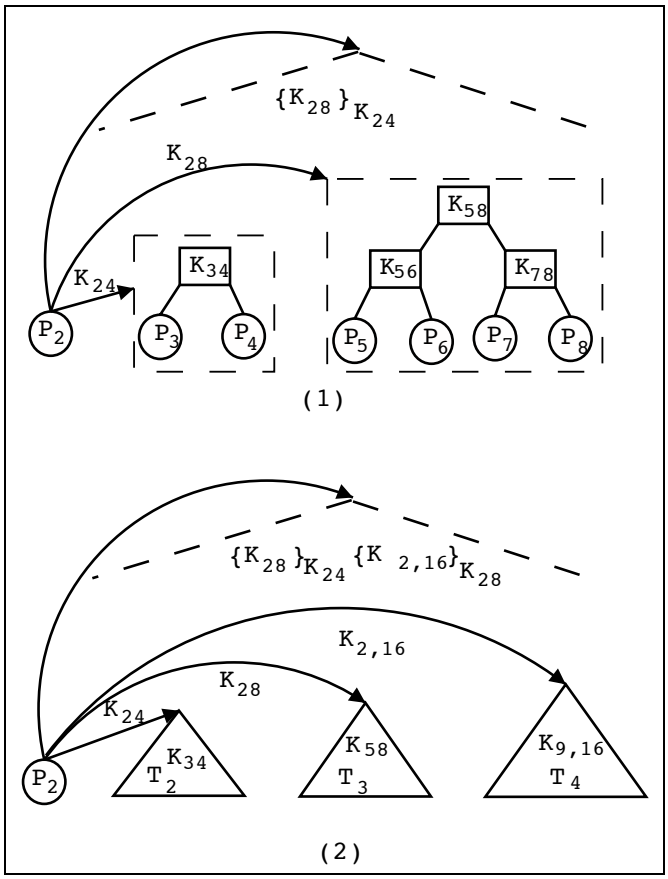


Fig. 7 Optimizing the leave case.

The same reasoning applies to the optimized version of $\mathcal{B}$ described in the next section.

5 Optimized solution ($\mathcal{O}$)

First, we describe an example showing that $\mathcal{B}$ can be substantially improved. Then we describe the optimized algorithm $\mathcal{O}$.

Examine the case where member p_1 leaves the group. There are three components to merge, T_1, T_2, T_3 and two tree levels to reconstruct. This requires two *agree* rounds. However, we can transform the protocol and improve it substantially by having p_2 choose all required keys at the same time. See Figure 7(1).

The protocol used is as follows:

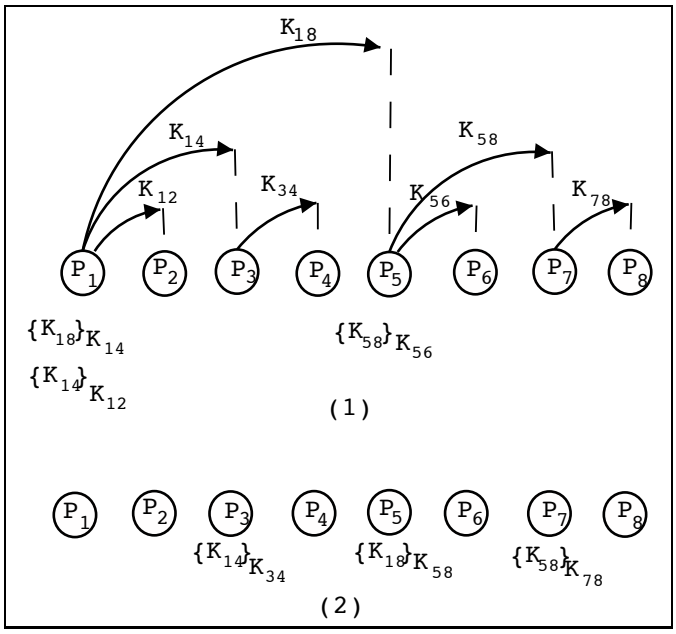


Fig. 8 Tree construction for an eight member group.

- Round I: p_2 chooses K_{24}, K_{28}. It sends K_{24} to the leader of T_2, K_{28} to the leader of T_3. Finally, it multicasts $\{K_{28}\}_{K_{24}}$ so that members of T_2 can retrieve K_{28}.
- Round II: The leader of T_2 multicasts $\{K_{24}\}_{K_{34}}$.
  The leader of T_3 multicasts $\{K_{28}\}_{K_{58}}$.

A larger example is depicted in Figure 7(2). Here, in a 16 member group, p_1 leaves. The regular algorithm requires three agree rounds, costing six communication rounds. This can be optimized to cost only two communication rounds, similarly to the above example.

- Round I: p_2 chooses $K_{24}, K_{28}, K_{2,16}$. It sends K_{24} to the leader of T_2, K_{28} to the leader of T_3, and $K_{2,16}$ to the leader of T_4. Finally, it multicasts $\{K_{28}\}_{K_{24}}$, $\{K_{2,16}\}_{K_{28}}$, so that members of T_2 and T_3 can retrieve K_{28} and $K_{2,16}$.
- Round II: The leader of T_2 multicasts $\{K_{24}\}_{K_{34}}$.
  The leader of T_3 multicasts $\{K_{28}\}_{K_{58}}$.
  The leader of T_4 multicasts $\{K_{2,16}\}_{K_{9,16}}$.

Prior to presenting the general solution, we provide an example for the creation of a complete key-tree of a group of eight members (see Figure 8).

In the first stage (Figure 8(1)), members engage in a protocol similar to the leave case. It is performed in parallel by all leaders in the group. New

keys are denoted by full arrows. Multicasted keys are written underneath member nodes. In the second stage, members pass received keys along, using multicast.

Round 1:

p_1 chooses K_{12}, K_{14}, K_{18}.
$m_1 \rightarrow m_2 : K_{12}$
$m_1 \rightarrow m_3 : K_{14}$
$m_1 \rightarrow m_5 : K_{18}$
$p_1 \rightarrow G : \{K_{14}\}_{K_{12}}, \{K_{18}\}_{K_{14}}$
p_3 chooses K_{34}.
$m_3 \rightarrow m_4 : K_{34}$
p_5 chooses K_{56}, K_{58}.
$m_5 \rightarrow m_6 : K_{56}$
$m_5 \rightarrow m_7 : K_{58}$
$p_1 \rightarrow G : \{K_{58}\}_{K_{56}}$
p_7 chooses K_{78}.
$m_7 \rightarrow m_8 : K_{78}$

Round 2:

$p_3 \rightarrow G : \{K_{14}\}_{K_{34}}$
$p_5 \rightarrow G : \{K_{18}\}_{K_{58}}$
$p_7 \rightarrow G : \{K_{58}\}_{K_{78}}$

At the end of the protocol, all members have all the keys. For example, member p_1 has all the keys at the end of the first round. It learns no other keys as the protocol progresses. Member p_8 receives in round one K_{78}. In round two it receives: $\{K_{18}\}_{K_{58}}$ and $\{K_{58}\}_{K_{78}}$. Thus, it can retrieve K_{58}, and K_{18}.

We now generalize the protocol. We shall describe how the leader, after retrieving subtree layouts $\{T_1, \ldots, T_m\}$, creates an optimal schedule describing how to merge the subtrees together. Since members simply follow the leader's schedule, we shall focus on the scheduling algorithm (Sched).

Sched works recursively. First, we use the centralized algorithm, and merge $T_1, \ldots, T_m$ together. There are $m-1$ instances where merge operations occur, each such operation is translated using a simple template.

Assuming subtrees L and R are to be merged, and $h(L) \geq h(R)$, then there is a subtree L' of L with which to merge R. Mark the list of keys on the route from $K_{L'}$ to the root of L by L_{path}.

The template is:

Stage 1:

$C_{L'}$ choose a new key $K_{L'R}$ and:
$C_{L'} \rightarrow C_R : K_{L'R}$
$C_{L'} \rightarrow G : \{K_{L'R}\}_{K_{L'}}$, $\{L'_{path}\}_{K_{L'R}}$

Stage 2:

$C_R \rightarrow G : \{K_{L'R}\}_{K_R}$

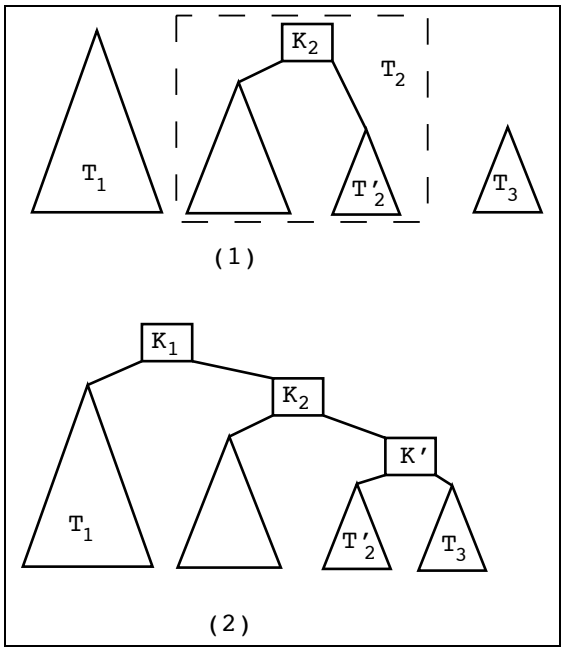


Fig. 9 The leader of T_2' must send K_2 to T_3.

Building a complete schedule requires performing Sched iteratively for $\{T_1, \ldots, T_k\}$ and storing the set of instructions in a data structure with two fields: one for the first stage, and another for the second stage. Each application of Sched adds two multicasts and one point-to-point message to the total. The number of rounds remains two.

An example for a more general case of Sched can be seen in Figure 9. The figure shows a set of three subtrees T_1, T_2, T_3 that need to be merged.

The resulting schedule will be:

Stage1:

C_{T_1} chooses K_1.

$C_{T_1} \rightarrow C_{T_2} : K_1$

$C_{T_1} \rightarrow G : \{K_1\}_{K_{T_1}}$

$C_{T_2'}$ chooses K'.

$C_{T_2'} \rightarrow C_{T_3} : K'$

$C_{T_2'} \rightarrow G : \{K'\}_{K_{T_2'}}$

$C_{T_2'} \rightarrow G : \{K_2\}_{K'}$

Stage2:

$C_{T_2} \rightarrow G : \{K_1\}_{K_{T_2}}$

$C_{T_3} \rightarrow G : \{K'\}_{K_{T_3}}$

For example, all members of T_3 will receive: $\{K'\}_{K_{T_3}}$ from C_{T_3}, $\{K_2\}_{K'}$ from $C_{T_2'}$, and $\{K_1\}_{K_2}$ from C_{T_2}. Using K_{T_3} they can decrypt K', K_2, and finally K_1. Hence, they can retrieve all the keys on the route to the root. Notice that $K_{T_2'}$ must send the path inside T_2 to all members of T_3. In this case, the path included only K_2.

Claim Algorithm Sched produces a schedule that guarantees all members receive exactly all the keys on the path to the root.

Proof: The proof is performed by induction on the number of merge steps. If m trees need to be merged, then there are $m-1$ steps to perform. The induction invariant is that the leader of a subtree knows all keys on the path to the root of its subtree in stage 1.

Base case:

If m trees need to merged, then the base case is merging the first two. For two trees L, R, we assume w.l.o.g that $h(L) \geq h(R)$. At the end of the protocol, C_R learns $K_{L'R}$, and the set of multicasts: $\{K_{L'R}\}_{K_{L'}}$, $\{L_{path}\}_{K_{L'R}}$, $\{K_{L'R}\}_{K_R}$ is sent. Members of R learn (exactly) $K_{L'R}$ and L_{path}. Members of L learn $K_{L'R}$, and the rest of the members learn nothing.

Note that the leader of L' chooses the new key $K_{L'R}$, hence the invariant holds.

Induction step:

Assume $k-1$ steps can be performed in two stages. Now we need to show for the k'th step. We perform the first $k-1$ steps, and get a tree L coupled with a two step schedule. The k'th step consists of scheduling a merge between the smallest tree in the heap R and L. Assume w.l.o.g that $h(L) \geq h(R)$, and that $h(R) = h(L')$, where L' is a subtree of L. The final tree will be L with L' replaced with $Br(L', K_{L'R}, R)$.

$C_{L'}$ chooses $K_{L'R}$ and passes it to C_R. It knows $K_{L'}$, hence it multicasts $\{K_{L'R}\}_{K_{L'}}$. All members of L' will know $K_{L'}$ at the end of stage two, hence they will also know $K_{L'R}$.

Leader C_R knows K_R in the first stage, hence, it multicasts $\{K_{L'R}\}_{K_R}$ in the second stage. By induction, all members of R will know K_R at the end of the second stage, hence they will also be able to retrieve $K_{L'R}$.

Furthermore, In the first stage, $C_{L'}$ multicasts $\{L_{path}\}_{K_{L'R}}$. This guarantees that members of R will know all the keys on the path to the root at the end of the second stage.

Note that the leader of L' chooses $K_{L'R}$, hence the invariant holds.

□

5.1 Three round solution ($\mathcal{O}_3$)

The optimized solution $\mathcal{O}$ is optimized for rounds, i.e., it reduces the number of communication rounds to a minimum. However, it is not optimal with

respect to the number of multicast messages. Each subtree-leader sends $\log_2 n$ multicast messages, potentially one for each level of recursion. Since there are $n/2$ such members, we may have up to $O(n \times \log_2 n)$ multicast messages sent in a protocol run.

Here we improve $\mathcal{O}$ and create protocol $\mathcal{O}_3$. Protocol $\mathcal{O}_3$ is equivalent to $\mathcal{O}$ except for one detail, in each view, a member p_x is chosen. All subtree-leaders, in stage 2, send their multicasts messages point-to-point to p_x. Member p_x concatenates these messages and sends them as one (large) multicast. The other members will unpack this multicast and use the relevant part. This scheme reduces costs to $n/2$ point-to-point messages from subtree leaders to p_x, and one multicast message by p_x. Hence, we add another round to the protocol but reduce multicast traffic.

5.2 Costs

Here, we compare the three-round solution with the regular centralized solution. Such a comparison is inherently unfair, since the distributed algorithm must overcome many obstacles that do not exist for the centralized version. To even out the playing ground somewhat, we do not take into account (1) collection of acknowledgments (2) sending tree-layouts. We compare three scenarios — building the key-tree, the join algorithm and the leave algorithm. We use tables to compare the solutions and we use the following notations:

pt-2-pt: The number of point-to-point messages sent.
multicast: The number of multicast messages sent.
bytes: The total number of bytes sent
rounds: The number of rounds the algorithm takes to complete

First, we compare the case of building a key-tree for a group of size 2^n where there are no preexisting subtrees. The following table summarizes the costs for each algorithm:

	# pt-2-pt	# multicast	# bytes	# rounds
$\mathcal{C}$	0	1	$2\ell n$	1
$\mathcal{O}_3$	$1.5n-1$	1	$3\ell n$	3

Since the group contains n members, there are $n-1$ keys to create. A single secure point-to-point message is used to create each key. There are $n/2$ members that act as subleaders. These all send multicast messages in the first and second stages. These messages are converted into point-to-point messages sent to the leader. All counted, there are $1.5n-1$ point-to-point messages. The number of bytes is broken down as follows: (1) the $n-1$ secure point-to-point messages cost ℓn. (2) The messages to the leader cost a total of ℓn (3) The final multicast bundles together all point-to-point messages, and it therefore costs an additional ℓn. The cost is in fact ℓn for the second

and third items because the final multicast contains essentially all the group key-tree, except for the lowest level.

The leave algorithm costs:

	# pt-2-pt	# multicast	# bytes	# rounds
$\mathcal{C}$	0	1	$2\ell \log_2 n$	1
$\mathcal{O}_3$	$log_2 n$	1	$3\ell \log_2 n$	3

The join algorithm costs:

	# pt-2-pt	# multicast	# bytes	# rounds
$\mathcal{C}$	0	1	$\log_2 n$	1
$\mathcal{O}_3$	2	1	$\log_2 n$	3

6 Performance

We have fully implemented our algorithm in the Ensemble [32] group communication system. This section describes its performance. Our test-bed was a set of 20 PentiumIII 500Mhz machines running the Linux operating system (kernel version 2.2), connected by switched 10Mbit/sec Ethernet. Machines were lightly loaded during testing. A group of n members was created, a set of member join/leave operations was performed, and measurements were taken. Unlike the previous subsection, the measurements take into account both acknowledgments and tree-layouts. To simulate configurations larger than 20 members, several processes were run on the same machine.

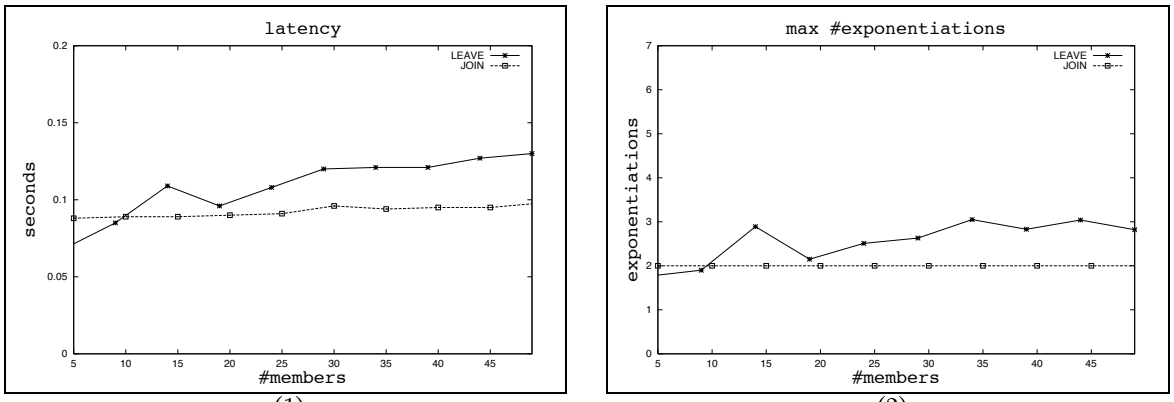
As described in (Section 2.1), point-to-point secure channels are cached by group members. The secure-channel cache is refered to as the *cache* in this section. Each channel is created by a Diffie-Hellman exchange, costing two integer exponentiations for a total price of 80 milliseconds. The cache is governed by two simple rules: (1) only connections to present group members are kept. (2) the cache is flushed every 24 hours[4] to prevent cryptanalysis.

Secure channel creation is the primary source of overhead in rekeying. For example, a join operation involves the creation of a single new secure connection. Its total cost is 100 milliseconds, of which 80 milliseconds are spent computing the Diffie-Hellman exponents, and the other 20 milliseconds on communication.

Hence, the focus here is on the number of exponentiations performed in each group scenario, and on attempts to reduce this number. To simulate real conditions in the tests, the cache was flushed once every 30 rekey operations, and "cold-start" results were discarded.

Figure 10(1) describes the latency of join/leave operations. In the join case, latency is a constant 100 milliseconds regardless of group size. Passing

[4] This is a settable parameter.



(1) (2)

Fig. 10 (1)Latency of the dLKH algorithm for join/leave operations.(2) The maximal number of exponentiations on the critical path.

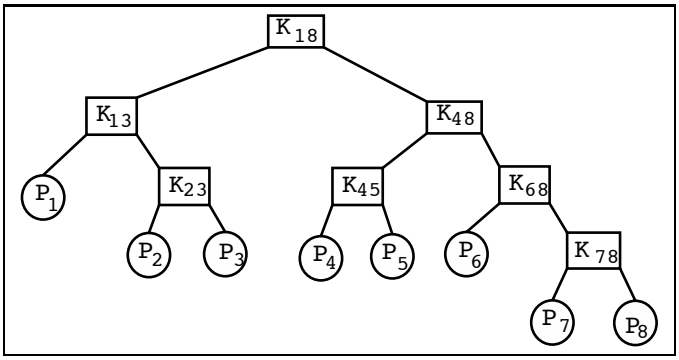


Fig. 11 A skewed tree with eight members.

a secret key to a newly joined member requires at least a single new secure-channel, this bound is achieved in the join case. The trick is to add the member on the *correct* side of the tree. If a new member is added to the left-most position in the tree, then that member must create connections to $\log_2 n$ components. On the other hand, if the member is added in the right-most position then only a single new connection is needed. More generally, a *tree-skewing* technique is employed, whereby new members are added as far to the right as possible. Since the tree must maintain the AVL invariants, it can be skewed until it reaches a state depicted in figure 11.

When a member leaves, naively, $\log_2 n$ components should be merged together. This should cost $2\log_2 n$ exponentiations. Examining the latency graph, and Figure 10(2), we can see that very few exponentiations take place. This is due to the caching optimization, and due to tree-skewing. To see how tree-skewing is beneficial, examine Figure 11. Assume member

P_1 leaves, and keys K_{13}, K_{18} must be reconstructed. The new leader P_2 needs two secure connections in order to disseminate new keys. Had the tree been fully balanced, the depth of P_1 would have been three, incurring the creation of an additional channel. A different scenario occurs when the right-most member P_8 leaves. In this case, keys K_{78}, K_{68}, K_{48}, and K_{18} must be discarded. However, new keys can be constructed concurrently by the pair-wise interactions: $P_1 \rightarrow P_4, P_4 \rightarrow P_6, P_6 \rightarrow P_7$. Even if all these secure-channels are missing, then their creation will occur in parallel, for a total latency of a single Diffie-Hellman exchange.

In a skewed-tree with height h, the shallowest member can be found at depth $h/2$. The shallowest member will also be the left most member. The latency, in terms of the number of exponentiations, in case of a single member leave is between h, if the member is the left-most member, and 2 if the member is the right most member.

Figure 12(1) describes the average size of the multicast message describing the layout of the group-tree. Figure 12(2) depicts the average size of the round three multicast message containing the set of encrypted keys. Figure 12(3) depicts the average total number of exponentiations. For the join case, this is a constant two, whereas for the leave case, this slowly rises.

To summarize, the protocol does not incur significant communication overhead, and the number of exponentiations is kept to a bare minimum. In some cases, the number of exponentiations is in fact optimal.

7 Related Work

Ensemble is a direct descendent of three systems: Isis [6], Horus [33], and Transis [3]. The Ensemble security architecture [37] has evolved from seminal work by Reiter [30,31] done in the context of the Isis and Horus systems.

Many other GCSs have been built around the world. The secure GCSs that we know of are: Antigone [24], and Spread [2,4]. Spread splits the GCS functionality into a server and client sides. Protection, in the form of a shared encryption and MAC key, is offered to the client while the server is left unprotected. Access control is not supported. The shared group-key is created using Cliques cryptographic toolkit [39]. Cliques uses contributed shares from each member to create the group-key. Cliques's keys are stronger than our own, however, they require substantially more computation.

Antigone has been used to secure video conferences over the web, using the VIC and VAT tools. However, to date, it has not been provided with a fault tolerance architecture. The Totem [22], and Rampart [29] systems can survive Byzantine faults, at the cost of a further degradation of performance.

The Enclave system [16] allows a set of applications to create a shared security context in which secure communicate is possible. All multicast communication is encrypted and signed using a symmetric key. The security context is managed by a member acting as leader. Security is afforded to any application implementing the Enclave API. The Enclave system addresses the security concerns of a larger set of applications than our own,

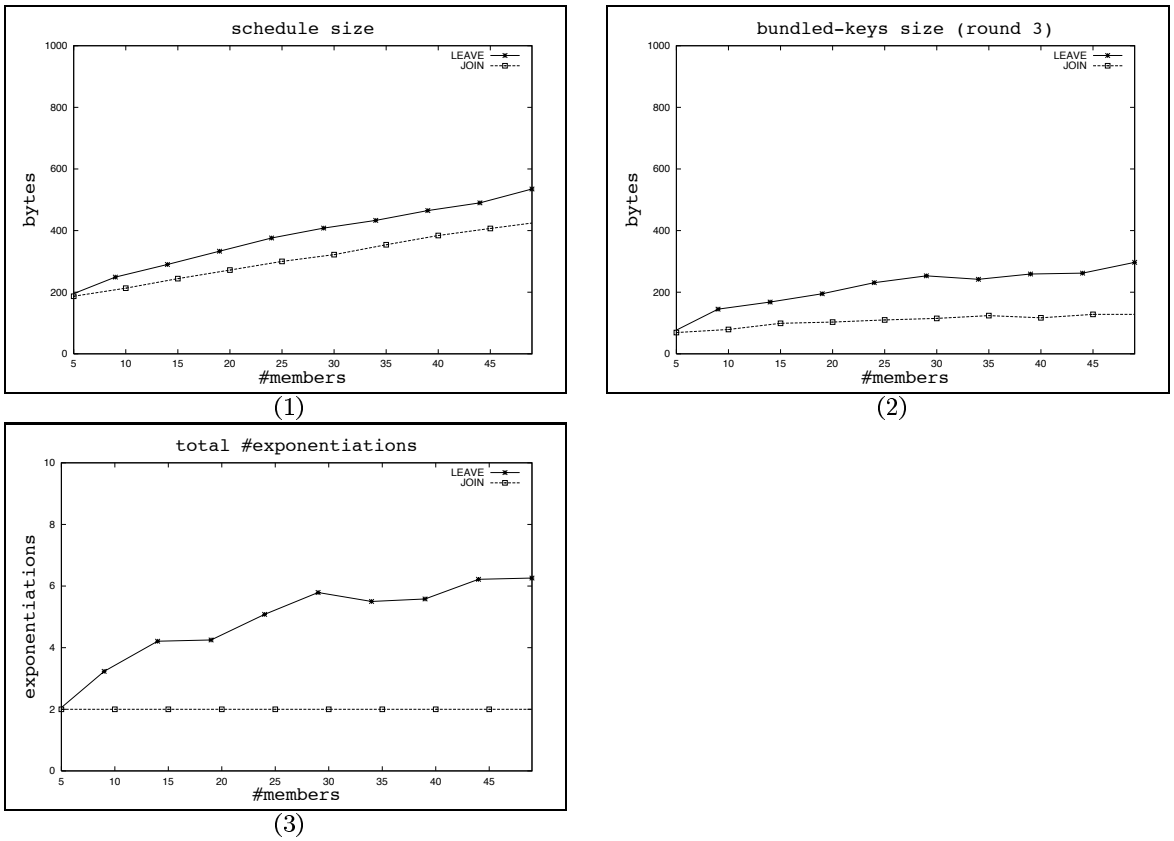


Fig. 12 Additional performance measurements. (1) Size of the schedule sent by the leader. (2) Size of the bundled keys sent in the third round. (3) Total number of integer exponentiations.

however, fault-tolerance is not addressed. Should the group-leader fail, the shared security context is lost and the group cannot recover.

The Cactus system [20] is a framework allowing the implementation of network services and applications. A Cactus application is typically split into many small layers (or *micro-protocols*), each implementing specific functionality. Cactus has a security architecture [19] that allows switching encryption and MAC algorithms as required. Actual micro-protocols can be switched at runtime as well. This allows the application to adapt to attacks, or changing network conditions at runtime.

Of all systems, ours is closest to Reiter's security architecture for Horus [31]. Horus is a group communication system, sharing much of the characteristics of Ensemble. The system followed the fortress security model, where a single partition was allowed, and members could join and leave the group, protected by access control, and authentication barriers. Group

members share a symmetric group key used to encrypt and MAC all inner group messages. Furthermore, the system allocated public keys for groups, that clients could use to perform secure group-RPC. Horus was built at a time when authentication services were not standard, therefore, it included a secure time service, and a replicated byzantine fault-tolerant authentication service. Symmetric encryption was optimized through the generation of one-time-pads in the background.

By comparison, our system ([36]) uses off-the-shelf authentication services, it does not handle group-RPC, and symmetric encryption is not a bottleneck. In Ensemble we handle the "next tier" of issues: supporting efficient group merge (not just join and leave), allowing multiple partitions (not just primary partition), and efficient group rekeying with FCY (and a weak form of BCY).

8 Conclusions

We have described an efficient protocol for the management of group-keys for Group Communication Systems. Our protocol is based on the notion of key-graphs, or Logical Key Hierarchy, as originally suggested by Wong Gauda and Lam. We adapt and extend this work, making the protocol completely decentralized and fault-tolerant (to the extent possible), and employing a highly efficient tree balancing scheme.

In contrast, keygraphs were previously used in centralized settings, where a large group of clients is managed by a central server. The server builds a keygraph encompassing all the clients, allowing it to manage the set of clients. In a GCS, where no single point of failure is allowed, we could not afford to delegate the server-task to any single member.

Therefore, our protocol differs substantially from the centralized approach. Rather, members enlist in a collaborative effort to create the group key-graph. The surprising result is that the completely distributed solution has comparative performance to the centralized one.

An issue for future work is supporting Backward Confidentiality efficiently. Currently, we support it in a weak sense.

Another problematic area is scalability to thousands of nodes. Our protocol relies on a Group Communication system, that can operate up to a hundred nodes. The protocol strongly relies on the agreed membership, and virtual synchrony properties of the GCS. It remains to be seen whether or not the protocol can be rewritten to use a weaker, yet more scalable type of infrastructure. For example, recent work on probabilistic failure tracking [17] has yielded a scalable membership mechanisms but with properties weaker than virtual synchrony. Applying our algorithm to such a scalable system is an interesting open question.

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