Efficient Key Distribution for Secure Multicast

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Multicast Security

- Multicast is broadcast to a group, not to everyone.
- Multicast group – group of members who have a right (have paid) to be in the group.
- Applications
  - Pay-per-view live broadcast
  - Video-on-demand for a fee
  - Software update group
  - Authorized for database access

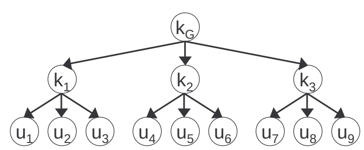
Key Distribution Problem

- Group key to secure content
  - Change (re-key) on membership change
    - *ADD(u)* - u does not have access to data prior to operaton, but does after operation
    - *DELETE(u)* - u does not have access to data after operation
  - Distribute group key to current members
    - Additional keys needed to secure group key

Logical Key Trees

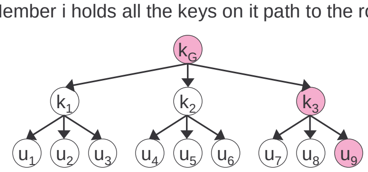
(Wong *et al.*, 1998)
(Wallner *et al.*, 1998)

- Shows keys held by each member
  - Nodes represent keys
  - Leaf nodes represent members
  - Members hold all keys on path to root

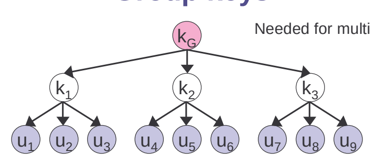


Encryption

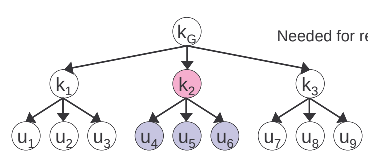
- Each member i has a private key u_i which is distributed using public key encryption.
- Each key k_g encrypts data multicast to the leaves of the tree rooted at g.
- Member i holds all the keys on it path to the root.



Group keys



Needed for multicast



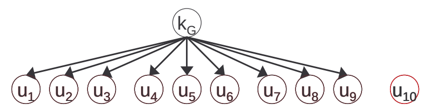
Needed for re-keying

Re-keying Messages

- $E(k_a,k_g)$ is a message to the group rooted at g that is encrypted using k_g and contains a new key k_a for some ancestor a of g.
- Goal is to minimize the number of these re-keying messages.

Re-keying (ADD)

- 2 level tree
- *ADD(u)* requires 2 messages per key
- Example: *ADD(u_{10})*



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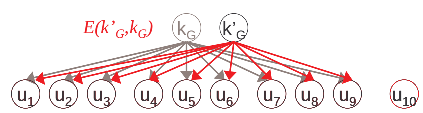

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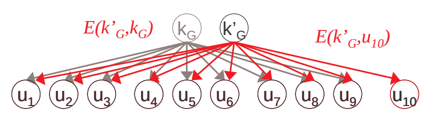

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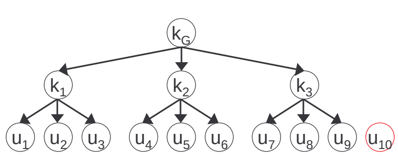

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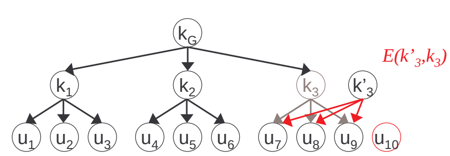

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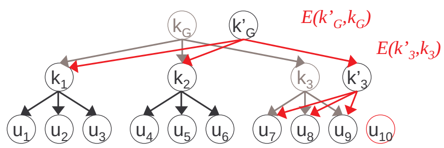

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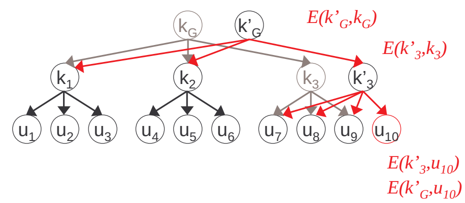
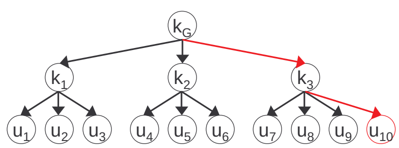


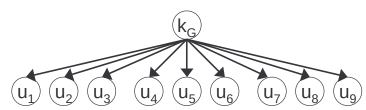
Re-keying (ADD)

- Define d_u to be the depth of u.
- $ADD(u)$ cost is $2d_u$ messages



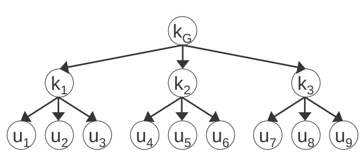
Re-keying (DELETE)

- $DELETE(u)$ requires a linear number of messages, each of the form $E(k'_G,u_i)$



Re-keying (DELETE)

- Example: $DELETE(u_9)$



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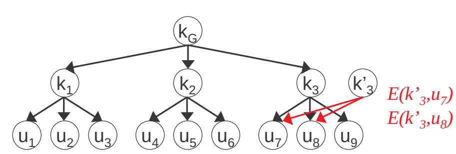

Re-keying (DELETE)

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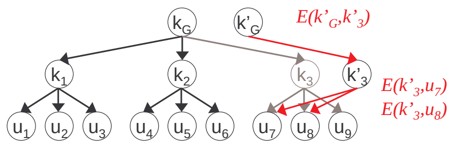

Re-keying (DELETE)

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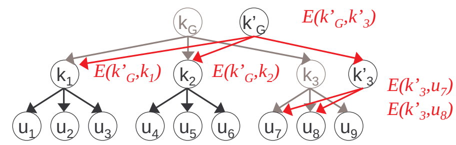
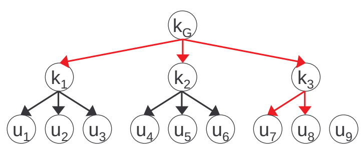


Re-keying (DELETE)

- Define ancestor weight w_u to be sum of degrees on path from *u* to root
- *DELETE(u)* cost is w_u - 1 messages



Asymetry

- ADD and DELETE have different costs
  - ADD $2d_u$
  - DELETE w_u - 1
- ADD has more freedom than DELETE
  - ADD can go anywhere in the tree
  - DELETE is where it happens

Fundamental Problem

- What is the best key tree for a given mix of ADDs and DELETEs?
- Our approach is to use balanced trees.
- Evaluation of the approach
  - Theoretical worst case analysis
  - Simulation studies

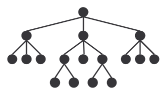
Previous Results

(Poovendran and Baras, 2001)
(Snoeyink *et al.*, 2001)

- Amortized worst-case cost lower bound is *Ω(log n)* per operation.
- Constructed static multiway trees that are optimal for ancestor weight.

Cost Components for On-line Algorithms

- Tree structure cost due to w_u
- Restructuring cost to maintain structure



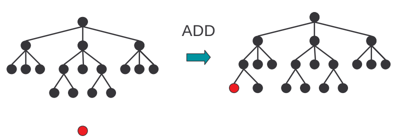
Algorithms

- K-ary trees
- B-trees
- 2-k trees (like AVL trees)
- Weight balanced trees

K-ary Trees

(Wong *et al*, 2000)

- ADD(u) - insert into the tree to keep w_u as small as possible.
- DELETE(u) - simple remove it at cost w_u
  - If only one child, then collapse



B-Tree Algorithm

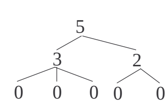
- All leaves have same depth
- All internal nodes (except the root) have degree in the interval [$\lceil t/2 \rceil$, *t*], where t is the order of the B-tree.
- Use existing algorithms for maintaining B-Tree property
  - John Hopcroft, 2-3 trees, 1970
  - Bayer and McCreight, 1972.

Height-Balanced 2-k Algorithm

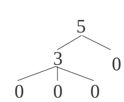
- All nodes are balanced
  - Height of children differ by at most
- All internal nodes have degree in the interval [2,*k*]
- Extension of the AVL tree algorithm of Rodeh *et al.* (2001)

Weight-balanced Algorithm

- Node weight of *u* = max w_i over all leaf nodes *i* in sub-tree rooted at *u*
- Node *u* is weight-balanced if its children differ in node weight by at most 1



Weight balanced



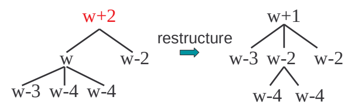
Not weight balanced

Weight-balanced Algorithm

- *DELETE(u)* costs proportional to ancestor weight w_u
- How about balancing by w_u?
  - Can be done for 2-3 and 2-3-4 trees

Weight-balanced Algorithm

- Defined restructuring rules to maintain balance
- Apply to key tree bottom up
- Example for 2-3 trees



Worst-case Tree Structure Cost Analysis

- Optimal worst-case bound is $\lceil 3\log_3 n \rceil$
- Derived worst-case bounds for our algorithms

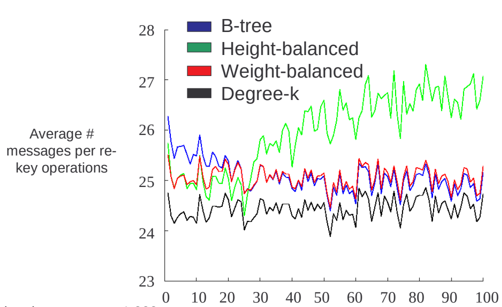
Algorithm	w_u	Algorithm Bound / Optimal Bound
Height-balanced 2-4	$4\log_\phi n$, $\phi \approx 1.618$	≈ 3.04
B-tree of order 4	$4\log_2 n$	≈ 2.11
Weight-balanced 2-3-4	$\log_b n$, $b \approx 1.325$*	≈ 1.30

* $b^3 = b+1$

Simulation Results

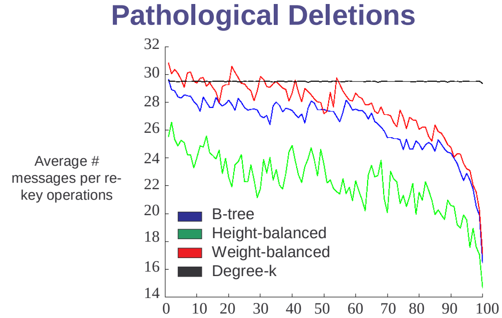
- Does good tree structure help performance?
  - We do not have a way to analyze restructuring cost
  - Trace data for multicast is problematic
- Simulation may yield insights

Random Re-keying



Each point represents 1,000 consecutive operations

Pathological Deletions



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Summary: Online Key Tree Algorithms

- Algorithms to maintain balanced trees
- Identified 2 cost components
- Derived worst-cast tree weight bounds
- Good performance, especially when tree becomes highly unbalanced

Future Potential

- Crypto technology is probably adequate for deployment
- Future depends on popularity of multicast
- May be other distributed applications that need secure group management
  - Access control in databases
  - Access control in file systems