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Scalable Multicast Key Distribution

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Abstract

The benefits of multicasting are becoming ever-more apparent, and its use much more widespread. This is evident from the growth of the MBONE [1]. Providing security services for multicast, such as traffic integrity, authentication, and confidentiality, is particularly problematic since it requires securely distributing a group (session) key to each of a group's receivers. Traditionally, the key distribution function has been assigned to a central network entity, or Key Distribution Centre (KDC), but this method does not scale for wide-area multicasting, where group members may be widely-distributed across the internetwork, and a wide-area group may be densely populated.

Even more problematic is the scalable distribution of sender-specific keys. Sender-specific keys are required if data traffic is to be authenticated on a per-sender basis.

This memo provides a scalable solution to the multicast key distribution problem.

NOTE: this proposal requires some simple support mechanisms, which, it is recommended here, be integrated into version 3 of IGMP. This support is described in Appendix B.

1. Introduction

Growing concern about the integrity of Internet communication [13] (routing information and data traffic) has led to the development of an Internet Security Architecture, proposed by the IPSEC working group of the IETF [2]. The proposed security mechanisms are implemented at the network layer - the layer of the protocol stack at which networking resources are best protected [3].

Unlike many network layer protocols, the Core Based Tree (CBT) multicast protocol [4] makes explicit provision for security; it has its own protocol header, unlike existing IP multicast schemes [10,11], and other recently proposed schemes [12].

In this document we describe how the CBT multicast protocol can provide for the secure joining of a CBT group tree, and how this same process can provide a scalable solution to the multicast key distribution problem. These security services are an integral part of the CBT protocol [4]. Their use is optional, and is dependent on each individual group's requirements for security. Furthermore, the use of the CBT multicast protocol for multicast key distribution does not preclude the use of other multicast protocols for the actual multicast communication itself, that is, CBT need only be the vehicle with which to distribute keys.

Secure joining implies the provision for authentication, integrity, and optionally, confidentiality, of CBT join messages. The scheme we describe provides for the authentication of tree nodes (routers) and receivers (end-systems) as part of the tree joining process. Key distribution (optional) is an integral part of secure joining.

Network layer multicast protocols, such as DVMRP [7] and M-OSPF [9], do not have their own protocol header(s), and so cannot provision for security in themselves; they must rely on whatever security is provided by IP itself. Multicast key distribution is not addressed to any significant degree by the new IP security architecture [2].

The CBT security architecture is independent of any particular cryptotechniques, although many security services, such as authentication, are easier if public-key cryptotechniques are employed.

What follows is an overview of the CBT multicasting. The description of our proposal in section 6.1 assumes the reader is reasonably familiar with the CBT protocol. Details of the CBT architecture and protocol can be found in [7] and [4], respectively.

2. Overview of BCT Multicasting

CBT is a new architecture for local and wide-area IP multicasting, being unique in its utilization of just one shared delivery tree per group, as opposed to the source-based delivery tree approach of existing IP multicast schemes, such as DVMRP and MOSPF.

A shared multicast delivery tree is built around several so-called core routers. A group receiver's local multicast router is required to explicitly join the corresponding delivery tree after receiving an

IGMP [8] group membership report over a directly connected interface. A CBT join message is targeted at one of the group's core routers. The resulting acknowledgement traverses the reverse-path of the join, resulting in the creation of a tree branch. Routers along these branches are called non-core routers for the group, and there exists a parent-child relationship between adjacent routers along a branch of the same tree (group).

3. How the CBT Architecture Complements Security

The CBT architecture requires "leaf" routers to explicitly join a CBT tree. Hence, CBT is not data driven; the ack associated with a join "fixes" tree state in the routers that make up the tree. This so-called "hard state" remains until the tree re-configures, for example, due to receivers leaving the group, or because an upstream failure has occurred. The CBT protocol incorporates mechanisms enabling a CBT tree to repair itself in the event of the latter.

As far as the establishment of an authenticated multicast distribution tree is concerned, DVMRP, M-OSPF, and PIM, are at a disadvan- tage; the nature of their "soft state" means a delivery tree only exists as long as there is data flow. Also, routers implementing a multicast protocol that builds its delivery tree based on a reverse-path check (like DVMRP and PIM dense mode) cannot be sure of the previous-hop router, but only the interface a multicast packet arrived on.

These problems do not occur in the CBT architecture. CBT's hard state approach means that all routers that make up a delivery tree know who their on-tree neighbours are; these neighbours can be authenticated as part of delivery tree set-up. As part of secure tree set-up, neighbours could exchange a secret packet handle for inclusion in the CBT header of data packets exchanged between those neighbours, allowing for the simple and efficient hop-by-hop authentication of data packets (on-tree).

The presence of tree focal points (i.e. cores) provides CBT trees with natural authorization points (from a security viewpoint) -- the formation of a CBT tree requires a core to acknowledge at least one join in order for a tree branch to be formed. Thereafter, authorization and key distribution capability can be passed on to joining nodes that are authenticated.

In terms of security, CBT's hard state approach offers several additional advantages: once a multicast tree is established, tree state maintained in the routers that make up the tree does not time out or change necessarily to reflect underlying unicast topology. The security implications of this are that nodes need not be subject

to repeated authentication subsequent to a period of inactivity, and tree nodes do not need to re-authenticate themselves as a result of an underlying unicast topology change, unless of course, an network (node) failure has occurred.

Hard-state protocol mechanisms are often thought of as being less fault tolerant than soft-state schemes, but there are pros and cons to both approaches; we see here that security is one of the pros.

4. The Multicast Key Distribution Problem

We believe that multicast key distribution needs to be combined with group access control. Without group access control, there is no point in employing multicast key distribution, since, if there are no group restrictions, then it should not matter to whom multicast information is divulged.

There are different ways of addressing group access control. The group access control we describe requires identifying one group member (we suggest in [14] that this should be the group initiator) who has the ability to create, modify and delete all or part of a group access control list. The enforcement of group access control may be done by a network entity external to the group, or by a group member.

The essential problem of distributing a session (or group) key to a group of multicast receivers lies in the fact that some central key management entity, such as a key distribution centre (KDC) (A Key Distribution Centre (KDC) is a network entity, usually residing at a well-known address. It is a third party entity whose responsibility it to generate and distribute symmetric key(s) to peers, or group receivers in the case of multicast, wishing to engage in a "secure" communication. It must therefore be able to identify and reliably authenticate requestors of symmetric keys.), must authenticate each of a group’s receivers, as well as securely distribute a session key to each of them. This involves encrypting the relevant message n times, once with each secret key shared between the KDC and corresponding receiver (or alternatively, with the public key of the receiver), before multicasting it to the group. (Alternatively, the KDC could send an encrypted message to each of the receivers individually, but this does not scale either.) Potentially, n may be very large. Encrypting the group key with the secret key (of a secret-public key pair) of the KDC is not an option, since the group key would be accessible to anyone holding the KDC’s public key, and public keys are either well-known or readily available. In short, existing multicast key distribution methods do not scale.

The scaling problem of secure multicast key distribution is compounded for the case where sender-specific keys need to be distributed to a group. This is required for sender-specific authentication of data traffic. It is not possible to achieve per-sender authentication, given only a group session key.

Recently a proposal has emerged, called the Group Key Management Protocol (GKMP) [15]. This was designed for military networks, but the authors have demonstrated how the architecture could be applied to a network like the Internet, running receiver-oriented multicast applications.

GKMP goes a considerable way to addressing the problems of multicast key distribution: it does not rely on a centralised KDC, but rather places the burden of key management on a group member(s). This is the approach adopted by the CBT solution, but our solution can take this distributed approach further, which makes our scheme that much more scalable. Furthermore, our scheme is relatively simple.

The CBT model for multicast key distribution is unique in that it is integrated into the CBT multicast protocol itself. It offers a simple, low-cost, scalable solution to multicast key distribution. We describe the CBT multicast key distribution approach below.

5. Multicast Security Associations

The IP security architecture [2] introduces the concept of "Security Associations" (SAs), which must be negotiated in advance during the key management phase, using a protocol such as Photuris [20], or ISAKMP [21]. A Security Association is normally one-way, so if two-way communication is to take place (e.g. a typical TCP connection), then two Security Associations need to be negotiated. During the negotiation phase, the destination system normally assigns a Security Parameter Index to the association, which is used, together with the destination address (or, for the sender, the sender’s user-id) to index into a Security Association table, maintained by the communicating parties. This table enables those parties to index the correct security parameters pertinent to an association. The security association parameters include authentication algorithm, algorithm mode, cryptographic keys, key lifetime, sensitivity level, etc.

The establishment of Security Associations (SA) for multicast communication does not scale using protocols like Photuris, or ISAKMP. This is why it is often assumed that a multicast group will be part of a single Security Association, and hence share a single SPI. It is assumed that one entity (or a pair of entities) creates the SPI "by some means" (which may be an SA negotiation protocol,

like [20] and [21]), which is then simply multicast, together with the SA parameters, to the group for subsequent use. However, this precludes multicast receivers from performing sender-specific origin authentication; all a receiver can be sure of is that the sender is part of the multicast Security Association.

We advocate that the primary core, either alone, or in conjunction with the group initiator, establish the security parameters to be used in the group communication. These are distributed as part of the secure join process. Thereafter, individual senders can distribute their own key and security parameters to the group. In the case of the latter, there are two cases to consider:

+ the sender is already a group member. In this case, the sender can decide upon/generate its own security parameters, and multicast them to the group using the current group session key.

+ the sender is not a group member. In this case, before the sender begins sending, it must first negotiate the security parameters with the primary core, using a protocol such as Photuris [20] or ISAKMP [21]. Once completed, the primary core multicasts (securely) the new sender's session key and security parameters to the group.

Given that we assume the use of asymmetric cryptotechniques throughout, this scheme provides a scalable solution to multicast origin authentication.

Sender-specific keys are also discussed in section 8.

6. The CBT Multicast Key Distribution Model

The security architecture we propose allows not only for the secure joining of a CBT multicast tree, but also provides a solution to the multicast key distribution problem [16]. Multicast key distribution is an optional, but integral, part of the secure tree joining process; if a group session key is not required, its distribution may be omitted.

The use of CBT for scalable multicast key distribution does not preclude the use of other multicast protocols for the actual multicast communication. CBT could be used solely for multicast key distribution -- any multicast protocol could be used for the actual multicast communication itself.

The model that we propose does not rely on the presence of a centralised KDC -- indeed, the KDC we propose need not be dedicated to key distribution. We are proposing that each group have its own

group key distribution centre (GKDC), and that the functions it provides should be able to be "passed on" to other nodes as they join the tree. Hence, our scheme involves truly distributed key distribution capability, and is therefore scalable. It does not require dedicated KDCs. We are proposing that a CBT primary core initially take on the role of a GKDC.

6.1 Operational Overview

When a CBT group is created, it is the group initiator's responsibility to create a multicast group access control list (ACL) [14]. It is recommended that this list is a digitally signed "document", the same as (or along the lines of) an X.509 certificate [9], such that it can be authenticated. The group initiator subsequently unicasts the ACL to the primary core for the group. This communication is not part of the CBT protocol. The ACL's digital signature ensures that it cannot be modified in transit without detection. If the group membership itself is sensitive information, the ACL can be additionally encrypted with the public key of the primary core before being sent. The ACL can be an "inclusion" list or an "exclusion" list, depending on whether group membership includes relatively few, or excludes relatively few.

The ACL described above consists of group membership (inclusion or exclusion) information, which can be at the granularity of hosts or users. How these granularities are specified is outside the scope of this document. Additionally, it may be desirable to restrict key distribution capability to certain "trusted" nodes (routers) in the network, such that only those trusted nodes will be given key distribution capability should they become part of a CBT delivery tree. For this case, an additional ACL is required comprising "trusted" network nodes.

The primary core creates a session key subsequent to receiving and authenticating the message containing the access control list. The primary core also creates a key encrypting key (KEK) which is used for re-keying the group just prior to an old key exceeding its life-time. This re-keying strategy means that an active key is less likely to become compromised during its lifetime.

The ACL(s), group key, and KEK are distributed to secondary cores as they become part of the distribution tree.

Any tree node with this information can authenticate a joining member, and hence, secure tree joining and multicast session key distribution are truly distributed across already authenticated tree nodes.

6.2 Integrated Join Authentication and Multicast Key Distribution

For simplicity, in our example we assume the presence of an internetwork-wide asymmetric key management scheme, such as that proposed in [17]. However, we are not precluding the use of symmetric cryptographic techniques -- all of the security services we are proposing, i.e. integrity, authentication, and confidentiality, can all be achieved using symmetric cryptography, albeit a greater expense, e.g. negotiation with a third party to establish pairwise secret keys. For these reasons, we assume that a public (asymmetric) key management scheme is globally available, for example, through the Domain Name System (DNS) [17] or World Wide Web [18].

NOTE: given the presence of asymmetric keys, we can assume digital signatures provide integrity and origin authentication services combined.

The terminology we use here is described in Appendix A. We formally define some additional terms here:

+ grpKey: group key used for encrypting group data traffic.

+ ACL: group access control list.

+ KEK: key encrypting key, used for re-keying a group with a new group key.

+ SAparams: Security Association parameters, including SPI.

+ group access package (grpAP): sent from an already verified tree node to a joining node.

  [token_sender, [ACL]^SK_core, {[grpKey, KEK, SAparams]^SK_core}^PK_origin-host, {[grpKey, KEK, SAparams]^SK_core}^PK_next-hop]^SK_sender

  NOTE: SK_core is the secret key of the PRIMARY core.

As we have already stated, the elected primary core of a CBT tree takes on the initial role of GKDC. In our example, we assume that a group access control list has already been securely communicated to the primary core. Also, it is assumed the primary core has already participated in a Security Association estabishment protocol [20,21], and thus, holds a group key, a key-encrypting key, and an SPI.

NOTE, there is a minor modification required to the CBT protocol [4], which is as follows: when a secondary core receives a join, instead of sending an ack followed by a re-join to the primary,

the secondary forwards the join to the primary; the ack travels from the primary (or intermediate on-tree router) back to the join origin. All routers (or only specific routers) become GKDCs after they receive the ack.

We now demonstrate, by means of an example, how CBT routers join a tree securely, and become GKDCs. For clarity, in the example, it is assumed all routers are authorised to become GKDCs, i.e. there is no trusted-router ACL.

In the diagram below, only one core (the primary) is shown. The process of a secondary joining the primary follows exactly what we describe here.

In the diagram, host h wishes to join multicast group G. Its local multicast router (router A) has not yet joined the CBT tree for the group G.

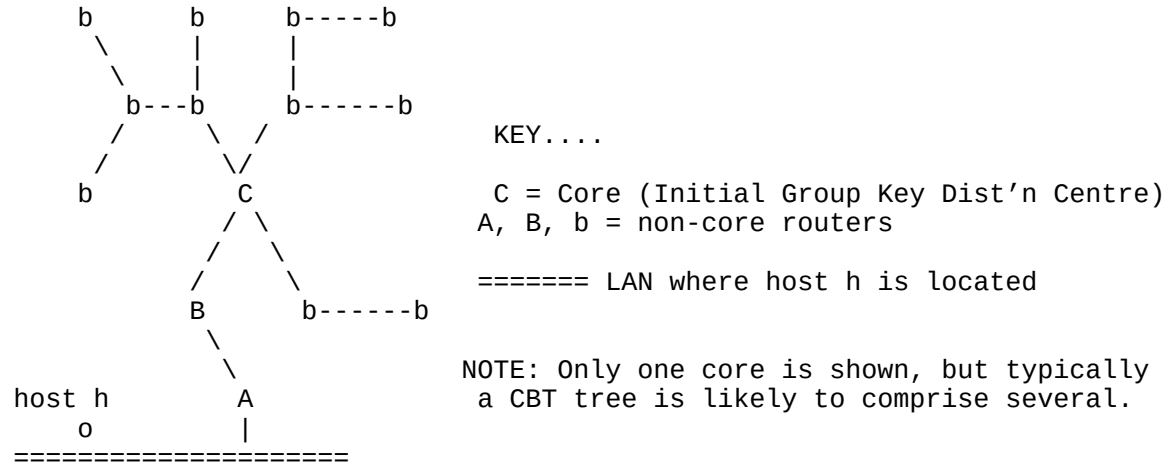

Figure 1: Example of Multicast Key Distribution using CBT

A branch is created as part of the CBT secure tree joining process, as follows:

+ Immediately subsequent to a multicast application starting up on host h, host h immediately sends an IGMP group membership report, addressed to the group. This report is not suppressible (see Appendix B), like other IGMP report types, and it also includes the reporting host's token, which is digitally signed

  h --> DR (A): [[token_h]^SK_h, IGMP group membership report]

(A host's token differs in two respects compared with tokens defined in [9]. To refresh, a token assists a recipient in the verification process, and typically contains: recipient's unique identity, a timestamp, and a pseudo-random number. A token is also usually digitally signed by its originator. Firstly, A host's token does not contain the intended recipient's identity, since this token may need to traverse several CBT routers before reaching a GKDC. A host does not actually know which router, i.e. GKDC, will actually acknowledge the join that it invoked. Secondly, the host's token is digitally signed -- this is usual for a token. However, tokens generated by routers need not be explicitly digitally signed because the JOIN-REQUESTs and JOIN-ACKs that carry them are themselves digitally signed.)

+ In response to receiving the IGMP report, the local designated router (router A) authenticates the host's enclosed token. If successful, router A formulates a CBT join-request, whose target is core C (the primary core). Router A includes its own token in the join, as well as the signed token received from host h. The join is digitally signed by router A.

  NOTE 1: router A, like all CBT routers, is configured with the unicast addresses of a prioritized list of cores, for different group sets, so that joins can be targeted accordingly.

  NOTE 2: the host token is authenticated at most twice, once by the host's local CBT router, and once by a GKDC. If the local router is already a GKDC, then authentication only happens once. If the local router is not already a GKDC, a failed authentication check removes the overhead of generating and sending a CBT join-request.

  Router A unicasts the join to the best next-hop router on the path to core C (router B).

      A --> B: [[token_A], [token_h]^SK_h, JOIN-REQUEST]^SK_A

+ B authenticates A's join-request. If successful, B repeats the previous step, but now the join is sent from B to C (the primary, and target), and the join includes B's token. Host h's token is copied to this new join.

      B --> C: [[token_B], [token_h]^SK_h, JOIN-REQUEST]^SK_B

+ C authenticates B's join. As the tree's primary authorization point (and GKDC), C also authenticates host h, which triggered the join process. For this to be successful, host h must be

included in the GKDC's access control list for the group. If h is not in the corresponding access control list, authentication is redundant, and a join-nack is returned from C to B, which eventually reaches host h's local DR, A.

Assuming successful authentication of B and h, C forms a group access package (grpAP), encapsulates it in a join-ack, and digitally signs the complete message. C's token, host h's signed token, a signed ACL, and two (group key, KEK) pairs are included in the group access package; one for the originating host, and one for the next-hop CBT router to which the join-ack is destined. Each key pair is digitally signed by the issuer, i.e. the primary core for the group. The host key pair is encrypted using the public key of the originating host, so as to be only decipherable by the originating host, and the other key pair is encrypted using the public key of the next-hop router to which the ack is destined -- in this case, B. Host h's token is used by the router connected to the subnet where h resides so as to be able to identify the new member.

C --> B: [[token^h]^SK_h, grpAP, JOIN-ACK]^SK_C

+ B authenticates the join-ack from C. B extracts its encrypted key pair from the group access package, decrypts it, authenticates the primary core, and stores the key pair in encrypted form, using a local key. B also verifies the digital signature included with the access control list. It subsequently stores the ACL in an appropriate table. The originating host key pair remains enciphered.

The other copy of router B's key pair is taken and deciphered using its secret key, and immediately enciphered with the public key of next-hop to which a join-ack must be passed, i.e. router A. A group access package is formulated by B for A. It contains B's token, the group ACL (which is digitally signed by the primary core), a (group key, KEK) pair encrypted using the public key of A, and the originating host's key pair, already encrypted. The group access package is encapsulated in a join-ack, the complete message is digitally signed by B, then forwarded to A.

B --> A: [[token^h]^SK_h, grpAP, JOIN-ACK]^SK_B

+ A authenticates the join-ack received from B. A copy of the encrypted key pair that is for itself is extracted from the group access package and deciphered, and the key issuer (primary core) is authenticated. If successful, the enciphered key pair is stored by A. The digital signature of the included access

control list is also verified, and stored in an appropriate table. The key pair encrypted for host h is extracted from the group access package, and is forwarded directly to host h, which is identified from the presence of its signed token. On receipt, host h decrypts the key pair for subsequent use, and stores the SA parameters in its SA table.

A --> h: [[token^h]^SK_h, {grpKey, KEK, SAparams}^PK_h]

Going back to the initial step of the tree-joining procedure, if the DR for the group being joined by host h were already established as part of the corresponding tree, it would already be a GKDC. It would therefore be able to directly pass the group key and KEK to host h after receiving an IGMP group membership report from h:

A --> h: [[token^h]^SK_h, {grpKey, KEK, SAparams}^PK_h]

If paths, or nodes fail, a new route to a core is gleaned as normal from the underlying unicast routing table, and the re-joining process (see [4]) occurs in the same secure fashion.

7. A Question of Trust

The security architecture we have described, involving multicast key distribution, assumes that all routers on a delivery tree are trusted and do not misbehave. A pertinent question is: is it reasonable to assume that network routers do not misbehave and are adequately protected from malicious attacks?

Many would argue that this is not a reasonable assumption, and therefore the level of security should be increased to discount the threat of misbehaving routers. As we described above, routers periodically decrypt key pairs in order to verify them, and/or re-encrypt them to pass them on to joining neighbour routers.

In view of the above, we suggest that if more stringent security is required, the model we presented earlier should be slightly amended to accommodate this requirement. However, depending on the security requirement and perceived threat, the model we presented may be acceptable.

We recommend the following change to the model already presented above, to provide a higher level of security:

All join-requests must be authenticated by a core router, i.e. a join arriving at an on-tree router must be forwarded upstream to a core if the join is identified as being a "secure" join (as indicated by the presence of a signed host token).

The implication of this is that key distribution capability remains with the core routers and is not distributed to non-core routers whose joins have been authenticated. Whilst this makes our model somewhat less distributed than it was before, the concept of key distribution being delegated to the responsibility of individual groups remains. Our scheme therefore retains its attractiveness over centralized schemes.

8. The Multicast Distribution of Sender-Specific Keys

Section 5, in part, discussed the scalable distribution of sender-specific keys and sender-specific security parameters to a multicast group, for both member-senders, and non-member senders. If asymmetric cryptotechniques are employed, this allows for sender-specific origin authentication.

For member-senders, the following message is multicast to the group, encrypted using the current group session key, prior to the new sender transmitting data:

{[sender_key, senderSAparams]^SK_sender}^group_key

Non-member senders must first negotiate (e.g. using Photuris or ISAKMP) with the primary core, to establish the security association parameters, and the session key, for the sender. The sender, of course, is subject to access control at the primary. Thereafter, the primary multicasts the sender-specific session key, together with sender's security parameters to the group, using the group's current session key. Receivers are thus able to perform origin authentication.

Photuris or ISAKMP
1. sender <----------> primary core

2. {[sender_key, senderSAparams]^SK_primary}^group_key

For numerous reasons, it may be desirable to exclude certain group members from all or part of a group's communication. We cannot offer any solution to providing this capability, other than requiring new keys to be distributed via the establishment of a newly-formed group (CBT tree).

9. Summary

This memo has offered a scalable solution to the multicast key distribution problem. Our solution is based on the CBT architecture and protocol, but this should not preclude the use of other multicast protocols for secure multicast communication subsequent to key distribution. Furthermore, virtually all of the functionality present in our solution is in-built in the secure version of the CBT protocol, making multicast key distribution an optional, but integral part, of the CBT protocol.

Appendix A

The following terminology is used throughout this document:

+ PK_A indicates the public key of entity A.

+ SK_A indicates the secret key of entity A. The secret key can be used by a sender to digitally sign a digest of the message, which is computed using a strong, one-way hash function, such as MD5 [19].

+ Unencrypted messages will appear enclosed within square brackets, e.g. [X, Y, Z]. If a message is digitally signed, a superscript will appear outside the right hand bracket, indicating the message signer. Encrypted messages appear enclosed within curly braces, with a superscript on the top right hand side outside the closing curly brace indicating the encryption key, e.g. {X, Y, Z}^{PK_A}.

+ a token is information sent as part of a strong authentication exchange, which aids a receiver in the message verification process. It consists of a timestamp, t (to demonstrate message freshness), a random, non-repeating number, r (to demonstrate message originality), and the unique name of the message recipient (to demonstrate that the message is indeed intended for the recipient). A digital signature is appended to the token by the sender (which allows the recipient to authenticate the sender). The token is as follows:

  [t_A, r_A, B]^{SK_A} -- token sent from A to B.

+ A --> B: -- denotes a message sent from A to B.

Appendix B

The group access controls described in this document require a few simple support mechanisms, which, we recommend, be integrated into version 3 of IGMP. This would be a logical inclusion to IGMP, given that version 3 is expected to accommodate a variety of multicast requirements, including security. Furthermore, this would remove the need for the integration of a separate support protocol in hosts.

To refresh, IGMP [8] is a query/response multicast support protocol that operates between a multicast router and attached hosts.

Whenever an multicast application starts on a host, that host generates a small number of IGMP group membership reports in quick succession (to overcome potential loss). Thereafter, a host only

issues a report in response to an IGMP query (issued by the local multicast router), but only if the host has not received a report for the same group (issued by some other host on the same subnet) before the host's IGMP random response timer expires. Hence, IGMP, incorporates a report "suppression" mechanism to help avoid "IGMP storms" on a subnet, and generally conserve bandwidth.

We propose that IGMP accommodate "secure joins" - IGMP reports that indicate the presence of a digitally signed host (or user) token. These report types must not be suppressible, as is typically the case with IGMP reports; it must be possible for each host to independently report its group presence to the local router, since a GKDC bases its group access control decision on this information.

This functionality should not adversely affect backwards compatibility with earlier versions of IGMP that may be present on the same subnet; the new reports will simply be ignored by older IGMP versions, which thus continue to operate normally.

Security Considerations

Security issues are discussed throughout this memo.

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