Efficient and Dynamic Group Key Agreement in Ad hoc Networks

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Abstract: Confidentiality, integrity and authentication are more relevant issues in Ad hoc networks than in wired fixed networks. One way to address these issues is the use of symmetric key cryptography, relying on a secret key shared by all members of the network. But establishing and maintaining such a key (also called the session key) is a non-trivial problem. We show that Group Key Agreement (GKA) protocols are suitable for establishing and maintaining such a session key in these dynamic networks. We take an existing GKA protocol, which is robust to connectivity losses and discuss all the issues for the good functioning of this protocol in Ad hoc networks. We give implementation details and network parameters, which significantly reduce the computational burden of using public key cryptography in such networks.

Key-words: Ad Hoc Networks, cryptographic protocoles, Diffie-Hellmann protocol

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AGDH (Asymetric Group Diffie Hellman), un protocole de mise en accord de clé efficace pour les réseaux Ad Hoc

Résumé : Les problèmes de confidentialité, d'intégrité et d'authentification sont de plus en plus prévalents dans les réseaux Ad Hoc, mais aussi dans les réseaux fixes filaires. Une approche à ces problèmes est d'utiliser la cryptographie symétrique (ou à clé secrète), reposant sur une clé partagée par tous les membres du réseau. Mais étblir et maintenir une telle clé, dite de session, est un problème non trivial. Nous montrons que les protocoles de mise en accord de clé de groupe (GKAs : Group Key Agreement protocols) sont bien adaptés pour établir et maintenir de telles clés de session dans les réseaux dynamiques. Nous considérons un protocole déjà établi, qui est robuste aux pertes de onnectivité, et nous envisageons tous les problèmes relatifs au bon fonctionnement de ce protocole dans les réseaux Ad Hoc. Nous donnons des détails d'implémentation, des paramètres réseaux, ce qui permet de réduire considérablement la charge calculatoire liée à l'emploi de la clé publique dans de tels réseaux.

Mots-clés : Réseaux Ad Hoc, protocoles cryptographiques, Diffie-Hellmann protocol

1 Introduction

A Mobile Ad hoc NETwork (MANET) is a collection of mobile nodes connected via a wireless medium forming an arbitrary topology. Implicit herein is the ability for the network topology to change over time as links in the network appear and disappear. To maintain the network connectivity, a routing protocol must be used. An important security issue is that of the integrity of the network itself. Quite a lot of studies have been already done to resolve security issues in existing routing protocols (see [HPJ02],[PMdS03],[ACJ$^+$03b],[ACL$^+$05]).

An orthogonal security issue is that of maintaining confidentiality and integrity of data exchanged between nodes in the network. The task of ensuring end-to-end security of data communications in MANETs is equivalent to that of securing end-to-end security in traditional wired networks. Many studies have been carried out to solve this problem. One widespread solution is to create a virtual private network (VPN) in a tunnel between the two communicating nodes. IPSec is a well known security architecture which allows such VPNs to be built between two communicating nodes. However this solution requires a different secret key for each end-to-end connection. Moreover the VPN solution can simply handle unicast traffic. An alternative solution is the use of a shared secret key. There are many issues with such an approach. First this key must be distributed among the network nodes. Second, to avoid the compromising of this key it is required to renew the key often. A solution to these two issues is the use a Group Key Agreement protocol, which relies on the principles of the public key cryptography.

A Group Key Agreement protocol (GKA) is a key establishment technique in which a shared secret is derived by more than two participants as a function of information publicly contributed by each of them. They are especially well suited to moderate sized groups with no central authority to distribute keys. An authenticated group key agreement protocol provides the property of key authentication (also called implicit key authentication), whereby each participant is assured that no other party besides the participants can gain access to the computed key. GKA protocols are different from group key distribution (or key transport) protocols wherein one participant chooses the group key and communicates it to all others. GKA protocols help in deriving keys which are composed of each one's contribution. This ensures that the resulting key is fresh (for a given session) and is not favorable to one participant in any way. The following security goals can be identified for any GKA protocol.

1) **Key Secrecy**: The key can be computed only by the participants.

2) **Key Independence**: Knowledge of any set of group keys does not lead to the knowledge of any other group key not in this set (see [BM03]).

3) **Forward Secrecy**: Knowledge of some long term secret does not lead to the knowledge of past group keys.

An important advantage of a group key agreement protocol over a simple group key distribution scheme is the forward secrecy. This property can be particularly interesting in situations where some nodes are likely to be compromised (e.g. in military scenarios).

In such scenarios, using a GKA, the knowledge of the long term secret of this node does not compromise all past session keys. From a functional point of view, it is desirable to have procedures to handle the dynamism in the network. These procedures enable efficient merging or partitioning of two groups in the network.

2 Related Work

Key establishment protocols for networks can be broadly classified into three classes: *Key transport using symmetric cryptography*, *Key transport using asymmetric cryptography* and *Key agreement using asymmetric cryptography.* In key transport protocols, one participant chooses the group key and securely transfers it to other participants using a priori shared secrets (symmetric or asymmetric). These protocols are not suitable for ad hoc networks for two reasons; firstly, they require a single trusted authority to distribute keys and secondly, compromise of the a priori secret of any participant breaches the security of all past group keys, thus failing to provide forward secrecy. Thus GKA protocols are more relevant since they provide this forward secrecy property.

Most group key agreement protocols are derived from the two-party Diffie-Hellman key exchange protocol. GKA protocols, not based on Diffie-Hellman, are few and include the protocols of Pieprzyk and Li [PL00], Tzeng and Tzeng [TT00] and Boyd and Nieto [BN03]. Both protocols of Pieprzyk and Li [PL00] and Boyd and Nieto [BN03] fail to provide *forward secrecy* while the protocol of Tzeng and Tzeng [TT00] is quite resource-intensive and prone to certain attacks [BN03]. Forward Secrecy is a very desirable property for key establishment protocols in ad hoc networks, as some nodes can be easily compromised due to low physical security of nodes. Thus it is essential that compromise of one single node does not compromise all past session keys. We summarize and compare in Table 1 existing GKA protocols based on Diffie-Hellman protocols. We compare essentially the unauthenticated versions of the protocols, as most achieve authentication by using digital signatures in a very similar manner and thus have similar added costs for achieving authentication. We compare the efficiency of these protocols based on the following parameters:

- **Number of synchronous rounds**: In a single synchronous round, multiple independent messages can be sent in the network. The total time required to run a round-efficient GKA protocol can be much less than other GKA protocols that have the same number of total messages but more rounds. This is because the nodes spend less time waiting for other messages before sending their own.

- **Number of messages:** This is the total number of messages (unicast or broadcast) exchanged in the network to derive the group key. For multiple hop ad hoc networks, the distinction between unicast and broadcast messages is important as the latter can be much more energy consuming (for the whole network) than the former.

- **Number of exponentiations**: All Diffie-Hellman based GKA protocols require a number of modular exponentiations to be performed by each participant. Relative

	Expo per U_i	Messages	Broadcasts	Rounds
ITW [ITW82]	m	$m(m-1)$	0	$m-1$
GDH.1 [STW96]	$i+1$	$2(m-1)$	0	$2(m-1)$
GDH.2 [STW96, BCP02]	$i+1$	$m-1$	1	m
GDH.3 [STW96]	3	$2m-3$	2	$m+1$
Perrig [Per99]	$\log_2 m+1$	m	$m-2$	$\log_2 m$
Dutta [DB05]	$\log_3 m$	m	m	$\log_3 m$

Table 1: Comparison of non constant rounds GKA protocols

	Expo per U_i	Messages	Broadcasts	Rounds	Structure	FS
Octopus [BW98]	4	$3m-4$	0	4	Hypercube	Yes
BDB [BD94, KY03]	3	$2m$	m	2	Ring	Yes
BCEP [BCEP03]	$2^{\dagger}$	$2m$	0	2	None	No
Catalano [BC04]	$m+1$	$2m$	0	2	None	Yes
KLL [KSML04]	3	$2m$	$2m$	2	Ring	Yes
NKYW [NLKW04]	$2^{\ddagger}$	m	1	2	None	Yes
STR [SSDW88, KPT04]	$(m-i)^*$	m	1	2	Skewed tree	Yes
Ours (AGDH)	2^{**}	m	1	2	None	Yes

†: m exponentiations for the base station.
‡: $m+1$ exponentiations and m-1 inverse calculations for the parent node.
$*$: Up to $2m$ exponentiations for the sponsor node.
$**$: m exponentiations for the leader.

Table 2: Comparison of constant round GKA protocols

to all cryptographic operations, a modular operation is the most computationally intensive operation and thus gives a good indication of the computational cost for each node.

Communication costs still remain the critical factor for choosing energy-efficient protocols for most ad hoc networks. A modular exponentiation (which is most efficiently done using elliptic curve cryptography) can be performed in a few tens of milliseconds on most palmtops, whereas message propagation in multi-hop ad hoc networks can be easily of the order of few seconds and has energy implications for multiple nodes in the network. As can be seen in Table 1, most existing GKA protocols require $O(m)$ rounds of communication for m participants in the protocol. Such protocols do not scale well in ad hoc networks. Even tree-based GKA protocols with $O(\log m)$ rounds can be quite demanding for medium to large sized ad hoc networks. Therefore constant-round protocols are better suited for ad hoc networks.

Among the constant round protocols (see Table 2), Octopus [BW98], BDB [KY03] and KLL [KSML04] require special ordering of the participants. This results in messages sent by some participant being dependent on that of others. In such a case, failure of a single node can often halt the protocol. Thus such protocols are not robust enough to adapt well to the dynamism of ad hoc networks. The BCEP protocol [BCEP03] involves a base station, and fails to provide forward secrecy if the long-term secret of the base station is revealed. The Bresson and Catalano protocol [BC04] is computationally demanding with $O(m)$ exponentiations for each participant. Another drawback is that if any participant's message is lost in first round, the whole protocol is brought to a halt, as the secret sharing schemes implies all m contributions are required to compute the key. Thus only the protocols NKYW and STR (described below in details) seem to be usable in MANETs.

NKYW[NLKW04]: The original paper proposes this protocol for ad hoc networks composed of devices with unequal computational powers. In the first round, each participant M_i unicasts its contribution $g^{r_i}, i \in [1, n-1]$ to a fixed node M_n, called the parent node. The parent node chooses random r and r_n and computes $w = g^r$, $x_n = g^{r r_n}$ and $x_i = (g^{r_i})^r$ for each received g^{r_i}. It broadcasts w and $\{x_n * \Pi_{j \neq i} x_j\}_i$. The key is derived from $\Pi_i x_i$. The protocol remains a bit expensive computationally compared to the protocol that will be described in this paper.

STR[SSDW88, KPT04]: This protocol was proposed by Steer *et al.* in [SSDW88] for static groups. Perrig *et al.* proposed procedures to handle group changes in [KPT04]. Although this protocol has not been cited as a constant round protocol till now, we explain here in details why this protocol is indeed a constant round protocol. In the first round, each participant M_i broadcasts its contribution g^{r_i} (also known as its blinded key). In the second round, a key-tree as shown in Figure 1 where each leaf node represents a participant is constructed using participant IDs or the value of the contributions. The node in the bottom-most, left-most position in the tree is called the sponsor. The sponsor node broadcasts the set of blinded keys for all the intermediate nodes upto the root node. For the case shown in Figure 1, the broadcast message is $\{g^{r_1}, g^{r_2}, g^{r_3}, g^{r_4}, g^{g^{r_1 r_2}}, g^{g^{r_3 \cdot g^{r_1 r_2}}}\}$. The group key is $K = g^{r_4 \cdot g^{r_3 \cdot g^{r_1 r_2}}}$. Participant M_i has to perform $m - i$ exponentiations except the sponsor which has to compute $2m$ exponentiations. The protocol lacks a proof of security against active adversaries.

Thus both these protocols are computationally more expensive compared to the protocol that will be described in this paper.

The contributions of this paper are the following:

- an authenticated dynamic group key agreement protocol is recalled [ABIS05],
- the mechanisms that must be used in a MANET to implement this group key agreement protocol are described,
- a precise study of the cryptographic parameters that this group key agreement protocol must use in the context of an ad hoc network is carried out.

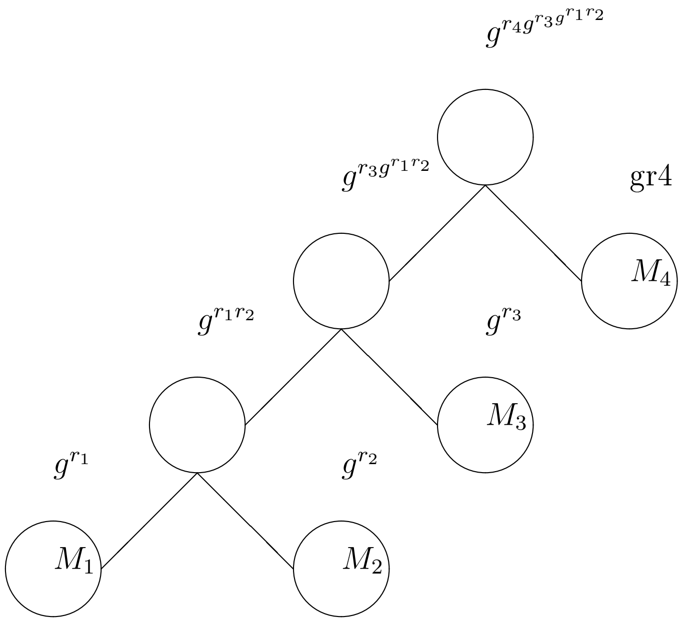

Figure 1: The STR Protocol

Finally the adapted version of the group key agreement protocol that we propose, we call this protocol AGDH for Asymetric Group Diffie Hellman, is among the very few group key agreement protocols suitable for ad hoc networks.

The paper is organized as follows:

- Section 3 recalls the group key agreement protocol. We describe the basic functioning of the protocol only,
- Section 4 explains how this group key agreement protocol can be implemented in an ad hoc network. The main issues discussed in this section include the election of a leader in the ad hoc network and the actions that must be undertaken to handle splits and mergers in the ad hoc network,
- Section 5 discusses the overhead of cryptographic operations.

3 Presentation of AGDH

We recall an existing group key agreement protocol in this section. We first illustrate the basic principle of key exchange, followed by a detailed explanation of how it is employed to derive Initial Key Agreement, Join/Merge and Delete/Partition procedures to handle dynamism in ad hoc groups.

3.1 Notation

G: A subgroup (of prime order q with generator g) of some group.
U_i: i^{th} participant amongst the n participants in the current session.
U_l: The current group leader ($l \in \{1, \ldots, n\}$).
r_i: A random number (from $[1, q-1]$) generated by participant U_i. Also called the *secret* for U_i.
g^{r_i}: The *blinded secret* for U_i.
$g^{r_i r_l}$: The *blinded response* for U_i from U_l.
$\mathcal{M}$: The set of indices of participants (from $\mathcal{P}$) in the current session.
$\mathcal{J}$: The set of indices of the joining participants.
$\mathcal{D}$: The set of indices of the leaving participants.
$x \leftarrow y$: x is assigned y.
$x \overset{r}{\leftarrow} \mathcal{S}$: x is randomly drawn from the uniform distribution S.
$U_i \longrightarrow U_j : \{M\}$: U_i sends message M to participant U_j.
$U_i \xrightarrow{B} \mathcal{M} : \{M\}$: U_i broadcasts message M to all participants indexed by $\mathcal{M}$.
N_i: Random nonce generated by participant U_i.
$\mathcal{V}_{PK_i}\{msg_i, \sigma_i\}$: Signature verification algorithm which returns 1 if σ_i is a valid signature on message msg_i else 0.

3.2 A Three Round Protocol

3.2.1 The formal description

Please note that in the following rounds each message is digitally signed by the sender (σ_i^j is signature on message msg_i^j in Tables 3- 5) and is verified (along with the nonces) by the receiver before following the protocol. Thus we omit to describe these steps which are formally shown in Tables 3- 5.

Protocol Steps:

Round 1: The chosen group leader, M_l makes a initial request (**INIT**) with his identity, U_l and a random nonce N_l to the group $\mathcal{M}$.

Round 2: Each interested M_i responds to the **INIT** request, with a **IREPLY** message which contains his identity U_i, a nonce N_i and a blinded secret g^{r_i} to M_l (see Table 3 for exact message contents).

Round 3: M_l collects all the received blinded secrets, raises each of them to its secret (r_l) and broadcasts them along with the original contributions to the group, i.e. it sends an **IGROUP** message that contains $\{U_i, N_i, g^{r_i}, g^{r_i r_l}\}$ for all $i \in \mathcal{M} \setminus \{l\}$.

Key Calculation: Each M_i checks if its contribution is included correctly and obtains g^{r_l} by computing $(g^{r_i r_l})^{r_i^{-1}}$. The group key is

$$Key = g^{r_l} * \Pi_{i \in \mathcal{M} \setminus \{l\}} g^{r_i r_l} = g^{r_l(1+\sum_{i \in \mathcal{M} \setminus \{l\}} r_i)}.$$

Note:

$\boxed{\textbf{Round 1}}$
$l \stackrel{r}{\leftarrow} \mathcal{M}, N_l \stackrel{r}{\leftarrow} \{0,1\}^k$
$U_l \stackrel{B}{\longrightarrow} \mathcal{M} : \{msg_l^1 = \{\ \textbf{INIT}\ , U_l, N_l\}, \sigma_l^1\}$
$\boxed{\textbf{Round 2}}$
$\forall i \in \mathcal{M} \setminus \{l\}, if(\mathcal{V}_{PK_l}\{msg_l^1, \sigma_l\} == 1), r_i \stackrel{r}{\leftarrow} [1, q-1], N_i \stackrel{r}{\leftarrow} \{0,1\}^k,$
$U_i \longrightarrow U_l : \{msg_i = \{\ \textbf{IREPLY}, U_l, N_l, U_i, N_i, g^{r_i}\}, \sigma_i\}$
$\boxed{\textbf{Round 3}}$
$r_l \stackrel{r}{\leftarrow} [1, q-1],$
$\forall i \in \mathcal{M} \setminus \{l\}, if(\mathcal{V}_{PK_i}\{msg_i, \sigma_i\} == 1)$ and N_l is as contributed
$U_l \stackrel{B}{\longrightarrow} \mathcal{M} : \{msg_l^2 = \{\textbf{IGROUP}, U_l, N_l, \{U_i, N_i, g^{r_i}, g^{r_i r_l}\}_{i \in \mathcal{M}\setminus\{l\}}\}, \sigma_l^2\}$
$\boxed{\textbf{Key Computation}}$
$if(\mathcal{V}_{PK_l}\{msg_l^2, \sigma_l^2\} == 1)$ and g^{r_i} and N_i are as contributed
$Key = g^{r_l(1+\sum_{i\in\mathcal{M}\setminus\{l\}} r_i)}$

Table 3: IKA

1) The original contributions g^{r_i} are included in the last message as they are required for key calculation in case of group modifications (see below), and also, because it may be possible that a particular contribution has not been received by some member.

2) Even though $\Pi_{i\in\mathcal{M}\setminus\{l\}} g^{r_i r_l}$ is publicly known, it is included in key computation, to derive a key composed of everyone's contribution. This ensures that the key can not be pre-determined and is unique to this session.

3) Even though the current group leader chooses his contribution after others, he cannot pre-determine the group key.

The protocol is formally defined in Table 3. Table 4 (respectively Table 5) show how the protocol is run when a group wants to join (respectively leave) an existing group

3.2.2 Example runs of the protocol

We now see how this protocol can be used to derive Initial Key Agreement (IKA), Join/Merge and Delete/Partition procedures for ad hoc networks.

Initial Key Agreement Secure ad hoc group formation procedures typically involve peer discovery and connectivity checks before a group key is derived. Thus, an $INIT$ request is issued by a participant and all interested peers respond. The responses are collected and connectivity checks are carried out to ensure that all participants can listen/broadcast to the group (see for instance [RHH01]). After the group membership is defined, GKA procedures are implemented to derive a group key. Such an approach is quite a drain on the limited resources of ad hoc network devices. Thus an approach which integrates the two separate procedures of group formation and group key agreement is required. The above

$\boxed{\textbf{Round } 1}$
$\forall i \in \mathcal{J}, r_i \xleftarrow{r} [1, q-1], N_i \xleftarrow{r} \{0,1\}^k$,
$U_i \xrightarrow{B} \mathcal{M} : \{msg_i = \{\ \textbf{JOIN}, U_i, N_i, g^{r_i}\}, \sigma_i\}$
$\boxed{\textbf{Round } 2}$
$\forall i \in \mathcal{J}, if(\mathcal{V}_{PK_i}\{msg_i, \sigma_i\} == 1)\ r_l \xleftarrow{r} [1, q-1], l' \xleftarrow{r} \mathcal{M} \cup \mathcal{J}$
$U_l \longrightarrow U_{l'} : \{msg_l = \{\ \textbf{JREPLY}, \{U_i, N_i, g^{r_i}\}_{\forall i \in \mathcal{M} \cup \mathcal{J}}\}, \sigma_l\}$
$\boxed{\textbf{Round } 3}$
$if(\mathcal{V}_{PK_i}\{msg_l, \sigma_l\} == 1), l \leftarrow l', r_l \xleftarrow{r} [1, q-1], \mathcal{M} \leftarrow \mathcal{M} \cup \mathcal{J}$
$U_l \xrightarrow{B} \mathcal{M} : \{msg_l^2 = \{\ \textbf{JGROUP}, U_l, N_l, \{U_i, N_i, g^{r_i}, g^{r_i r_l}\}_{i \in \mathcal{M} \setminus \{l\}}\}, \sigma_l^2\}$
$\boxed{\textbf{Key Computation}}$
$if(\mathcal{V}_{PK_l}\{msg_l^2, \sigma_l^2\} == 1)$ and g^{r_i} and N_i are as contributed
$Key = g^{r_l(1+\sum_{i \in \mathcal{M} \setminus \{l\}} r_i)}$

Table 4: Join/Merge

protocol fits well with this approach. Round 1 and Round 2 of the above protocol can be incorporated into the group formation procedures. In this way, blinded secrets, g^{r_i}'s, of all potential members, U_i's, are collected before the group composition is defined. When the fully connected ad hoc group is defined, a single broadcast message (Round 3 in Table 3) from the group leader, U_l, (using contributions of only the joining participants) helps every participant to compute the group key. An example is provided below.

Suppose U_1 initiates the group discovery and initially 5 participants express interest and send g^{r_2}, g^{r_3}, g^{r_4}, g^{r_5} and g^{r_6} respectively along with their identities and nonces. Finally only 3 join because of the full-connectivity constraint. Suppose the participants who finally join are U_2, U_4 and U_5. Then the group leader, U_1, broadcasts the following message: $\{g^{r_2}$, g^{r_4}, g^{r_5}, $(g^{r_2})^{r_1}$, $(g^{r_4})^{r_1}$, $(g^{r_5})^{r_1}\}$. On receiving this message, each participant can derive g^{r_1} using his respective secret. Thus the key $g^{r_1(1+r_2+r_4+r_5)}$ can be computed.

Join/Merge Suppose new participants, U_9 and U_{10} join the group of U_1, U_2, U_4 and U_5 with their contributions g^{r_9} and $g^{r_{10}}$ respectively. Then the previous group leader (U_1) changes its secret to r_1' and sends $g^{r_1'}$, g^{r_2}, g^{r_4}, g^{r_5}, g^{r_9}, $g^{r_{10}}$ to U_{10} (say the new group leader). U_{10} generates a new secret r_{10}' and broadcasts the following message to the group: $\{g^{r_1'}$, g^{r_2}, g^{r_4}, g^{r_5}, g^{r_9}, $g^{r_{10}' r_1'}$, $g^{r_{10}' r_2}$, $g^{r_{10}' r_4}$, $g^{r_{10}' r_5}$, $g^{r_{10}' r_9}\}$. And the new key is $g^{r_{10}'(1+r_1'+r_2+r_4+r_5+r_9)}$.

Delete/Partition When participants leave the group, they send a **DEL** message, the group leader changes his secret contribution and sends an **IKA** Round 3 like message to the group, omitting the leaving participants' contributions. Refer to Table 5 and below for an example.

$\boxed{\textbf{Round } 1}$
$\forall i \in \mathcal{D}, U_i \longrightarrow U_l : \{msg_i = \{\ \textbf{DEL}, U_i, N_i\}, \sigma_i\}$
$\boxed{\textbf{Round } 2}$
$\forall i \in \mathcal{D}, if(\mathcal{V}_{PK_i}\{msg_i, \sigma_i\} == 1), r_l \stackrel{r}{\leftarrow} [1, q-1], \mathcal{M} \leftarrow \mathcal{M} \setminus \mathcal{D}$
$U_l \stackrel{B}{\longrightarrow} \mathcal{M} : \{msg_l = \{\ \textbf{DGROUP}, U_l, N_l, \{U_i, N_i, g^{r_i}, g^{r_i r_l}\}_{i \in \mathcal{M} \setminus \{l\}}\}, \sigma_l\}$
$\boxed{\textbf{Key Computation}}$
$if(\mathcal{V}_{PK_l}\{msg_l, \sigma_l\} == 1)$ and g^{r_i} and N_i are as contribute d
$Key = g^{r_l(1+\sum_{i \in \mathcal{M} \setminus \{l\}} r_i)}$

Table 5: Delete/Partition

Suppose a participant, U_2, leaves the group of U_1, U_2, U_4, U_5, U_9 and U_{10}. Then the leader, U_{10} changes its secret to $r_{10}^{''}$ and broadcasts $\{g^{r_1^{'}}$, g^{r_4}, g^{r_5}, g^{r_9}, $(g^{r_1^{'}})^{r_{10}^{''}}$, $(g^{r_4})^{r_{10}^{''}}$, $(g^{r_5})^{r_{10}^{''}}$, $(g^{r_9})^{r_{10}^{''}}\}$ to the group. And the new key is $g^{r_{10}^{''}(1+r_1^{'}+r_4+r_5+r_9)}$.

4 Using this GKA protocol within an ad hoc network

In the following we are considering a multi-hop ad hoc network. We are not assuming any particular property of the routing protocol which ensures the connectivity of the network. We can use reactive protocols as AODV or DSR [PBRD03, JMH04] where the connectivity is created on demand when a route is needed. We can also use proactive protocols as OLSR or TBRPF [ACJ+03a, OTL04] where synchronous packets are used to maintain the knowledge of the topology. We will assume that we have a broadcast mechanism to flood messages within the ad hoc network. We are not assuming that this flooding mechanism is reliable, but we assume that the network is connected and that flooding messages finally reaches all the network nodes [1].

A key point in the GKA protocol described above is the existence of group leader. Thus it is necessary to have a robust mechanism to elect such a leader in an ad hoc network. That is the first issue that we study.

4.1 Election of a group leader

A key requirement is that all members of a group agree on the same group leader. A simple solution is that the group leader periodically broadcasts messages. These messages then serve as a proof, for nodes that are within reach of the group leader, that a group leader exists and operates properly. We can simply use the **INIT** message of GKA protocol to demonstrate the existence and the correct functioning of the group leader. When the other

[1] We mean that synchronous flooded messages will finally reach all the network nodes even if there are messages loosses

nodes in the network receive this **INIT** message each replies with an **IREPLY** message including their contribution. Using these **IREPLY** messages, the group leader defines a group and sends to all members of the group an **IGROUP** message. The **INIT** message can be seen as an **IGROUP** message when the group is not yet defined. In the following we will only use the term **IGROUP** message.

These **IGROUP** messages are sent periodically; depending on the dynamics of the group, the group leader will send a new **IGROUP** message or exactly the same message as before. If the network only comprises of the group leader, the latter will send periodically empty **IGROUP** messages. It will stop sending this message when a node joins its network by replying to its **IGROUP** message with an **IREPLY** message. The mechanism to elect a group leader simply follows from the property that, in a network with a group leader, periodic messages are broadcasted by the group leader and are, in principle, received by the group members. If a node does not receive a message for a fixed period T, known a priori by the network nodes, this node sets a random timer. At the expiration of this timer and if no **IGROUP** message has been received meanwhile, the node becomes the group leader. It then sends an empty **IGROUP** message.

There may be a collision on **IGROUP** messages if two nodes or more have selected the same value for their random timer. In such a case, there may be **IGROUP** messages generated by two (or more) group leaders. To select a group leader, we can use additional rules. The first rule is that when a group leader A receives an **IGROUP** message from a group leader B which has a smaller ID than its own ID, the group leader A just stops to send its periodic messages. The group members that will receive periodic messages from more than one group leader will only consider the message issued by the group leader with the smallest index. Thus if an **IGROUP** message showing a larger ID than a previously received **IGROUP** message is received, then this message is simply discarded and no **IREPLY** message is issued. On the contrary if an **IGROUP** message showing a smaller ID is received then the node issues a **IREPLY** message.

Another issue is how the GKA protocol takes into account the dynamism of an ad hoc network. For instance a node may leave the network without being able to send the group leader a message pointing out its departure from the network. This issue is handled in the next subsection

4.2 Handling join and withdrawal of a node

A node which joins the network will receive the periodic **IGROUP** message of the group leader. He will just have to send a **JREPLY** message, with its contribution, to join the group. The group leader will incorporate this new contribution in its next **IGROUP** message. Actually there is no need in the protocol to differentiate between **JREPLY** and **IREPLY**. Thus, for simplicity sake, we will only keep the **IREPLY** message.

In an ad hoc network, the only conceivable way for the group leader to be sure that a node still belongs to a group is to receive a message from it. Thus to handle the dynamism of a group, the group leader will use the periodic reception of the **IREPLY** messages. The period with which an **IREPLY** message is sent by a member of the group should be the same for all the nodes of the group. If the group leader is not receiving a **IREPLY** message for a given number of periods (greater than 1 to handle possible packet loss), the lack of reception of these messages should be handled in the same way as the reception of a **DEL** message. In such a case the group leader will change its own contribution in the **IGROUP** message and will re-send the **IGROUP** message.

When a node deliberately wishes to withdraw from a group it can use the **DEL** message to announce this wish to the group leader. Upon the reception of such a message the group leader will change its own contribution in the **IGROUP** message and will re-send the **IGROUP** message. The use of the **DEL** message will speed up the taking into account of the node withdrawal.

4.3 Handling merge or split of groups

The merger of groups (two or more) leads group leaders to receive **IGROUP** messages from other group leaders. The scheme used in the group leader election can be used to resolve the conflict. When the conflict is resolved only one group leader is left in the group. If a group splits, a part of the group will remain without group leader. The technique used in the group leader election can be used in the subgroups without leader to elect a new leader.

4.4 Renewing its contribution

The group leader and group members will have to renew their contribution periodically. For the group leader, the change of its contribution or of some member of the group will lead to a change in the content of the **IGROUP** message. To simplify we can assume that the group leader and the group members change their contribution at the same rate.

We have given all the principles of the protocol. We precise the details of the whole protocol in the next section.

4.5 Implementation issues

We will consider a given period T. To simplify, this period will be used both by the group leader or by the member of the group as a period to send their GKA messages.

A node can be in one of the following two states : **member state** or **group leader state**. A node in a member state will enter the process to become a group leader if it has not received **IGROUP** message for a duration kT. A node which has not received any message from a group leader for a duration kT with $k \geq 2$ will suppose that there is no group leader and starts the procedure to become a leader. Since a node may not have received a packet of the group leader because this packet has been lost, k must be selected so that the probability that $k-1$ successive transmissions of a GKA message are lost is small. Then, to become a group leader, the node selects a random integer i_r between 1 and a given number l (backoff window size) and initializes a timer at $i_r t_{rtd}$, where t_{rtd} is a predefined duration computed to be at least the round trip delay of a message throughout the ad hoc network. With such a figure for t_{rtd} we can be sure that if two nodes draw different integers i_r and $i_{r'}$, the node having selected the larger integer will receive the **IGROUP** message of the other node and then will stop its election process. The backoff window size l must be chosen with respect to the total number of nodes in the network so that the probability that two nodes choose the same integer is small. This back-off procedure is performed to avoid possibly multiple group leader candidates, for instance, when a group is set up or split into two subgroups.

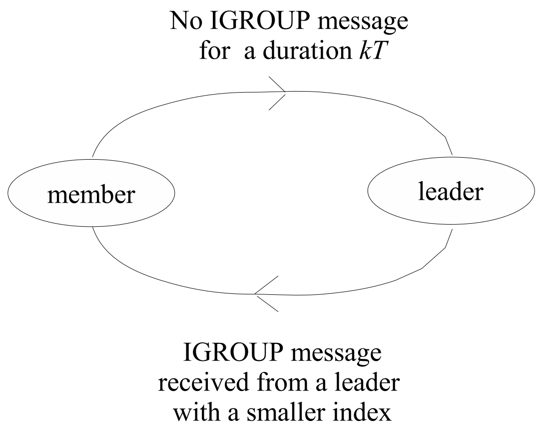

Figure 2: Transition between the member and the leader state

When the node in the state member sends its first **IGROUP** message, it is in the group leader state, see Figure 2. In the group leader state, a node must collect **IREPLY** messages and form the related **IGROUP** message. When there is a change in the group (arrival or withdrawal) the group leader must change its contribution. Additionally, irrespective of the modification of the composition of the group, the group leader must change its contribution periodically, to maintain the security of the session key.

When a group leader is elected, the latter may choose to wait additional periods before sending a **IGROUP** containing the contributions of the group members. Doing so, the group leader may avoid unnecessary changes to the session key due to the lack of receipt of all contributions in time.

In the group leader state, a node will also look out for **IGROUP** messages from another group leader. If it receives such a message from another group leader holding a smaller node index, the node changes its state to the member state. In the member state, a node will have to send **IREPLY** messages periodically. Like the group leader, a group member must change its contribution periodically with a period P see figure 3. We will assume that P is a large multiple of T. To simplify the procedure and to avoid unnecessary computations we can assume that the group leader does not instantly include a new contribution of a group member in the **IGROUP** message, instead it will wait for the change of its own contribution

Parameter	Value	Constraint
P: key renew period	20 min	
T: period of IGROUP messages	5s	
k: number of messages losses before assuming a node leaves	3	large enough to be sure that the message is not simply lost
l: backoff window	20	large enough to avoid collision during the group leader election
t_{rtd}: backoff slot for leader election	100 ms	more than a round trip delay

Table 6: Protocol parameters

to take into account all new contributions of nodes. This is possible since the contribution of the node member is included in the **IGROUP** message.

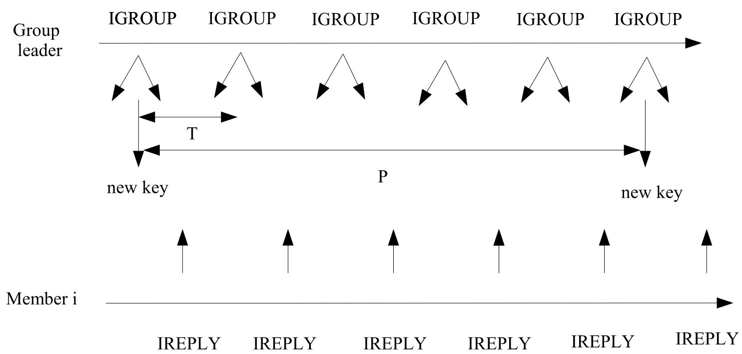

Figure 3: Sending **IGROUP** and **IREPLY** messages

Both **IGROUP** and **IREPLY** messages must be sent periodically for each interval T. To reduce the probability of collision of these messages, we add a jitter to times when the GKA messages shall be sent by the group members and the group leader.

In the table 6, we have given examples of figures for our GKA protocol. We can notice that l and t_{rtd} will heavily depend of the number of nodes in the network and of the topology of the network.

Group	Size of contributions	blindings/second=recoveries/second
Modular Field	1024 bits	10
Elliptic curve	160 bits	93

Figure 4: Performance of elliptic curve cryptography, versus a classical group (modular integers)on a iPAQ, StrongARM-1110, using the `openssl` implementation, for a security level of 2^{80}. Blinding means computing g^{r_i}, and recovering means computing g^{r_0} from the blinded response $g^{r_i r_0}$ of the leader .

5 Computational overhead

Figure 4 describes the cost, on an average small device (COMPAQ iPAQ), of elliptic curve cryptography which is more efficient than classical cryptographic relying on biger groups. Basically, for a security level of 2^{80}, such a device can perform almost 100 operations per second. Thus the latency of elliptic curve exponentiation is 10 msec per device, except for the leader whose computational cost grows linearly with the size of the group. Thus there is concern for this particular node. Assuming that the leader devotes half its times towards cryptogaphic operations, managing a group of size 50 will impose a delay of 1 second before being able to send the blinded response.

The above computational load on the group leader is in the case where the group leader receives all the blinded secrets at once, and has to give the blinded response also at once. In practice, the group leader will receive the blinded secret at different time slots. It is then possible to perform operations in batch: the group leader can generates its own secret in advance, and compute on the fly the blinded reponses $(g^{r_i})^{r_0}$ upon reception of each blinded secret g^{r_i}. He can also stepwise compute the product $(g^{r_1})^{r_0} \cdots (g^{r_m})^{r_0}$, where m is the index of the last received contribution. When he has to broadcat the `IGROUP` message, all the computationaly intense cryptographical operations, necessary to generate the blinded responses, have already been performed.

6 Conclusion

We have discussed a group key agreement protocol for handling ad hoc group of small to moderate size. We have fully specified the implementation details needed for actual use of the protocol, relying on know network techniques such as self election, periodic broadcast, back-off techniques. The protocol is robust in the sense that connectivity losses does not impair its functioning. We have experienced that the computational cost of public key cryptography is kept reasonably low. If we consider constraints in ad hoc networks: no network structure, high dynamism, restricted bandwidth the presented protocol is among the few GKA protocols which is suitable for ad hoc networks.

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