The Hsu-Harn-Mu-Zhang-Zhu group key establishment protocol is insecure

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Abstract

A significant security vulnerability in a recently published group key establishment protocol is described. This vulnerability allows a malicious insider to fraudulently establish a group key with an innocent victim, with the key chosen by the attacker. This shortcoming is sufficiently serious that the protocol should not be used.

1 Introduction

Hsu, Harn, Mu, Zhang and Zhu [3] recently published a protocol (which for convenience we refer to as the HHMZZ protocol) designed to provide authenticated group key establishment in a wireless network (although there are no obvious wireless-specific aspects of the protocol). In this brief note we describe a serious security issue with this scheme; in particular it does not provide the properties claimed.

The remainder of the paper is structured as follows. Section 2 sets out the protocol, including the intended context of use. Section 3 then describes a serious security vulnerability in the protocol. The paper concludes in section 4.

2 The Hsu-Harn-Mu-Zhang-Zhu protocol

2.1 Context and goals

The HHMZZ protocol is intended for use by a pre-established collection of users, and enables any subset (group) of this community to be equipped with a shared secret key by a trusted Key Generation Centre (KGC). Such protocols have been widely discussed in the literature — see, for example, chapter 6 of Boyd and Mathuria [1]. The area is sufficiently well-established that an ISO/IEC standard for group key establishment [4] was published in 2011.
The threat model for such protocols varies, but typically the goal is that, after completion of the protocol, all participants agree on the same key, they know it is ‘fresh’, and that no parties other than those intended learn anything about the key. The authors of the HHMZZ protocol are a little vague as to the assumed capabilities of attackers, although they do refer to both insider and outsider attackers ([3], section 4). It is thus legitimate to assume that the claimed protocol properties are intended to apply even in a malicious insider scenario.

Note that the protocol is described in a way that seems to imply that the group of users between which a key is established is always the same. However, closer examination, e.g. of the discussion following Theorem 3 of section 4, reveals that this is a result of notational assumptions made to simplify the presentation. To avoid confusion, in the description of the protocol given below we have generalised the notation slightly to make it clear that the group can change.

2.2 Related work

The HHMZZ protocol uses a combination of cryptographic hash-functions and a secret sharing scheme. The use of secret sharing as part of a group key establishment protocol is long-established (see, for example, section 6.7.2 of Boyd and Mathuria [1]). However, this approach is known to have shortcomings, [1].

Indeed, the fact that the HHMZZ protocol has serious flaws is hardly surprising given the unfortunate history of the area. Back in 2010, Harn and Lin [2] described a group key transfer protocol based on secret sharing which is not only mathematically flawed, but also possesses very serious security issues; not only did this give rise to a number of papers pointing out the flaws (see, for example, [6, 7]), but also further flawed protocols attempting to ‘fix’ the flaws in the original scheme. Some of the rather sad history of the area can be found in the recent paper of Liu et al. [5].

2.3 The protocol

The following requirements apply for use of the protocol. Note that we have made some minor changes to the notation of Hsu et al. [3] for the purposes of clarity.

- The protocol is designed to work within a set of users \( \mathcal{U} = \{U_i\} \), all of which must have registered with the KGC (and this KGC must be trusted by all users to generate and distribute secret keys).

- All participants must agree on a large ‘safe’ prime \( p \) and a representation of the finite field \( \mathbb{K} = \mathbb{Z}_p \) of \( p \) elements. The participants must also
agree on two cryptographic hash-functions $h_1$ and $h_2$, both mapping to $\mathbb{K}$.

- All participants must agree on the function $v_m : \mathbb{K} \rightarrow \mathbb{K}^{m+1}$ defined by:
  \[ v_m(x) = (1, x, x^2, \ldots, x^m) \]
  (where $m \geq 2$).

- Every user $U_i$ must:
  - have a unique identifier $ID_i$;
  - choose a secret key $x_i \in \mathbb{K}$, which is shared with the KGC.

Now suppose an *initiator* wishes to arrange for a new secret key to be shared by the members of a group of users $U' (U' \subseteq U)$. Suppose $U' = \{U_{z1}, U_{z2}, \ldots, U_{zt}\}$ for some $t \geq 2$.

The protocol proceeds as follows (where all arithmetic is computed in $\mathbb{K}$).

1. The initiator sends a key generation request to the KGC along with the set of $t$ identifiers $\{ID_i : i \in U'\}$.
2. The KGC broadcasts the set of identifiers $\{ID_i : i \in U'\}$ as a response.
3. Each user $U_{zj}$ in $U'$, i.e. each user $U_{zj}$ for which $ID_{zj}$ is in the broadcast set of identifiers, chooses a fresh random challenge $r_j \in \mathbb{K}$ and sends it to the KGC.
4. The KGC performs the following steps.
   (a) The KGC randomly chooses a group key $S \in \mathbb{K}$ and a value $r_0 \in \mathbb{K}$, and assembles the $(t+1)$-tuple $r = (r_0, r_1, r_2, \ldots, r_t)$.
   (b) For every $i \ (1 \leq i \leq t)$ the KGC now computes the inner product
       \[ s_{zi} = (v_t(x_{zi} + h_1(x_{zi}||r_i||r_0)), r) \]
       where $||$ denotes concatenation of bit strings (and the finite field values that are concatenated are converted to bit strings using an agreed representation). The KGC also computes $u_{zi} = S - s_{zi}$.
   (c) The KGC now computes the tag $Auth$ as
       \[ Auth = h_2(S||ID_1||ID_2||\ldots||ID_t||r_0||r_1||r_2||\ldots||r_t||u_{z1}||u_{z2}||\ldots||u_{zt}) \]
       where, as previously, in assembling the input to $h_2$, elements of $\mathbb{K}$ are converted to bit strings using an agreed representation.
Finally, the KGC broadcasts

\[ \text{Auth}, r_0, (u_{z_1}, u_{z_2}, \ldots, u_{z_t}) \]

to all members of the group \( U' \).

5. On receipt of the broadcast, each user \( U_{z_i} \in U' \) (1 ≤ \( i \) ≤ \( t \)) proceeds as follows.

(a) \( U_{z_i} \) computes

\[ s_{z_i} = (v_i(x_{z_i} + h_1(x_{z_i}||r_i||r_0), r)) \]

using its secret key \( x_{z_i} \), the random challenges \( r_i \) (1 ≤ \( i \) ≤ \( t \)) sent earlier in the protocol, and the broadcast value \( r_0 \).

(b) \( U_{z_i} \) now computes the group key as \( S = u_{z_i} + s_{z_i} \).

(c) Finally, \( U_{z_i} \) verifies the tag \( \text{Auth} \) by recomputing it using the newly computed group key and the values sent earlier in the protocol.

2.4 Two minor observations

In the form that the protocol is specified by Hsu et al. [3], every participating group member is required to intercept the random challenges \( r_j \) sent by every other group member to the KGC. This seems likely to be problematic, at least in some environments. It would make more sense for the KGC to broadcast the values \((r_1, r_2, \ldots, r_t)\) to all group members in step 4d of the protocol.

It would appear that the computation \( x_{z_i} + h_1(x_{z_i}||r_i||r_0) \) is intended to be a one-way function of the three field elements \( x_{z_i}, r_i \) and \( r_0 \). However, if \( h_1 \) is chosen appropriately, precisely the same property can be achieved without the addition, i.e. simply by computing \( h_1(x_{z_i}||r_i||r_0) \).

2.5 Security claims

Hsu et al. [3] (see Theorem 1 of section 4) make the following claims regarding the security of the protocol. They state: ‘The proposed protocol achieves the security features\(^1\) with key freshness, key confidentiality and key authentication’. In the ‘proof’ of Theorem 1, the following statements are made.

Key authentication is provided through the value \( \text{Auth} \) in step 4. . . . Any insider also cannot forge a group key without being detected since the group key is a function of each member’s long-term secret \( x_i \).

As we show below, this claim is incorrect; that is, an insider can forge a group key.

\(^1\)In fact, the paper refers to ‘security feathers’, but this is presumably a misprint.
3 Analysis

We now describe a serious security vulnerability in the protocol.

3.1 Attack goal and model

We consider the scenario where a ‘victim user’ \( U_v \) is a member of a group \( \mathcal{U}' \) of \( t \) users for which a new key is requested. We make the following assumptions.

- One of the users, \( U_m \) say, in the group \( \mathcal{U}' \) is malicious.
- \( U_m \) can control the channel between the KGC and the victim user \( U_v \). In fact \( U_m \) only needs to be able to modify the content of what \( U_v \) receives in the final broadcast from the KGC sent in step 4d.
- \( U_m \) wishes to make \( U_v \) accept a key \( S^* \) of the malicious user’s choice.

3.2 Attack operation

The attack is very simple to describe. We suppose that the protocol proceeds as described in section 2.3 where \( U_v, U_m \in \mathcal{U}' \).

In step 4d, \( U_m \) intervenes and prevents the broadcast from the KGC reaching \( U_v \). Because the malicious user is a valid member of \( \mathcal{U}' \), \( U_m \) can calculate the secret key \( S \) generated and distributed by the KGC. \( U_m \) now chooses a different secret key \( S^* \in \mathbb{K} \), and computes

\[
  u_v^* = u_v - S + S^*
\]

and

\[
  Auth^* = h_2(S^*||ID_1 \ldots ||ID_t||r_0||r_1|| \ldots ||r_t||u_1|| \ldots ||u_{v-1}||u_v^*||u_{v+1}|| \ldots ||u_t).
\]

That is, \( Auth^* \) is computed using exactly the same inputs as \( Auth \) except that \( S \) and \( u_v \) are changed to \( S^* \) and \( u_v^* \).

\( U_m \) now sends a modified version of the KGC’s broadcast to \( U_v \), where \( Auth \) and \( u_v \) are replaced by \( Auth^* \) and \( u_v^* \). It is straightforward to see that the victim user \( U_v \) will compute the secret key as \( S^* \), and the tag \( Auth^* \) will verify correctly. The attack is complete.

4 Conclusions

As demonstrated above, the HHMZZ protocol fails to possess the properties claimed of it. This means that the protocol should not be used. It is important to observe that Hsu et al. \cite{3} do not provide a rigorous security proof using state of the art ‘provable security’ techniques, nor do they give
a formal model of security for the protocol. This helps to explain why fundamental flaws exist. Indeed, the following observation, made by Liu et al. [5] with respect to a number of previously proposed but flawed group key establishment protocols, is highly relevant.

The security proof for each vulnerable GKD protocol only relies on incomplete or informal arguments. It can be expected that they would suffer from attacks.

It would, of course, be tempting to try to repair the protocol to address the issues identified, but, unless a version can be devised with an accompanying security proof, there is a strong chance that flaws will remain.

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