How not to secure wireless sensor networks revisited: Even if you say it twice it's still not secure

Chris J. Mitchell
Information Security Group, Royal Holloway, University of London
`www.chrismitchell.net`

20th November 2020

Abstract

Two recent papers describe almost exactly the same group key establishment protocol for wireless sensor networks. Quite apart from the duplication issue, we show that both protocols are insecure and should not be used — a member of a group can successfully impersonate the key generation centre and persuade any other group member to accept the wrong key value. This breaks the stated objectives of the schemes.

1 Introduction

Essentially the same group key establishment protocol aimed at wireless sensor networks has been presented in two published papers, [2, 3], both of which appeared online in early 2016. The sets of authors of the two papers are slightly different, although three names (Hsu, Harn and Zhang) appear as authors of both papers. Thus it is clearly no accident that the same material has been published twice. To clarify matters, the papers are as follows:

- *Paper A*, [2], by Hsu, Harn, He and Zhang;
- *Paper B*, [3], by Hsu, Harn, Mu, Zhang and Zhu.

Paper A [2] was submitted on January 11th 2016 and accepted for publication on March 2nd 2016. The date of submission of Paper B [3] is not given but it was published online on February 2nd 2016. It thus seems likely that the two papers were submitted and revised at very similar times. It is noteworthy that neither paper refers to the other.

The fact that the same material has been published twice is clearly disturbing. The duplication of publications is somehow made worse by the fact that, as we discuss below, the scheme described is obviously insecure. This was pointed out in a March 2018 arXiv document [5], which refers to Paper B. However, at the time this document was written I was unaware of Paper A, discovering which has motivated this further note.

The title of this document implicitly refers to another paper, [6], which describes attacks against three very closely-related key predistribution schemes, also aimed at wireless sensor networks. There is a significant overlap in authorship between the three papers considered there and the two papers considered here. It might be that a pattern of behaviour can be discerned.

The remainder of this short paper is structured as follows. §2 provides a brief description of the scheme in Paper A, and the trivial differences from the scheme in Paper B are also noted. An attack against this scheme is outlined in §3. Brief concluding remarks are given in §4.

2 The Hsu-Harn-He-Zhang scheme

The scheme described in Hsu et al. [2] operates as follows. The description below is based closely on reference [5]. The following requirements apply; note that we have made minor changes to the notation of Hsu et al. [2] for consistency with the March 2018 analysis, [5].

- The protocol works for a set of users $\mathcal{U} = \{U_i\}$, all registered with a KGC trusted by all users to generate and distribute secret keys.
- All participants agree on a large integer $m = pq$, where p and q are distinct large safe primes. Hsu et al. require all computations to take place in a (sic) finite field $\mathbb{K}$ with m elements. Of course, such a finite field cannot exist, so we assume instead that calculations are performed in the commutative ring $\mathbb{Z}_m$[1]; the scheme will work with very high probability in such a ring, because the probability of randomly choosing a ring element which does not have a multiplicative inverse is vanishingly small given that p and q are large. Indeed, if this wasn't true then factoring RSA moduli would be easy! This is the first of two minor differences from the scheme presented in Paper B, [3], where it is assumed that calculations take place in a field of p elements for a large prime p.
- The participants must also agree a cryptographic hash-function h.

---

[1] The fact that this is what was intended by the authors becomes clear later in the paper, where there are references to calculations being performed 'mod m'.

- All participants must agree on the function $\mathbf{v}_w : \mathbb{Z}_m \rightarrow (\mathbb{Z}_m)^{w+1}$ defined by:
$$\mathbf{v}_w(x) = (1, x, x^2, \ldots, x^w)$$
(where $w \geq 2$).
- Every user U_i must have a unique identifier ID_i and a secret key $x_i \in \mathbb{Z}_m$ 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 $\mathcal{U}'$ ($\mathcal{U}' \subseteq \mathcal{U}$), where $\mathcal{U}' = \{U_{z_1}, U_{z_2}, \ldots, U_{z_t}\}$ for some $t \geq 2$.

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

1. The initiator sends a request to the KGC with the list of t identifiers $\{\mathrm{ID}_i : i \in \mathcal{U}'\}$.
2. The KGC broadcasts the list of identifiers $\{\mathrm{ID}_i : i \in \mathcal{U}'\}$ in response.
3. Each user $U_j \in \mathcal{U}'$ chooses a fresh random challenge $r_j \in \mathbb{Z}_m$ and sends it to the KGC.
4. The KGC performs the following steps.
   (a) The KGC randomly chooses a group key $S \in \mathbb{Z}_m$ and a value $r_0 \in \mathbb{Z}_m$, and assembles the $(t+1)$-tuple $\mathbf{r} = (r_0, r_1, r_2, \ldots, r_t)$.
   (b) For every i ($1 \leq i \leq t$) the KGC now computes the inner product
   $$s_i = (\mathbf{v}_t(x_{z_i}, \mathbf{r}).$$
   The KGC also computes $u_i = S - s_i$. Note that this represents the second minor difference from the scheme in Paper B, [3], where s_i is instead calculated as:
   $$s_i = (\mathbf{v}_t(x_{z_i} + h_1(x_{z_i}||r_i||r_0)), \mathbf{r})$$
   where $||$ denotes concatenation of bit strings and h_1 is an appropriate cryptographic hash function.
   (c) The KGC now computes the tag *Auth* as
   $$Auth = h(S||\mathrm{ID}_1||\mathrm{ID}_2||\ldots||\mathrm{ID}_t||r_0||r_1||r_2||\ldots||r_t||u_1||u_2||\ldots||u_t)$$
   where in assembling the input to h, elements of $\mathbb{Z}_m$ are converted to bit strings using an agreed representation.
   (d) Finally, the KGC broadcasts
   $$Auth, r_0, (u_1, u_2, \ldots, u_t)$$
   to all members of the group $\mathcal{U}'$.

5. On receiving the broadcast, user $U_{z_i} \in \mathcal{U}'$ $(1 \le i \le t)$:
   (a) computes
   $$s_i = (\mathbf{v}_t(x_{z_i}, \mathbf{r}))$$
   using its secret key x_{z_i}, the random challenges r_i $(1 \le i \le t)$ sent earlier in the protocol, and the broadcast value r_0;
   (b) computes the group key as $S = u_i + s_i$; and finally
   (c) verifies *Auth* by recomputing it using the newly computed group key and the values received in the protocol.

3 Analysis

The analysis of the protocol precisely follows the analysis in the 2018 note [5]. We suppose a 'victim user' U_v is a member of a group of t users for which a new key is requested, and that one of the users, U_x say, in the group $\mathcal{U}'$ is malicious. We also assume that U_x can control the channel between the KGC and the victim user U_v so that U_x can modify what U_v receives in the final KGC broadcast in step 4d. As we show below, U_x is able to make U_v accept a key S^* of U_x's choice.

We suppose that the protocol proceeds as described in section 2, where $U_v, U_x \in \mathcal{U}'$. In step 4d, U_x prevents the broadcast from the KGC reaching U_v. Because U_x is a valid member of $\mathcal{U}'$, U_x can calculate the secret key S generated and distributed by the KGC. U_x now chooses a different secret key $S^* \in \mathbb{Z}_m$, and computes

$$u_v^* = u_v - S + S^*$$

and

$$Auth^* = h_2(S^*||\mathrm{ID}_1 \ldots ||\mathrm{ID}_t||r_0||r_1|| \ldots ||r_t||u_1|| \ldots ||u_{v-1}||u_v^*||u_{v+1}|| \ldots ||u_t).$$

That is, $Auth^*$ is computed using the same inputs as *Auth* except that S and u_v are switched to S^* and u_v^*. U_x 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 victim user U_v will compute the secret key as S^*, and the tag $Auth^*$ will verify. The attack is complete.

4 Concluding remarks

Apart from the double publication issue, it is difficult to go much beyond the conclusions of the 2018 note [5]. Neither Paper A not Paper B provide a rigorous security proof using state of the art 'provable security' techniques, nor do they give a formal security model. This is despite the existence of well-established security models within which the security properties of group key establishment protocols can be established (see, for example, §2.7.1 of Boyd et al. [1]). This certainly helps to explain why fundamental flaws exist.

Indeed, the following observation of Liu et al. [4] regarding 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'. We conclude that, although it might be tempting to try to repair the protocol to address the issues identified, unless a version can be devised with an accompanying security proof (which may well not be possible without significantly increasing the complexity) this would be foolhardy since there is a strong chance that flaws will remain.

The American philosopher and psychologist William James (1842-1910) reputedly said 'There's nothing so absurd that if you repeat it often enough, people will believe it'[2]. Clearly in this case twice is not enough times!

References

[1] C. Boyd, A. Mathuria, and D. Stebila, *Protocols for authentication and key establishment*, 2nd ed., Information Security and Cryptography, Springer, 2020.

[2] C.-F. Hsu, L. Harn, T. He, and M.-Y. Zhang, *Efficient group key transfer protocol for WSNs*, IEEE Sensors Journal **16** (2016), no. 11, 4515–4520.

[3] C.-F. Hsu, L. Harn, Y. Mu, M. Zhang, and X. Zhu, *Computation-efficient key establishment in wireless group communications*, Wireless Networks **23** (2017), 289–297.

[4] J. Liu, Y. Wu, X. Liu, Y. Zhang, G. Xue, W. Zhou, and S. Yao, *On the (in)security of recent group key establishment protocols*, The Computer Journal **60** (2017), 507–526.

[5] C. J. Mitchell, *The Hsu-Harn-Mu-Zhang-Zhu group key establishment protocol is insecure*, arXiv:1803.05365 [cs.CY], `http://arxiv.org/abs/1803.05365`, March 2018.

[6] ———, *How not to secure wireless sensor networks: A plethora of insecure poynomial-based key pre-distribution schemes*, arXiv:2004.05597 [cs.CY], `http://arxiv.org/abs/2004.05597`, April 2020.

---

[2] See, for example, `http://libertytree.ca/quotes/William.James.Quote.7EE1`