Comments on “ALAM: Anonymous Lightweight Authentication Mechanism for SDN Enabled Smart Homes”

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ABSTRACT Smart home is intended to be able to enhance home automation systems and achieves goals such as reducing operational costs and increasing comfort while providing security to mobile users. However, an attacker may attempt security attacks in smart home environments because he/she can inject, insert, intercept, delete, and modify transmitted messages over an insecure channel. Secure and lightweight authentication protocols are essential to ensure useful services in smart home environments. In 2020, Iqbal et al. [1] designed an anonymous lightweight authentication protocol to provide secure services in smart home environments. They claimed that ALAM protocol could withstand security threats, such as desynchronization and replay attacks, and also ensure user anonymity and mutual authentication. However, this comment paper demonstrates that ALAM protocol suffers from many security threats, including impersonation, session key disclosure and man-in-the-middle (MITM) attacks. Moreover, ALAM protocol cannot also provide user anonymity and mutual authentication. Thus, we propose the essential security guidelines to overcome the security flaws of ALAM protocol.

INDEX TERMS Cryptanalysis, smart homes, key establishment, authentication, security protocol.

I. INTRODUCTION

With the advances in wireless technologies and portable devices, users can access various services via mobile device in smart home environments. The smart home allows useful services for the mobile users, including humidity of the house, automatic checking of the temperature, controlling light bulbs, and so on. In general, the smart home comprises several indoor smart devices, gateways, users, and controllers. Mobile users are registered in the controller, and they can access various services. However, these services are susceptible to potential attacks because sensitive messages are exchanged via an insecure channel. If the data collected by smart devices is compromised, a malicious attacker can obtain the private information of users, including habits and daily routines in smart home, and also utilize the information for criminal purposes. Therefore, a secure and lightweight authentication protocol is essential to provide mobile users with useful services in smart home environments.

In 2020, Iqbal et al. [1] designed an anonymous lightweight authentication protocol to provide secure services in smart home environments. They claimed that ALAM protocol could withstand security threats, such as desynchronization and replay attacks, and also ensure user anonymity and mutual authentication. However, this comment paper demonstrates that ALAM protocol suffers from many security threats, including impersonation, session key disclosure and man-in-the-middle (MITM) attacks. Moreover, ALAM protocol cannot also provide user anonymity and mutual authentication. Thus, we propose the necessary guidelines to overcome the security flaws of ALAM scheme [1].

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The rest of this comment paper is organized as follows. In Section II and III, we review Iqbal et al.’s protocol and then show cryptanalysis of Iqbal et al.’s protocol, respectively. Section IV proposes some guidelines to overcome the security shortcomings of Iqbal et al.’s protocol. Finally, Section V summarizes and concludes the work.

### A. ATTACKER MODEL
We present the widely-known Dolev-Yao (DY) model [2] to evaluate the security of ALAM protocol. The capabilities of an attacker in the DY model are as follows:

- Referring to DY model [2], a malicious adversary (MA) can replay, eavesdrop, modify, intercept, insert, and delete transmitted messages over an insecure channel.
- Software-defined networking (SDN) database modules and controllers are considered to be secure and cannot be compromised by MA. In other words, the controller’s private key is not accessible to the MA [1].
- During a lost mobile device attack, MA obtains all secret credentials stored in mobile device by physical means, even if the mobile device has a certain degree of tamper resistance. Thus, MA can steal the legitimate user’s mobile device and extract the secret credentials stored in memory by performing power analysis [3]–[5].
- After obtaining the secret credentials of the mobile device, MA may attempt various attacks such as “insider attack”, “MITM attack”, and “desynchronization attack”, etc [6], [7].

### B. RESEARCH CONTRIBUTIONS AND MOTIVATION
The major goal of this comment paper is to identify the security flaws present in ALAM scheme. ALAM does not ensure the required security functionalities such as “session key disclosure attack”, “MITM attack”, “impersonation attack”, “mutual authentication”, and “user anonymity” in smart home environments. These facts motivated us to come up with the necessary security guidelines which can ensure security functionalities and overcome security threats and flaws that exist in smart home environments.

### II. REVIEW OF IQBAL ET AL.’S PROTOCOL
We review ALAM scheme [1] for a smart home environment. ALAM scheme consists of three phases: a) user registration, b) smart device registration and c) mutual authentication. The notations used in this comment are presented in Table 1.

### A. USER REGISTRATION PHASE
The mobile users \( MU_i \) must register with the SDN controller \( CT \) to receive smart home services. We show the user registration phase of ALAM protocol, and the detailed steps are as follows:

- **UR-1:** \( MU_i \) chooses user identity \( U_{ID} \), and mobile identity \( M_{ID} \). Then, \( MU_i \) sends \( \{ U_{ID}, M_{ID} \} \) to \( CT \) via a secure channel.

### B. SMART DEVICE REGISTRATION PHASE
The smart device \( SD_i \) must register with the SDN controller to ensure useful home services. We present the smart device registration phase of ALAM protocol, and the detailed steps are as below:

- **SR-1:** \( SD_i \) chooses smart device identity \( SD_{ID} \) and then sends \( \{ SD_{ID} \} \) to the \( CT \) over a secure channel.
- **SR-2:** Upon getting message \( \{ SD_{ID} \} \), the \( CT \) generates controller identifier \( CID \) and random nonce \( C_n \). Then, \( CT \) computes \( CSP_{SD_{ID}} = h(SD_{ID} || C_m) \) and \( SID_{SD_{ID}} = E_{k_{uc}}(SD_{ID}, CSP_{SD_{ID}}, C_m) \). After that, the \( CT \) sends \( \{ SID_{SD_{ID}}, CID \} \) to the smart device \( SD_i \) over a secure channel. Finally, \( CT \) sends \( \{ SID_{SD_{ID}}, CSP_{SD_{ID}} \} \) to the \( Reg.DB \) and \( Auth.DB \).
- **SR-3:** Upon getting message \( \{ SID_{SD_{ID}}, CID \} \) from the \( CT \), \( SD_i \) stores them in memory.
- **SR-4:** Upon getting message \( \{ SID_{SD_{ID}}, CSP_{SD_{ID}} \} \), \( Reg.DB \) and \( Auth.DB \) also store them in secure database.

### C. MUTUAL AUTHENTICATION PHASE
In this phase, a mobile user \( MU_i \) requests authentication to the SDN controller to receive secure service. We describe

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**TABLE 1. Notations.**

| Symbol | Description |
|--------|-------------|
| \( MU_i \) | Mobile user |
| \( CT \) | Controller |
| \( SD_i \) | Smart device |
| \( U_{ID} \) | Identity of user |
| \( M_{ID} \) | Identity of mobile device |
| \( C_{sc} \) | Counter of controller |
| \( k_{uc} \) | Shared secret key between controller and user |
| \( C_n, U_n \) | Random nonce of controller and user |
| \( CSP \) | Controller session parameter |
| \( SID \) | Session identifier |
| \( SDI_{ID} \) | Identity of IoT smart device |
| \( Auth.DB \) | Database of authenticator manager |
| \( Reg.DB \) | Database of registration manager |
| \( \Delta T \) | Threshold difference in time |
| \( E_{K}(), D_{K}() \) | Encryption/decryption |
| \( h() \) | Hash function |
| \( \oplus \) | XOR operation |
the authentication phase of ALAM protocol as summarized in Fig. 1 and the detailed steps of this phase are as follows.

- **AP-1:** The user generates a random nonce \( n \) and a timestamp \( T_1 \), computes \( U_n = U_p \oplus M_{ID} \) and \( Auth_n = h(SID_n \| U_p \| T_1) \), and sends the message \( M_1 = \{ Auth_n, SID_n, U_p, T_1 \} \) to the CT over an insecure channel.

- **AP-2:** Upon getting the message \( M_1 \), the CT checks timestamp \( T_2 - T_1 = \Delta T \) and decrypts \( U_n = U_p \oplus M_{ID} \). The CT decrypts \( SID_n = D_{kw}(U_ID, M_ID, CSP_{MDM}, \{'SID_{seq}'\}) \) and checks \( M_{seq}^{rev} = M_{seq}^{save} \). If it is valid, the CT can come across two scenarios. In the following, we discuss Case 1.

**Case 1:**

- **AP-3:** If \( TF_{seq}^{rev} \neq TF_{seq}^{save} \), the user \( U_n \) will always be true in authentication request after registration and decrypts \( U_n = U_p \oplus M_{ID} \). Then, the CT checks \( Auth_n^{rev} = Auth_n^{save} \). If it is valid, the CT generates a timestamp \( T_2 \) and computes \( Auth_d = h(SID_{SDM} \| T_2 \| CID) \). After that, the CT sends the message \( M_2 = \{ Auth_d, T_2 \} \) to the SD\(_i\) over an insecure channel.

- **AP-4:** Upon getting the message \( M_2 \), SD\(_i\) checks \( T_3 - T_2 = \Delta T \) and computes \( Auth_d^{rev} = h(SID_{SDM} \| T_2 \| CID) \), and checks \( Auth_d^{rev} = Auth_d \). If it is correct, SD\(_i\) computes \( Auth_{dc} = h(SID_{SDM} \| T_3 \| CID) \) and sends the message \( M_3 = \{ Auth_{dc}, T_3 \} \) to the CT via an open channel.

- **AP-5:** Upon getting the messages \( M_3 \), CT computes \( Auth_{dc}^{rev} = h(SID_{SDM} \| T_3 \| CID) \) and verifies \( Auth_{dc}^{rev} = Auth_{dc} \). If it is valid, the SD\(_i\) is authenticated successfully.

**Case 2:**

- **AP-6:** CT either the received \( Auth_{dc} \) from the SD\(_i\) in \( M_3 \) is checked or if the received \( TF_{seq}^{*} \) from the \( U_n \) is old, whereas CT is waiting for new \( TF_{seq}^{*} \). Then, CT verifies \( TF_{seq}^{*} \). If it is valid, CT generates \( TF_{seq}^{*} \) and updates \( \{'TF_{seq}^{*}\} \) with \( \{'TF_{seq}^{*}\} \), and stores both values in secure database. After that, CT generates a random nonce \( C^{n} \) and computes \( CSP_{MID}^{DC} = h(U_ID \| M_ID \| C^{n}) \). CT also chooses a timestamp \( T_4 \) and generates \( SID_u^{*} = E_{kw}(UID, M_ID, CSP_{MID}^{DC}, TF^{*}_{seq}), SID_u^{*} \oplus M_ID, \) and \( Auth_c = h(SID_u^{*} \| M_ID \| U_n \| T_4 \| k_u) \). Finally, the CT sends the message \( M_4 = \{ Auth_c, T_4 \} \) to the \( U_n \) via insecure channel.

- **AP-7:** After getting the message \( M_4 \), \( U_n \) checks \( T_5 - T_4 = \Delta T \) and decrypts \( SID_u^{*} = D_{kw}(UID, M_ID, CSP_{MID}, \{'TF_{seq}^{*}\}) \). Then, \( U_n \) computes the session key \( SID_u^{*} = Z \oplus M_ID \), the authentication message \( Auth_d^{*} = h(SID_u^{*} \| M_ID \| U_n \| T_4 \| k_u) \) and verifies \( Auth_d^{*} = Auth_d \). If it is valid, \( U_n \) is mutually authenticated successfully.
III. CRYPTANALYSIS OF IQBAL ET AL.’S PROTOCOL

This comment paper is about “ALAM: Anonymous Lightweight Authentication Mechanism for SDN Enabled Smart Homes” that is presented by Iqbal et al. [1]. Iqbal et al. claimed that ALAM scheme could resist various attacks and also ensure user anonymity and mutual authentication. However, we demonstrate that ALAM scheme is vulnerable to “impersonation”, “MITM”, and “session key disclosure” attacks. Furthermore, we show that ALAM protocol fails to ensure “user anonymity” and “mutual authentication”.

A. IMPERSONATION ATTACK

MA may attempt to impersonate legitimate user. Referring to Section I-A, MA can extract the secret credentials {SID_a, kuc} stored in mobile device. Moreover, MA can replay, intercept, modify, eavesdrop, insert, and delete transmitted messages over an insecure channel. The detailed steps of this attack are as follows:

- **Step 1**: MA first calculates D_mw(SID_a) = (UI_D, MID, CSP_MID, TF_seq) and U_m = U_p = MID. Then, MA generates a new random nonce A_n, and calculates U_MA = A_n ⊕ MID and Auth_MA = h(SID_a || U_MA || kuc) || T_1 || A_n || TF_seq). After that, MA sends the message M_MA1 = {Auth_MA, SID_a, U_MA, T_1} to the CT over an insecure channel.

- **Step 2**: After getting the message M_MA1, the CT checks the timestamp T_2 − T_1 = ΔT and decodes A_n = U_MA ⊕ MID. Then, CT decrypts SID_a = D_mw(UID, MID, CSP_MID, TF_seq) and verifies M_MA1^rev = M_MA1^save. If it is correct, CT can come across two scenarios. Both situations are provided below.

  **Case 1.**

  - **Step 3**: If TF_MA1^rev = TF_MA1^save, the CT decodes A_n = U_MA ⊕ MID. Then, CT verifies Auth_MA = Auth_MA^save. If it is valid, CT generates a timestamp T_2 and computes Auth_d = h(SID_SD || T_2 || CID). After that, CT sends M_2 = {Auth_d, T_2} to the SD over an insecure channel.

  - **Step 4**: Upon getting the message M_2, SD checks T_3 − T_2 = ΔT and computes Auth_d^* = h(SID_SD || T_3 || CID), and checks Auth_d = Auth_d^*. If it is correct, SD computes Auth_dc = h(SID_SD || T_3 || CID) and sends the message M_3 = {Auth_dc, T_3} to the CT via insecure channel.

  - **Step 5**: After getting the message M_3, CT computes Auth_d^* = h(SID_SD || T_3 || CID) and verifies Auth_d^* = Auth_d. If it is correct, SD is authenticated successfully.

  **Case 2.**

  - **Step 6**: CT verifies TF_MA1^old = TF_MA1^new. If it is valid, CT generates TF_MA1^new and updates TF(seq) with TF_MA1^new, and stores both values in secure database. After that, CT generates a random nonce C_n and computes CSP_MID = h(UID || MID || C_n). CT also chooses a timestamp T_4 and generates SID_a^* = E_kuc(UID, MID, CSP_MID, TF_seq), SID_a^* ⊕ MID, and Auth_MA = h(SID_a || MID || A_n || T_4 || kuc). Finally, CT sends the message M_4 = {Auth_MA, Z, T_4} to the MU_i via public channel.

- **Step 7**: After getting the message M_4, MA checks T_4 − T_4 = ΔT and computes session key SID_a^* = Z ⊕ MID, authentication message Auth_MA^* = h(SID_a^* || MID || A_n || T_4 || kuc), and verifies Auth_MA^* = Auth_MA. If it is valid, MA is authenticated successfully.

Consequently, ALAM protocol is vulnerable to the impersonation attack, because MA can impersonate as a mobile user, and establish successfully a session key with the CT on behalf of the mobile user MU_i.

B. SESSION KEY DISCLOSURE ATTACK

In Section III-A, this comment paper demonstrated that MA can impersonate a mobile user MU_i and calculate a session key SID_a^* = Z ⊕ MID as follows. Referring to Section I-A, MA can extract secret credentials stored in mobile device, and intercept the exchanged messages between MU_i, CT, and SD_i via an insecure channel. In addition, MA calculates D_mw(SID_a) = (UID, MID, CSP_MID, TF_seq) and U_m = U_p = MID. After getting message {M_4}, the MA computes the session key SID_a^* = Z ⊕ MID and authentication message Auth_MA^* = h(SID_a^* || MID || A_n || T_4 || kuc). Consequently, ALAM protocol cannot withstand the session key disclosure attack because MA can generate SID_a^* = Z ⊕ MID between MU_i and CT successfully.

C. MITM ATTACK

ALAM scheme cannot withstand MITM attack, because MA can compute the authentication request message M_1. According to Section III-A, the MA computes D_mw(SID_a) = (UID, MID, CSP_MID, TF_seq) and U_m = U_p = MID. After that, MA computes session key SID_a^* = Z ⊕ MID and authentication message Auth_MA^* = h(SID_a^* || MID || A_n || T_4 || kuc) successfully. Thus, ALAM scheme cannot resist to MITM attack.

D. USER ANONYMITY AND MUTUAL AUTHENTICATION

Iqbal et al. claimed that ALAM scheme ensures authentication between the MU_i, CT, and SD_i. However, referring to Section III-A and III-C, the MA can compute D_mw(SID_a) = (UID, MID, CSP_MID, TF_seq). Thus, MA can obtain the real identity UID and MID of the legitimate user and mobile device. Moreover, MA can compute the authentication request message M_1 and response message M_4 successfully. Thus, ALAM scheme cannot ensure user anonymity and mutual authentication.

IV. GUIDELINES ON ATTACKS RESILIENCE

In ALAM scheme [1], the major security issue is that the shared secret (long-term) key is stored in mobile device without any cryptographic methods. Because of this problem, an adversary can extract and obtain secret credentials using power analysis. According to Section III, we proved that ALAM scheme is vulnerable to various attacks, including
“session key disclosure”, “MITM”, and “impersonation” attacks. In addition, their scheme fails to provide “user anonymity” and “mutual authentication”. Thus, we propose the necessary guidelines to overcome the security flaws of ALAM scheme as also suggested in [8].

- **Guideline 1.** ALAM scheme adopts the two-factor authentication mechanism using the secret credentials and mobile device. However, referring to Section III, the MA is able to impersonate as a mobile user. Thus, ALAM should store the masked secret credentials with password and/or biometric using hash function and bitwise XOR operation to enhance the security level. This will increase the security level of the system.

- **Guideline 2.** In ALAM scheme, the mobile device can use the physical unclonable function (PUF) to prevent physical attacks. PUF-based authentication schemes can resist smart device physical capture attack because an attacker MA cannot access the PUF function even by stealing the smart device [9]–[11].

- **Guideline 3.** ALAM scheme may cause serious security problems in the future because the shared secret (long-term) key is not updated. Therefore, ALAM scheme should periodically update the shared secret (long-term) key to improve the security of the system.

- **Guideline 4.** All participants should securely encrypt and send messages using symmetric keys, because the attacker MA can modify, intercept, delete, and insert the exchanged messages during the mutual authentication phase.

It is worth to note that we do not claim that the guidelines suggested by us as a full-proof solution to the pointed-out drawback of ALAM scheme. However, it will definitely increase the complexity of the malicious adversary MA.

Iqbal et al. would have put best efforts to design a secure protocol for smart home applications. However, they would not have viewed their protocol from the point of view that we have analyzed and proved it. Thus, this comment paper will lead to the design of more secure and efficient authentication protocols for smart home applications.

**V. CONCLUSION**

This comment paper refers to “ALAM: Anonymous Lightweight Authentication Mechanism for SDN Enabled Smart Homes” presented by Iqbal et al. We proved that their scheme is vulnerable to potential attacks such as “impersonation”, “MITM”, and “session key disclosure” attacks. Moreover, their scheme cannot also provide “user anonymity” and “mutual authentication” functionality requirements. After stealing secret credentials stored in mobile device, an adversary can compute the session key between a legitimate user and the controller. Thus, we presented some guidelines to enhance the security flaws of ALAM protocol. Consequently, we can thwart the pointed out security problems not only in ALAM protocol, but we believe that these will be also helpful in other future authentication protocols.

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