On the (in)security of some smart-card-based password authentication schemes for WSN

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Abstract. In this study, we investigate a temporal-credential-based password authentication scheme introduced by Xue et al. in 2012. This protocol only involves hash and XOR operations and thus is suitable for the resource-constrained WSN environments where an external user wants to obtain real-time data from the sensor nodes inside WSN. However, notwithstanding their security arguments, we point out that Xue et al.'s protocol is still vulnerable to smart card security breach attack and privileged insider attack, and fails to provide identity protection. The proposed cryptanalysis discourages any practical use of the scheme under investigation and reveals some subtleties and challenges in designing this type of schemes. Remarkably, using Xue et al.'s scheme as a case study, we further put forward a principle: public-key techniques are indispensable to password-based authentication schemes using non-tamper-resistant smart cards for WSN. We hope that, by following this principle, similar mistakes repeated in the past can be avoided in the future.

Keywords: Wireless sensor networks, Cryptanalysis, Authentication protocol, Smart card, Non-tamper resistant.

1 Introduction

With the rapid development of micro-electromechanical systems and wireless network technologies, wireless sensor networks (WSN) have attracted increasing interest due to its wide range of applications from battlefield surveillance to civilian applications , e.g., environmental monitoring, real-time traffic control, industrial process monitoring and control, healthcare monitoring and home automation. In many critical applications, external users are generally interested in accessing real-time information from sensor nodes. To enable the external users to access the real-time data directly from the desired nodes inside WSN without involving the base station or gateway node when demanded, it is of great concern to protect the users and systems' security and privacy from malicious adversaries. Accordingly, user authentication becomes an essential security mechanism for the user to be first authorized to the nodes as well as the base station (or the gateway node) before allowing the user to access data. Generally speaking, authentication factors are grouped into three categories [26]: 1) what you have (e.g., tokens, smart card, portable storage devices); 2) what you know (e.g., passwords, PINs, private keys); and 3) who you are (e.g., fingerprints, iris). Among the numerous methods based on one or more of these three types, the combination of the first two factors is one of the most popular and effective approaches for authentication in security-critical applications [2] such as e-commerce, e-banking and e-health services.

In 2009, M.L. Das [5] proposed the first password authentication scheme using smart cards to provides mutual authentication between the external user, gateway node and the sensor node. However, shortly after this two-factor authentication [39] scheme was presented, it is found susceptible to various attacks, such as insider attack, impersonation attacks, offline password-guessing attack, GW-node bypassing attack and node compromise attack, by Khan and Alghathbar [14], Chen and Yeh [3] and He et al. [11], respectively. Accordingly, several improvements over Das's two-factor authentication scheme were proposed, typical ones include [3, 11, 14, 23, 40]. Unfortunately, most of these improvements are demonstrated insecure short after they were put forward [10, 21, 29], which outlines the needs for intensive further research.

In 2012, Xue et al. [38] pointed out that previous authentication schemes for real-time data access in WSN have various security flaws being overlooked, and propose a lightweight temporal-credential-based mutual authentication and key agreement scheme for practical use. As with A.K. Das et al.'s scheme [4], this protocol also only involves hash and XOR operations, with no additional symmetric encryption or asymmetric computations, and thus it is very efficient. Although the scheme has been equipped with a long list of heuristic security arguments, we demonstrate that it still cannot achieve the claimed security goals: 1) it is vulnerable to smart card security breach attack; 1) it is vulnerable to privileged-insider attack; 3) it fails to preserve user anonymity; and 4) the registration phase is insecure for no integrity assurance is provided.

The remainder of this paper is organized as follows: in Section 2, we review Xue et al.'s scheme. Section 3 describes the weaknesses of Xue et al.'s scheme. Section 4 discusses the principle learned from the cryptanalysis and Section 5 concludes the paper.

2 Review of Xue et al.'s scheme

In this section, we briefly review the temporal-credential-based two-factor authentication scheme for wireless sensor networks proposed by Xue et al. [38] in 2012. Xue et al.'s protocol also involves three participants, i.e., the user (U_i), the gateway node (GWN) and the sensor node (S_j). It should be noted that GWN is not only responsible for the registration but also involved in the authentication process of U_i and S_j. There are three phases in their protocol: registration, login, authentication and session key agreement. In the following, we employ the notations listed in Table 1 and we will follow the original notations in Xue et al.'s scheme as closely as possible. As we shall see, the descriptions of the scheme are rather tedious, but we manage to go through the jungle of protocol specification and to identify several serious security flaws.

2.1 Registration phase

Before the running of this phase, it is supposed that each user already has a secure password shared with GWN. More precisely, the identity of the user and the hash value of her password have already been stored on GWN side. And each sensor node is also with password pre-configured, the hash of which is stored on GWN side. This phase can be divided into two parts, namely, the user registration and the sensor node registration.

1) **User registration**

Step RU1. U_i gets the current timestamp TS_1, and computes $VI_i = H(TS_1 \parallel H(PW_i))$

Step RU2. $U_i \rightarrow GWN$: $\{ID_i, TS_1, VI_i\}$.

Step RU3. After receiving the registration request, GWN checks the validity of TS_1. If $T^*_{GWN} - TS_1 > \Delta T$, GWN rejects and sends a "REJ" message back to U_i, where T^*_{GWN} denotes the timestamp on GWN side and ΔT is the predefined admissible time-interval. GWN continues to extract $H(PW_i)$ corresponding to ID_i from its background database, then computes $VI^*_i = H(TS_1||H(PW_i))$ and checks whether

Table 1. Notations

Symbol	Description
U_i	i^{th} user
BS	Base station
$\mathcal{A}$	the adversary
CH_j	cluster head in the j-th cluster
ID_i	identity of user U_i
PW_i	password of user U_i
ID_{CH_j}	identity of cluster head CH_j
GWN	the gateway node
S_j	j^{th} sensor node
SID_j	identity of sensor node S_j
K_{GWN-U}	secret parameter only known to GWN
K_{GWN-S}	secret parameter only known to GWN
E/D	symmetric key encryption/decryption algorithm
X_s	secret parameter maintained by BS
X_A	secret parameter shared between the user and BS
y	a secret random number only known to the user
$\oplus$	the bitwise XOR operation
$\|\|$	the string concatenation operation
$h(\cdot)$	collision free one-way hash function
$A \rightarrow B : C$	message C is transferred through a common channel from A to B
$A \Rightarrow B : C$	message C is transferred through a secure channel from A to B

$VI_i^* \overset{?}{=} VI_i$. If the equality does not hold, GWN rejects; otherwise, GWN further computes $P_i = H(ID_i||TE_i)$, $TC_i = H(K_{GWN-U})||P_i||TE_i$ and $PTC_i = TC_i \oplus H(PW_i)$, where TE_i is the expiration time of the temporal credential set by GWN or the trust third party (TTP), K_{GWN-U} is GWN's private key and TC_i is the temporal credential for U_i issued by GWN. At last, GWN personalizes the smart card for U_i with the parameters $\{H(\cdot), ID_i, H(H(PW_i)), TE_i, PTC_i\}$.

Step RU4. $GWN \rightarrow U_i$: A smart card containing security parameters $\{H(\cdot), ID_i, H(H(PW_i)), TE_i, TC_i\}$.

2) **Sensor node registration**

Before the deployment, each sensor node S_j is configured with its identity SID_j and its random password PW_j. After the deployment, the following steps are performed:

Step RS1. Sensor node S_j gets its current timestamp TS_2 and computes $VI_j = H(TS_2||H(PW_j))$.

Step RS2. $S_j \rightarrow GWN : \{SID_j, TS_2, VI_j\}$.

Step RS3. After receiving the registration request, GWN checks whether the transmission delay is within the allowed time interval ΔT. If $T^*_{GWN} - TS_2 > \Delta T$, GWN sends a "REJ" message back to S_j, where T^*_{GWN} is the current timestamp on GWN side. Otherwise, GWN continues to extract $H(PW_j)$ corresponding to SID_j from its background database. Then, GWN computes $VI_j^* = H(TS_2||H(PW_j))$ and verifies whether $VI_j^* \overset{?}{=} VI_j$. If the equality does not hold, GWN rejects; otherwise, GWN further computes $TC_j = H(K_{GWN-S}||SID_j)$, $REG_j = H(H(PW_j)||TS_3) \oplus TC_j$, where TS_3 is the current timestamp on GWN side, K_{GWN-S} is GWN's private key and TC_j is the temporal credential for S_j issued by GWN. Then GWN sends TS_3 and REG_j to the sensor node S_j.

Step RS4. $GWN \rightarrow S_j : \{TS_3, REG_j\}$.

Step RS5. After receiving the response from *GWN*, S_j first checks the validity of TS_3 and then computes its temporal credential $TC_j = REG_j \oplus H(H(PW_j)||TS_3)$, and stores TC_j in its memory.

2.2 Login phase

When user U_i wants to login to S_j, the following operations will be performed:

Step L1. U_i inserts her smart card into a card reader and inputs her identity ID_i^* and password PW_i^*.

Step L2. The smart card verifies whether the input ID_i^* equals the stored ID_i and whether $h(PW_i^*)$ equals the stored $h(PW_i)$. If both verifications hold, it indicates that U_i is a legal card holder. Then, the smart card computes $TC_i = PTC_i \oplus H(PW_i)$.

2.3 Authentication and session key agreement phase

This phase aims to achieve the goal of mutual authentication among U_i, GWN and S_j. Meanwhile, a session key is negotiated between U_i and S_j.

Step A1. U_i gets the current timestamp TS_4 and chooses a random number K_i. Then U_i computes $DID_i = ID_i \oplus H(TC_i \| TS_4)$, $C_i = H(H(ID_i \| TS_4) \oplus TC_i)$ and $PKS_i = K_i \oplus H(TC_i \| TS_4 \| \text{“}000'')$. It should be noted that $H(TC_i \| TS_4 \| ''000'')$ is different from $H(TC_i \| TS_4)$, which is ensured by the feature of hash function.

Step A2. $U_i \rightarrow GWN$: $\{DID_i, C_i, PKS_i, TS_4, TE_i, P_i\}$.

Step A3. GWN first checks the validity of TS_4 and computes $ID_i = DID_i \oplus H(H(K_{GWN-U} \|P_i\|TE_i)\|TS_4), P_i^* = H(ID_i\|TE_i)$, $TC_i = H(K_{GWN-U} \parallel P_i^* \| TE_i)$ and $C_i^* = H(H(ID_i^*)||TS_4) \oplus TC_i^*$.

Step A4. GWN checks whether $C_i^* \neq C_i$ or $P_i^* \neq P_i$. If either check holds, the authentication request is rejected. Otherwise, GWN accepts U_i's login request and computes $K_i = PKS \oplus H(TC_i||TS_4||''000'')$.

Step A5. GWN chooses a nearby suitable sensor node as the accessed sensor node, say S_j, whose identity is SID_j, and computes $TC_j = H(K_{GWN-S} \parallel SID_j)$, $DID_{GWN} = ID_i \oplus H(DID_i \parallel TC_j \| TS_5)$, $C_{GWN} = H(ID_i \parallel TC_j \parallel TS_5)$ and $PKS_{GWN} = K_i \oplus H(TC_j \parallel TS_5)$, where TS_5 is the current timestamp.

Step A6. $GWN \rightarrow S_j : \{TS_5, DID_i, DID_{GWN}, C_{GWN}, PKS_{GWN}\}$

Step A7. After receiving the message from *GWN*, S_j checks the validity of TS_5. If it is not valid, the session is terminated. Otherwise, S_j computes $ID_i = DID_{GWN} \oplus H(DID_i||TC_j||TS_5)$ and $C^*_{GWN} = H(ID_i||TC_j\| TS_5)$. If $C^*_{GWN} \neq C_{GWN}$, S_j rejects. Otherwise, S_j is confirmed that the received message is from the legitimate *GWN*, and computes $K_i = PKS_{GWN} \oplus H(TC_j||TS_5)$. Then S_j gets the current timestamp TS_6 and chooses a random number K_j. Then S_j computes $C_j = H(K_j||D_i|| SID_j||TS_6)$ and $PKS_j = K_j \oplus H(K_i||TS_6)$.

Step A8. $S_j \rightarrow U_i, GWN : \{SID_j, TS_6, C_j, PKS_j\}$

Step A9. After receiving the response from S_j and checking the validity of TS_6, U_i and GWN can separately compute $K_j = PKS_j \oplus H(K_i||TS_6)$ and $C_j^* = H(K_j||ID_i||SID_j||TS_6)$. For GWN, if $C_j^* = C_j$, it is confirmed that S_j is a legitimate sensor node. For the user U_i, if $C_j^* = C_j$, she is confirmed that both S_j and GWN are legitimate. U_i and S_j can separately compute the shared session key $KEY_{ij} = H(K_i \oplus K_j)$.

Finally, the user U_i and the sensor node S_j agree on a common session key $SK = H(K_i \oplus K_j)$ for securing ensuing data communications.

3 Cryptanalysis of Xue et al.'s scheme

There are four assumptions explicitly made in Xue et al.'s scheme [4]:

(i) The sensitive data stored in the sensor nodes as well as cluster heads can be revealed once they are captured by an adversary $\mathcal{A}$.
(ii) The secret parameters stored in the smart card can be revealed once a legitimate user's smart card is somehow obtained (e.g. picked up or stolen) by $\mathcal{A}$.
(iii) $\mathcal{A}$ has total control over the communication channel among the user U_i, the base station BS and the cluster head CH_j. In other words, the attacker can intercept, block, delete, insert or alter any messages exchanged in the channel.
(iv) The user-memorable identities and passwords are weak, i.e., of low entropy.

Note that the above four assumptions, which are also made in the latest works [3, 11, 14, 20, 21, 23, 40], are indeed reasonable: (1) Assumptions *i* and *ii* are practical when taking the state-of-the-art side-channel attack techniques [12, 18, 25] into consideration; (2) Assumption *iii* is consistent with the common adversary model for distributed computing [36]; and (3) Assumption *iv* reveals the reality that users are allowed to choose their passwords at will during the password change phase and registration phase, and the users are usually apt to choose passwords that are related to their personal life [8], such as meaningful dates, phone numbers or license plate numbers, and the human-memorable passwords tends to be "weak passwords" [7, 13, 17]. User's identity, chosen in the way with the password, is often confined to a predefined format and kept static in its entire life-cycle, and thus it is as weak as (maybe weaker than) user's password.

In the following discussions of the security pitfalls of Xue et al.'s scheme, based on the above four assumptions, we assume that an adversary can extract the secret parameters $\{H(\cdot), ID_i, H(H(PW_i)), TE_i, TC_i\}$ stored in the legitimate user's smart card, and could also intercept or block the exchanged messages $\{DID_i, C_i, PKS_i, TS_4, TE_i, P_i, TS_5, DID_i, DID_{GWN}, C_{GWN}, PKS_{GWN}\}$ during the login and authentication processes. Although Xue et al.'s scheme has many attractive properties, such as provision of mutual authentication between the external user, gateway node and sensor node, high efficiency and key agreement, it fails to achieve many of the claimed security goals: 1) it cannot provide identity protection; 2) it is susceptible to smart card security breach attack (stolen smart card attack); 3) it cannot withstand privileged-insider attack; 4) the registration phase is vulnerable as there is no integrity assurance provided.

3.1 No provision of identity protection

A protocol with identity protection protects an individual's sensitive personal information, such as social circle, preferences, lifestyles, shopping patterns, etc., from being acquired by an adversary through analyzing the login information, the services or the resources being accessed [1,37]. Moreover, in mobile environments, the leakage of user-specific information may facilitate an unauthorized entity to track the user's current location and login history [30]. Hence, identity protection is a highly admired feature of remote user authentication schemes.

To provide identity protection, a feasible approach is to adopt the "dynamic ID technique" [6, 35]: a user's real identity is concealed in the session-variant pseudo-identities. Authentication schemes that employ this technique are the so-called "dynamic-ID" schemes. And Xue et al.'s scheme falls into this category. However, the following offline identity guessing attack demonstrates that this scheme actually cannot provide identity protection.

Step 1. Intercepts a login request message, say $\{DID_i, C_i, PKS_i, TS_4, TE_i, P_i\}$, sent by U_i;

Step 2. Guesses the value of ID_i to be ID_i^* from a dictionary space $\mathcal{D}_{id}$.
Step 3. Computes $P_i^* = h(ID_i^* \| TE_i)$, where TE_i is intercepted as in Step 1.
Step 4. Verifies the correctness of ID_i^* by checking if the computed P_i^* is equal to the intercepted P_i.
Step 5. Repeats the above steps until the correct value of ID_i is found.

Let $|\mathcal{D}_{id}|$ denotes the number of identities in $\mathcal{D}_{id}$. The running time of the above attack procedure is $\mathcal{O}(|\mathcal{D}_{id}| * T_H)$, where T_H is the running time for Hash operation. Since users' identities are human-memorable short strings but not high-entropy keys, that is to say, they are often drawn from a dictionary of small size. What's more, user's identity is static and often confined to a predefined format, and it is more easily guessed than user's password. As $|\mathcal{D}_{id}|$ is very limited in practice, e.g. $|\mathcal{D}_{id}| \leq |\mathcal{D}_{pw}| \leq 10^6$ [7, 17], the above attack can be completed in polynomial time. Note that, in this user-identity breach attack, the adversary only needs to keep an eye over the public channel and it does not involve any special cryptographic operations (e.g., power analysis). In this regard, the proposed attack is very practical and effective.

3.2 Smart card security breach attack

Let us consider the following scenarios. In case a legitimate user U_i's smart card is stolen by the adversary $\mathcal{A}$, and the stored secret parameters $H(\cdot), ID_i$ and $H(H(PW_i))$ can be extracted. Note that this assumption is reasonable as described in Assumption *ii* and it is also explicitly made in Xue et al.'s scheme. With the extracted $H(H(PW_i))$, $\mathcal{A}$ can successfully guess the password of U_i as follows:

Step 1. Guesses the value of PW_i to be PW_i^* from a dictionary space $\mathcal{D}_{pw}$.
Step 2. Computes $HK^* = H(H(PW_i^*))$.
Step 3. Verifies the correctness of PW_i^* by checking if the computed HK^* is equal to the received $H(H(PW_i))$.
Step 4. Repeats the above steps until the correct value of PW_i is found.

Let $|\mathcal{D}_{pw}|$ denote the number of passwords in the password space $\mathcal{D}_{pw}$. Then the running time of the attacker $\mathcal{A}$ is $\mathcal{O}(|\mathcal{D}_{pw}| * 2T_H)$, where T_H is the running time for Hash operation. So, the time for $\mathcal{A}$ to recover U_i's password is a linear function of the number of passwords in the password space. Since the password space is limited in practice, e.g., $|\mathcal{D}_{pw}| = 10^6$ [7, 17], U_m may recover the password in seconds on a PC.

3.3 Privileged-insider attack

As U_i simply submits the hashed value of her password, i.e. $H(H(PW_i))$, to the gateway node GWN in the registration phase, a privileged-insider of GWN can easily derive U_i's password PW_i using the same attack procedure with above smart card security breach attack.

Now, if U_i uses this PW_i to access other systems for her convenience, the malicious insider can impersonate U_i to login by abusing the legitimate users password and thus gets access to other systems [19]. Therefore, Xue et al.'s scheme is susceptible to privileged-insider attack.

3.4 No integrity assurance in the registration phase

In [38], Xue et al. explicitly stated that, in the registration phase, U_i and S_j communicate with GWN " in an open and public environment." In the light of this statement, we find there is no integrity assurance in the registration phase: take Step RS4 for example, what will happen if an attacker intercepts $\{TS_3, REG_j\}$ and substitutes REG_j with a random value X? It is not difficult to see that, on receiving $\{TS_3, X\}$, S_j will find no abnormality for there is no integrity check. As a result, S_j will unwittingly compute and store the wrong TC_j, and the subsequent authentication involving S_j will never succeed.

4 The public-key principle for two-factor authentication in WSN

Since sensor nodes and smart cards are typically resource-constrained devices, the protocol designers are faced with the hard task of reconciling security, efficiency and functionality requirements, and often must make design decisions that are seemingly well motivated but may have unintended consequences. As it is widely accepted that the traditional certificate-based authentication schemes are not suitable for WSN and asymmetric cryptographic operations (e.g., modular exponentiation and Elliptic Curve point multiplication) are comparatively expensive, most two-factor authentication schemes for WSN (e.g., [3–5, 11, 20, 22, 23, 31, 38, 38, 41, 42]) swing to the other extreme: they attempt to only adopt non-public-key techniques (e.g., hash functions, symmetric encryptions, XOR operations, MAC operations) to reduce the computational complexity, communication cost and storage overhead while fulfilling the stringent security requirements. However, according to our protocol cryptanalysis experience, this strategy is inviable under the non-tamper resistance assumption of the smart cards.

We have analyzed more than eighty recently proposed smart-cards-based password authentication schemes (some of our cryptanalysis results include [24,32–37], and observed that schemes that do not employ public-key techniques are definitely vulnerable to the smart card security breach attack when the smart cards are assumed to be non-tamper resistant. In other words, all these schemes that only employ non-public-key techniques but claim to be secure against smart card security breach attack are found problematic, some quite recent typical examples include [3, 5, 11, 14, 16, 27, 28].

We show that this is no accident. It is crucial to notice that, under the non-tamper resistance assumption of the smart cards, all the security parameters stored in the smart card can be extracted [12, 18, 25] and thus the smart-card-based password authentication scheme is downgraded to a traditional one-factor (i.e., only password-based) authentication scheme. That is to say, the security of the scheme now only relies on the security of the password. In a seminal work [9], Halevi and Krawczyk investigate the basic principle for constructing secure password-based authentication (the traditional one-factor password authentication) protocols, and provide very strong evidence (with a probability of $\boldsymbol{P \neq NP}$) that, under the common distributed computing adversary model, no password protocol can be free from offline password guessing attack if only symmetric cryptographic primitives are involved. Accordingly, we come to the conjecture that, under the non-tamper resistance assumption of the smart cards, no smart-card-based password protocol (i.e., two-factor authentication [39]) can withstand smart card security breach attack (offline password guessing attack) if the public-key techniques are not employed.

By following this principle, one can easily identify that all these newly proposed two-factor schemes for WSN [4, 20, 22, 23, 31, 38, 41, 42], which are only based on symmetric cryptographic primitives, are inherently unable to withstand smart card security breach attack (offline password guessing attack). To the best of our knowledge, most of these schemes were just made online and have not been cryptanalzed elsewhere. Some of them, like [22,31,41] even have been equipped with a formal security proof. And now the countermeasure is obvious: resorting to public-key techniques like [15, 33, 40].

5 Conclusion

In this paper, we have analyzed an efficient password-based authentication scheme using smart cards for WSN without employing any public-key techniques. This scheme is equipped with a claimed proof of security, however, we pointed out that it has various security defects being overlooked. Although there have been ample of works on the security analysis of two-factor authentication schemes for WSN, little (or even no) rationale is given and thus similar mistakes are repeated over and over again. To alleviate this situation, through the cryptanalysis of Xue et al.'s scheme and based on our protocol cryptanalysis experience, we put forward one principle that is helpful to explicate many of the security failures repeated in the past and vital for designing more robust two-factor authentication schemes for WSN in the future.

Acknowledgments. This research was in part supported by the National Natural Science Foundation of China (NSFC) under Grants No. 61170241 and No. 61073042, and the open program of State Key Laboratory of Networking and Switching Technology under Grant No. SKLNST-2009-1-10.

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