# Cryptanalysis of an Efficient Biometric Authentication Protocol for Wireless Sensor Networks

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**Abstract.** In 2013, Althobaiti et al. proposed an efficient biometric-based user authentication scheme for wireless sensor networks. We analyze their scheme for the security against known attacks. Though their scheme is efficient in computation, in this paper we show that their scheme has some security pitfalls such as (1) it is not resilient against node capture attack, (2) it is insecure against impersonation attack, (3) it is insecure against man-in-the-middle attack, and (4) it is also insecure against privileged insider attack. Finally, we give some pointers for improving their scheme so that the designed scheme needs to be secure against various known attacks.

**Keywords:** Wireless sensor networks, User authentication, Smart cards, Biometrics, Cryptanalysis.

## 1 Introduction

In a wireless sensor network (WSN), a large number of tiny computing nodes, also called sensors or motes, are scattered in an area (called the deployment field or target field) for the purpose of sensing some important information and transmitting those sensing information to the nearby *base stations* for further processing. Sensor nodes are generally deployed densely in a close proximity to the phenomenon to be monitored. A sensor node is a node in a WSN that is capable of performing some processing, gathering sensory information and communicating with other connected sensor nodes in that network. Sensor nodes communicate among each other by short range radio communications. The base station is usually a computationally well-equipped node in the network, whereas the sensor nodes are extremely resource-starved. The sensor nodes are scattered in a *sensor field* (i.e., deployment area or target field) and each of the scattered nodes has the capability to collect data and route data back to the base station via a multi-hop infrastructure-less communication through other sensor nodes.

Sensor networks are widely deployed in a variety of applications ranging from military to environmental and medical research. In many applications, such as target tracking, battlefield surveillance and intruder detection, WSNs often operate in hostile and unattended environments. Therefore, there is a strong need

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for protecting the sensing data and sensing readings. In wireless environments, an adversary not only can eavesdrop the radio traffic, but also has the ability to intercept or interrupt the exchanged messages. Thus, many protocols and algorithms do not work in hostile environments without adequate security measures. Hence, security becomes one of the major concerns when there are potential attacks against sensor networks. A survey on wireless sensor networks and the security issues could be found in [1], [3], [4], [6], [18].

Critical applications in wireless sensor network (WSN) are real-time based applications. Therefore, users are generally interested in accessing real-time information [9]. This is possible, if the users (called the external parties) are allowed to access the real-time data directly from the nodes inside WSN and not from the base station. The sensory information from nodes are gathered periodically in the base station and so, the gathered information may not be real-time. In order to get the real-time information from the nodes, the user needs to be first authorized to the nodes as well as the base station so that illegal access to nodes do not happen. As a result, the user authentication problem becomes a very important topic in research of WSN security in recent years.

Several password-based user authentication schemes have been proposed in the literature [5], [12], [13], [14], [16], [20], [22]. However, most of these schemes are insecure against various known attacks. Das et al. [9] proposed a novel and efficient password-based user authentication scheme for the hierarchical wireless sensor networks. Their scheme was shown to be secure against various known attacks including the replay and man-in-the-middle attacks with the help of formal security verification [7]. Further, an improved version of Das et al.'s scheme [9] has been proposed in [21] in the literature. Recently, biometric-based user authentication in WSNs has drawn a considerable research attention. Thus, the biometric-based user authentication in WSN becomes inherently more reliable and secure than usual traditional password-based user authentication schemes. Yuan et al.'s biometric-based user authentication scheme [23] provides better security as compared to that for M. L. Das's scheme [10] because the former scheme uses biometrics verification along with the password verification of the user. Yuan et al.'s scheme [23] has same drawbacks as in M. L. Das's scheme [10]. However, their scheme cannot resist denial-of-service attack and node compromise attack. Das et al. proposed a new secure biometric-based user authentication scheme in hierarchical wireless body area sensor networks [8]. Althobaiti et al. [2] proposed an efficient biometric-based user authentication scheme for WSNs. Unfortunately, we show that their scheme has several security pitfalls and as a result, their scheme is not practical to use for the real-life WSN applications.

The roadmap of this paper is sketched as follows. In Section 2, we describe the Althobaiti et al.'s scheme [2]. We then show that Althobaiti et al.'s scheme is insecure against four attacks in Section 3. In Section 4, we point out some suggestions to improve Althobaiti et al.'s scheme in order to withstand those security pitfalls. Finally, we conclude the paper in Section 5.

## 2 Review of Althobaiti et al.'s Scheme

In this section, we briefly review the recently proposed Althobaiti et al.'s biometric based user authentication scheme in wireless sensor networks [2]. The different phases of their scheme are discussed in the following subsections. We use the notations listed in Table 1 for describing and analyzing Althobaiti et al.'s scheme.

**Table 1.** The notations used in this paper

| Symbol | Explanation |
|---|---|
| $U_i$ | $i^{th}$ user |
| $SN_j$ | Identity of the $j^{th}$ sensor node $SN_j$ |
| $X$ | Secret information shared by GW-node and all deployed sensor nodes |
| $E_k(\cdot)$ | Symmetric encryption using the key $k$ |
| $D_k(\cdot)$ | Symmetric decryption using the key $k$ |
| $MAC_k(m)$ | Message authentication code of $m$ using the key $k$ |
| $h(\cdot)$ | Secure one-way collision-resistant hash function |
| $A\|\|B$ | Data $A$ concatenates with data $B$ |
| $A \oplus B$ | Data $A$ is bitwise XORed with data $B$ |

### 2.1 Registration Phase

For the registration of a user $U_i$, the system randomly selects an encryption key, say $ek_i$, and it is saved in the GW-node or the base station (BS) as a key of $U_i$. The features of $U_i$'s biometric (for example, iris) are extracted and then hashed by the one-way hash function $h(\cdot)$ (for example, SHA256 [19]). After that the hash digest is XORed with the key $ek_i$ in order to generate BE template, which is then saved in $U_i$'s device. In this phase, the user $U_i$'s data (identity $ID_i$, name, etc.) and $ek_i$ are saved in the GW-node's database. The GW-node computes $F_i = h(ID_i \oplus X)$, where $X$ is a secret parameter generated by the GW-node and it is also saved in all the sensor nodes $SN_j$ (the sensor login-nodes) before the deployment of those sensor nodes in a particular target field. Finally, the GW-node sends the registration message $\langle ID_i, F_i \rangle$ to the user $U_i$ via a secure channel. In this scheme, as in M. L. Das's scheme [10], all the deployed sensor nodes $SN_j$ are responsible to respond to the data/query that the users $U_i$ are looking for and know the secret parameter $X$. Note that $U_i$'s device contains the information $\{ID_i, F_i, h(ek_i), BE\}$, where $BE = h(biometric\_feature) \oplus ek_i$.

### 2.2 Login Phase

The user $U_i$ first inputs his/her identity $ID_i$ and personal biometric, iris by camera in the device. The biometric features of $U_i$'s iris are extracted, corrected by error correcting code, and then hashed by SHA256. After that the hashed value is XORed with saved BE template in the $U_i$'s device in order to regenerate the encryption key $ek_i$ as $ek'_i = BE \oplus h(biometric\_feature)$. Then $ek'_i$ is hashed and $h(ek_i)$ stored in the device is compared with $h(ek'_i)$. If there is a match, a login request $\langle ID_i, request\rangle$ is sent to the GW-node along with $ID_i$ via a public channel. Otherwise, the login phase is terminated immediately.

### 2.3 Authentication Phase

After receiving the login request from $U_i$, the GW-node replies to the user $U_i$ with the authentication request $\langle R\rangle$, where $R$ is a random challenge. When $U_i$ receives the message from the GW-node, $U_i$ encrypts $R$ and $T_1$ with the encryption key $ek_i$ derived in the login phase, where $T_1$ is the current timestamp of $U_i$'s device, and sends the message $\langle E_{ek_i}(R, T_1)\rangle$ to the GW-node via a public channel.

After receiving the message from $U_i$, the GW-node decrypts the message using the encryption key $ek_i$ stored in the GW-node and checks if $|T_1 - T_2| < \Delta T$, where $\Delta T$ denotes the interval of the expected time for the transmission delay in WSN and $T_2$ the time when the message was received. If it is invalid, the authentication phase is terminated immediately.

The GW-node computes $F_i = h(ID_i \oplus X)$ and $Y_i = MAC_{F_i}(ID_i||SN_j||T_3)$, where $SN_j$ denotes the sensor node which is supposed to reply to the query made by the user $U_i$, and $T_3$ is the GW-node's current timestamp. The GW-node then sends the message $\langle ID_i, Y_i, T_3\rangle$ to $SN_j$ via a public channel.

When $SN_j$ receives the message from the GW-node, $SN_j$ checks the validity of $T_3$ by verifying the condition $|T_3 - T_4| < \Delta T$, where $T_4$ is the time when the message was received. If the condition is valid, $SN_j$ computes $F_i = h(ID_i \oplus X)$, $Y'_i = MAC_{F_i}(ID_i||SN_j||T_3)$ and checks if $Y'_i = Y_i$. If it holds, $SN_j$ responds to the $U_i$'s query (RM), computes $V_i = h(ID_i||F_i||T_5)$, $C_i = h(RM)$ and $L = E_{V_i}(RM, C_i)$, and then sends the message $\langle L, T_5\rangle$ to the user $U_i$ via a public channel, where $T_5$ is the $SN_j$'s current timestamp.

Finally, when the user $U_i$ receives the message from $SN_j$ at time $T_6$, $U_i$ first validates by checking whether $|T_5 - T_6| < \Delta T$, and if it is valid then $U_i$ computes $V_i = h(ID_i||F_i||T_5)$. After that $U_i$ decrypts $L$ to retrieve $RM$ and $C_i$ as $(RM', C'_i) = D_{V_i}(L)$, and then computes $C^*_i = h(RM')$. If $C^*_i = C'_i$, $U_i$ accepts $RM$ as a valid query response from $SN_j$. Otherwise, $U_i$ rejects $RM$. Note that in this scheme $V_i = h(ID_i||F_i||T_5)$ is considered as a session key between $U_i$ and $SN_j$.

The summary of the login phase and authentication phase of Althobaiti et al.'s scheme is provided in Table 2.

## 3 Cryptanalysis of Althobaiti et al.'s Scheme

In this section, we first give a threat model in Section 3.1 under which the security of WSN is generally evaluated. After that we show that Althobaiti et al.'s scheme is insecure against four attacks, which are described in Section 3.2.

**Table 2.** Summary of exchanged messages in the login and authentication phases

| User $U_i$ | GW-node | Sensor $SN_j$ |
|---|---|---|
| *Login phase* | | |
| $\xrightarrow{\langle ID_i, request\rangle}$ | | |
| *Authentication phase* | | |
| | $\xleftarrow{\langle \text{A random challenge, } R\rangle}$ | |
| $\xrightarrow{\langle E_{ek_i}(R, T_1)\rangle}$ | | |
| | $\xrightarrow{\langle ID_i, Y_i, T_3\rangle}$ | |
| Receives $\langle L, T_5\rangle$ from $SN_j$ | | $\xleftarrow{\langle L, T_5\rangle}$ |

### 3.1 Threat Model

For evaluating the security analysis of Althobaiti et al.'s scheme, we use the threat model as follows. In most applications, sensor networks operate in the hostile environments. We assume that sensor nodes can be physically captured by an attacker. Sensor nodes are not usually equipped with tamper-resistant hardware due to cost constraints and as a result, once a node is captured by an attacker, all the sensitive data as well as cryptographic information stored in its memory are revealed to the attacker. Even if the sensor nodes are tamper-resistant, an attacker can still know all the sensitive information stored in their memory by monitoring the power consumption of the captured sensor nodes [15], [17]. However, we assume that in any case, the base station or gateway node (GW) will not be compromised by an attacker. As in [10], we make use of the Dolev-Yao threat model [11] in which two communicating parties (nodes) communicate over an insecure public channel. We adopt the similar threat model for WSNs where the channel is insecure and the end-points (sensor nodes) cannot in general be trustworthy. Finally, we assume that an attacker can eavesdrop on all traffic, inject packets and reply old messages previously delivered.

### 3.2 Attacks on Althobaiti et al.'s Scheme

In this section, we show that Althobaiti et al.'s scheme is insecure against the following attacks.

**Resilience against Node Capture Attack.** As described in [9], the resilience against node capture attack of a user authentication scheme in WSN is measured by estimating the fraction of total secure communications that are compromised by a capture of $c$ sensor nodes *not including* the communication in which the compromised nodes are directly involved. In other words, we want to find out the effect of $c$ sensor nodes being compromised on the rest of the network. For example, for any non-compromised sensor node $SN_j$, we need to find out the probability that the adversary can decrypt the secure communication between

$SN_j$ and a user $U_i$, when $c$ sensor nodes are already compromised by the adversary. If we denote this probability by $P_e(c)$, and $P_e(c) = 0$, we call such user authentication scheme as *unconditionally secure against node capture attack.*

Suppose an adverasry (attacker) captures a login-sensor node, say $SN_j$. Then the adversary knows the secret parameter $X$ stored in the sensor $SN_j$'s memory and the GW-node. Intercepting the messages $\langle ID_i, Y_i, T_3 \rangle$ and $\langle L, T_5 \rangle$ during the authentication phase, the adversary can compute $F_i = h(ID_i \oplus X)$ and $V_i = h(ID_i||F_i||T_5)$, which is the session key between a user $U_i$ and the sensor $SN_j$. Hence, the adversary knows the session key $V_i$. We now show that the adversary has the ability to compromise all the session keys between $U_i$ and any other non-compromised sensor node $SN'_j$ as follows. Let the GW-node send the message $\langle ID_i, Y'_i, T'_3 \rangle$ to $SN'_j$ and the sensor $SN'_j$, which is a non-compromised node, send the message $\langle L', T'_5 \rangle$ during the authentication phase, where $F_i = h(ID_i \oplus X)$, $Y'_i = MAC_{F_i}(ID_i||SN'_j||T'_3)$, $C'_i = h(RM)$, $V'_i = h(ID_i||F_i||T'_5)$ and $L' = E_{V'_i}(RM, C'_i)$. Since the adversary knows $X$, $ID_i$ and $T'_5$, so he/she can easily derive the session key $V'_i = h(ID_i||F_i||T'_5)$. It is then clear that the adversary can derive all the session keys between $U_i$ and any non-compromised sensor node $SN'_j$ even if a single login-sensor node is already compromised in WSN. As a result, compromise of a single sensor node leads to comprmise the successful decryptions of all secure communications between $U_i$ and any non-compromised sensor $SN'_j$. Thus, we have $P_e(c) = 1.0$. Hence, Althobaiti et al.'s scheme is not at all resilient against node capture attack.

**Impersonation Attack.** In this attack, we show that an adversary $\mathcal{A}$ can impersonate the GW-node to a login sensor node. The detailed description is as follows. Suppose $\mathcal{A}$ physically captures a login-sensor node, say $SN_j$. $\mathcal{A}$ then knows the secret parameter $X$ from the catured node $SN_j$. $\mathcal{A}$ also intercepts the message $\langle ID_i, Y_i, T_3 \rangle$ during the authentication phase. Let $\mathcal{A}$ wish to impersonate the GW-node to another non-compromised login-sensor node $SN'_j$. For this purpose, $\mathcal{A}$ can compute $F'_i = h(ID_i \oplus X)$ and $Y'_i = MAC_{F'_i}(ID_i||SN'_j||T'_3)$, where $SN'_j$ denotes the sensor node from which the user $U_i$ is expecting the reponse of the query, and $T'_3$ is the current timestamp of the adversary $\mathcal{A}$'s system. $\mathcal{A}$ then sends the message $\langle ID_i, Y'_i, T'_3 \rangle$ to $SN'_j$ via a public channel. After receiving the message, $SN'_j$ checks checks the validity of $T'_3$. If it is valid, $SN'_j$ computes $F_i = h(ID_i \oplus X)$, $Y^*_i = MAC_{F_i}(ID_i||SN'_j||T'_3)$ and checks the condition $Y^*_i = Y'_i$. If it holds, $SN'_j$ responds to the user $U_i$'s query $(RM')$, computes the session key $V'_i = h(ID_i||F_i||T'_5)$, $C'_i = h(RM')$ and $L' = E_{V'_i}(RM', C'_i)$, where $T'_5$ is the current timestamp of $SN'_j$, and finally sends the message $\langle L', T'_5 \rangle$ to $U_i$ via a public channel. Note that in this case, $\mathcal{A}$ can also derive the session key $V'_i$ using $X$, $ID_i$ and $T'_5$. As a result, Althobaiti et al.'s scheme fails to protect the impersonation attacks.

**Man-in-the-Middle Attack.** In this attack, an adversary $\mathcal{A}$ tries to modify, delete or change the contents of the messages in such a way that the login-sensor nodes as well as the user $U_i$ can not detect them. Assume that $\mathcal{A}$ captures a login-sensor node and then he/she knows the secret parameter $X$ from its memory. Suppose the GW-node sends the message $\langle ID_i, Y_i, T_3 \rangle$ to a login-sensor node $SN_j$ from which the user $U_i$ wants to get the response of the query. The adversary $\mathcal{A}$ intercepts this message, computes $F_i^* = h(ID_i \oplus X)$ using $ID_i$ and extracted $X$, $Y_i^* = MAC_{F_i^*}(ID_i||SN_j||T_3^*)$, where $T_3^*$ is the current timestamp of the adversary $\mathcal{A}$'s system, and sends the modified message $\langle ID_i, Y_i^*, T_3^* \rangle$ to the sensor node $SN_j$ instead of the original message $\langle ID_i, Y_i, T_3 \rangle$ via a public channel.

After receiving the message from $\mathcal{A}$, $SN_j$ believes that the message comes from the GW-node and proceeds to validate the timestamp $T_3^*$ and if it is valid, $SN_j$ computes $F_i = h(ID_i \oplus X)$, $Y_i^{**} = MAC_{F_i}(ID_i||SN_j||T_3^*)$ and checks the condition $Y_i^{**} = Y_i^*$. If it holds, $SN_j$ responds to the $U_i$'s query $(RM^*)$ by computing the session key shared with the user $U_i$ as $V_i^* = h(ID_i||F_i||T_5^*)$, $C_i^* = h(RM^*)$ and $L^* = E_{V_i^*}(RM^*, C_i^*)$, and then sendsing the message $\langle L^*, T_5^* \rangle$, where $T_5^*$ is the current timestamp of $U_i$'s device. $\mathcal{A}$ again intercepts the message $\langle L^*, T_5^* \rangle$. $\mathcal{A}$ computes $V_i^{**} = h(ID_i||F_i^*||T_5^*)$ and decrypts $L^*$ to retrive $RM^*$ and $C_i^*$. Note that $\mathcal{A}$ now knows the reponse to the query, $RM^*$ which is intended for $U_i$ only. However, $\mathcal{A}$ can create a totally face response $RM^{**}$ to the query instead of the original $RM^*$, and compute $C_i^{**} = h(RM^{**})$ and $L^{**} = E_{V_i^{**}}(RM^{**}, C_i^{**})$. Finally, $\mathcal{A}$ can send the modfied message $\langle L^{**}, T_5^* \rangle$ to the user $U_i$. It is noted that this message is successfully authenticated by the user $U_i$, and hence $U_i$ treats $RM^{**}$ as a valid response to his/her query. Thus, it is clear that Althobaiti et al.'s scheme fails to protect the man-in-the-middle attack.

**Privileged Insider Attack.** During the registration phase of Althobaiti et al.'s scheme, the GW-node generates a random encryption key $ek_i$ for a registered user $U_i$, which is stored directly in the GW-node's database. Note that $ek_i$ is used to encrypt a random challenge $R$ and timestamp $T_1$. As a result, an insider attacker of the GW-node can easily use $ek_i$ to forge the user $U_i$. Thus, Althobaiti et al.'s scheme fails to preserve the privileged insider attack.

## 4 Discussions

From the cryptanalysis of Althobaiti et al.'s scheme discussed in Section 3.2, it is clear that their scheme becomes insecure due to the fact that the master secret parameter $X$ is stored in every deployed sensor node, which is also shared with the GW-node as in M. L. Das's scheme [10]. As a remedy, one solution could be to generate a unique random master key $MK_{SN_j}$ for each sensor node $SN_j$ in WSN by the GW-node in offline, and then only $MK_{SN_j}$ needs to be preloaded in the sensor node $SN_j$'s memory prior to its deployment in the target field and also in the GW-node as pointed out in Das et al.'s scheme [9]. This strategy will certainly help to improve significantly the resilience against node capture attack, because compromise of a sensor node only reveals its master key, not the master keys of any other non-compromised sensor nodes. As a consequence, other attacks will also be eleminated. To avoid the privileged insider attack, the user $U_i$ must not share the encryption key $ek_i$ with the GW-node. In future, we aim to propose an improvement on Althobaiti et al.'s scheme in order to withstand the security waeknesses found in their scheme.

## 5 Conclusion

In this paper, we have first reviewed the recently proposed Althobaiti et al.'s scheme suited for WSNs. Althobaiti et al.'s scheme is efficient in computation. Unfortunately, we have shown that their scheme is insecure against several known attacks. Thus, their scheme is not suitable for practical application in WSNs. In addition, we have suggested some strategies in order to remedy the security weaknesses found in their scheme.

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