http://dx.doi.org/10.5755/j01.eee.19.6.2038 ELEKTRONIKA IR ELEKTROTECHNIKA, ISSN 1392-1215, VOL. 19, NO. 6, 2013

An Improved Dynamic Password-based User Authentication Scheme for Hierarchical Wireless Sensor Networks

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***Abstract*—User authentication is an important issue in wireless sensor networks. Das et al. recently proposed a dynamic password-based user authentication scheme for hierarchical wireless sensor networks, which provides high security and a simple authentication approach. In this paper we present a flaw in Das et al.'s scheme that makes it infeasible for real-life implementation. Additionally, we demonstrate that Das et al.'s scheme has redundant elements. To overcome these imperfections we propose an enhanced user authentication scheme based on Das et al.'s, which is both efficient and secure.**

***Index Terms*—Password-based, user authentication, smart card, wireless sensor networks.**

I. INTRODUCTION

Wireless sensor networks (WSNs) have become very popular and are being used in variety of applications (e.g., military, health, environment, etc.) [1]. The main goal of a WSN is to monitor, collect and process data from a specific location and deliver it to the end users. The end users, regarding the application, can be anything as a military headquarter, hospital doctor, farmer, etc., thus use the collected data for any kind of a reason (e.g., decision making process). Considering the fact that data collected from the WSN can be very important, it is crucial that it is also secure. The concern for security is even more crucial as communication is done wirelessly, using radio transmission and thus making eavesdropping more probable. To this date numerous researches has been done on the security of WSNs [2], [3]. Since a WSN consist of tiny sensor nodes with low processing power, the balance of efficiency and security is very important but sometimes hard to achieve [4].

One of the most important security issues for WSNs are so-called outside attacks, whereby user authentication is the first line of defense against these attacks [5]. Due to the resource constraint architecture of WSNs, public key infrastructure (PKI) is unsuitable, primarily because of the large energy consumption [6], [7]. Example of such a user authentication scheme based on PKI was presented by Watro, Kong [8], called TinyPK. In 2006, Wong, Zheng [9] proposed a password-based user authentication scheme using only hash functions. However the scheme was later found to be vulnerable to several attacks [10]. In the same paper Das et al. also proposed an improved scheme. Several schemes were later proposed to tackle the security issues of previous ones [11]–[18].

This paper demonstrates that Das et al.'s new dynamic password-based user authentication scheme [14] has a flaw and is infeasible for implementation in real-life environment. Moreover, we show that their scheme can be made more efficient by removing redundant elements. To overcome the flaw and the redundancy of Das et al.'s scheme we propose an improved dynamic password-based user authentication scheme for hierarchical wireless sensor networks.

The rest of the paper is organized as follows: Section 2 presents preliminary concepts and background, Section 3 briefly reviews Das et al.'s scheme, Section 4 elaborates on the flaw and practical weaknesses of Das et al.'s scheme, Section 5 presents our proposed improvement scheme, Section 6 presents the security analysis of the proposed scheme, Sections 7 compares the performance of our scheme with some related schemes and finally we conclude the paper in Section 8.

II. WIRELESS SENSOR NETWORK

This section discusses the architecture of the WSN. Sensor networks consist of one or more base stations and multiple tiny sensor nodes which are equipped with a processor that allows them to sense, process and communicate data. Thus every sensor node is constructed of four basic units, i.e., sensing unit, processing unit, transceiver unit and a power unit. Sensor nodes can be sometimes even smaller than one cubic centimeter and deployed in a bunch of hundreds or even millions. The base stations are in contrary powerful nodes that connect all the sensor nodes and act like a gateway for the end user (e.g., access point, processing center, etc.). The main condition of a sensor node is that they consume extremely low power, have low production cost, are adaptive and autonomous. There are a variety of sensor node types which can measure or monitor a large scale of conditions like humidity, temperature, light, etc. The advantage of a sensor network is the collaboration of multiple low-cost sensor nodes which can be randomly deployed irrespective of the terrain, thus enable real-time detection of the environment. The sensing

Manuscript received July 16, 2012; accepted April 19, 2013.

process of sensor nodes can be continuous or event based. Because of the utility of the sensor networks, they can be used in a variety of applications, i.e., military (e.g. battlefield surveillance, targeting help, attack detection, etc.), environmental (e.g. forest fire detection, agriculture, etc.), health (e.g. monitoring human physiological data) [19], etc. The deployment of sensor nodes in a specific field can be done using planes, catapults or placing them one by one. The biggest disadvantage of sensor nodes is the energy efficiency. Further details about WSN can be found in [20], [21].

A. Hierarchical wireless sensor network

Two main architectures of WSN organization are, distributed-flat and hierarchical [22]. Hierarchical wireless sensor networks (HWSN) are organized into several clusters and one main server (i.e., base station). Each cluster consist of one cluster head (CH) and several sensor nodes. CHs communicate with every cluster member (i.e., sensor node) in its cluster, with each CH in the network and with the base station (BS) of the network. Sensor nodes therefore communicate only with the CH and other sensor nodes in the cluster. Finally the hierarchy ends with the BS, whereby it communicates only with the CHs of the network and to the outside world as an access point for the collected data. Sensor nodes are tiny, low-cost, low-processing sensors with short radio transmission range and are responsible only for sensing. CHs in contrary are more powerful thus have more processing capabilities. They are responsible for collecting and processing the data from its cluster members and transferring it to the BS. Further details can be found in [23].

III. REVIEW OF DAS ET AL.'S SCHEME

This section briefly reviews Das et al.'s scheme [14]. There are four parties included in Das et al.'s scheme: a base station, a cluster head, a sensor node and a user. Sensor nodes are an inactive party since they have no function in the establishment of the secure connection. Their scheme consists of seven phases; the pre-deployment phase, the post-deployment phase, the registration phase, the login phase, the authentication phase, the password change phase and the dynamic node addition phase. The notations used in this paper are summarized in Table I.

TABLE I. NOTATIONS USED IN THIS PAPER.

Notation	Explanation
CH_j, ID_{CH_j}	Cluster head and the identifier of cluster head
PW_i, ID_i	User's password and identity
RPW_i	Computed masked password
E, D	Symmetric key encryption/decryption algorithm
X_s	Secret information known only to base station
X_A	Secret information shared between user and base station
y	Secret random number known only to user
T	Timestamp
$A \parallel B$	Concatenation
$A \oplus B$	XOR operation
$h(\cdot)$	Hash operation

A. Pre-deployment phase

Before deploying any cluster head or sensor node into the field, a so-called pre-deployment or initial phase is required to register all cluster heads and sensor nodes with the BS. The BS acts like a setup server in this phase. The setup server assigns a unique identifier (ID_{CH_j}, ID_{S_i}) and a randomly unique master key (MK_{CH_j}, MK_{S_i}) for every cluster head (CH_j) and sensor node (S_i). The master key MK_{CH_j} of the CH_j is known only to the BS and to the CH_j, likewise the MK_{S_i} of the S_i is known only to the BS and to the S_i. At the end, the setup server saves the information $\{ID_{CH_j}, MK_{CH_j}\}$ into the memory of each cluster head and $\{ID_{S_i}, MK_{S_i}\}$ into the memory of each sensor node.

B. Post-deployment phase

After the sensor nodes and cluster heads are deployed into the target field, the post-deployment phase starts. Each element (i.e., sensor node and cluster head) in the field, within the communication range, locates his physical neighbour. In Das et al.'s scheme [14] it is assumed that the elements in the field establish secure connection between each other. For this purpose a secure pairwise key establishment scheme is used [24]. Finally each element communicates securely with the elements in the communication range.

C. Registration phase

In this phase the user has to register to the BS. The following four steps are required. Step 1. User U_i selects an identifier ID_i, a password PW_i and a random number y which is known only to him/her. Next he/she computes $RPW_i = h(y \parallel PW_i)$ and sends RPW_i and ID_i to the BS via a secure channel. Step 2. After receiving RPW_i and ID_i, the BS computes $f_i = h(ID_i \parallel X_s)$, $x = h(RPW_i \parallel X_A)$, $r_i = h(y \parallel x)$ and $e_i = f_i \oplus x$. Step 3. For each $m + m'$ cluster heads the BS computes $K_j = E_{MK_{CH_j}}(ID_i \parallel ID_{CH_j} \parallel X_s)$, where $\{(K_j, ID_{CH_j}) \mid 1 \leq j \leq m + m'\}$. m is the number of initially deployed cluster heads and m' is the number of additionally prepared cluster heads for the purpose of the dynamic node addition phase. Step 4. At the end of the registration phase the BS generates a tamper-proof smart card which stores following information: $\{ID_i, y, X_A, r_i, e_i, \{(K_j, ID_{CH_j}) \mid 1 \leq j \leq m + m'\}\}$.

D. Login phase

After registering with the base station and admission of the smart card, the user U_i has to login to be able to access the real-time data from the network, i.e., from a specific cluster head CH_j. The login process is as follows. Step 1. The U_i inserts the SC into a card reader and inputs the password PW_i'. Step 2. SC computes $RPW_i' = h(y \parallel PW_i')$, $x' = h(RPW_i' \parallel X_A)$, $r_i' = h(y \parallel x')$ and verifies $r_i =? r_i'$. If the verification does not hold the session is terminated. Otherwise SC computes $N_i = h(x' \parallel T_1)$. Step 3. U_i selects from which CH_j he/she wants to access the real-time data and according to the selection, the SC selects the corresponding encrypted master key K_j from its memory. Afterwards SC encrypts the cipher text message $(ID_i \parallel ID_{CH_j} \parallel N_i \parallel e_i \parallel T_1)$. At the end, the U_i sends the following message $\{ID_i \parallel ID_{CH_j} \parallel E_{K_j}(ID_i \parallel ID_{CH_j} \parallel N_i \parallel e_i \parallel T_1)\}$ via a public channel to the BS.

E. Authentication phase

The following steps are required in order for the BS to authenticate the user U_i. Step 1. After receiving the message from the U_i, the BS finds the stored master key MK_{CH_j} of the specific cluster head ID_{CH_j} and computes $K = E_{MK_{CH_j}}(ID_i \parallel ID_{CH_j} \parallel X_s)$. Having the encryption key K, the BS can decrypt the encrypted part of the login message $D_K[E_{K_j}(ID_i \parallel ID_{CH_j} \parallel N_i \parallel e_i \parallel T_1)]$ and thus check if retrieved and received ID_i and ID_{CH_j} are equal. Furthermore, the BS checks the validity of the timestamp T_1 with its current timestamp T_1^*. If $|T_1 - T_1^*| < \Delta T_1$ holds, the BS further computes $X = h(ID_i \parallel X_s)$, $Y = e_i \oplus X$ and $Z = h(Y \parallel T_1)$. At the end of the step, the BS checks if $Z =? N_i$. If the verification holds, the BS accepts user's login request, otherwise the scheme terminates. Step 2. Afterwards, the BS computes $u = h(Y \parallel T_2)$, whereby T_2 is the current timestamp of the BS. Using the master key MK_{CH_j} of the CH_j as an encryption key, the BS encrypts the message $(ID_i \parallel ID_{CH_j} \parallel u \parallel T_1 \parallel T_2 \parallel X \parallel e_i)$ and sends following message $\{ID_i \parallel ID_{CH_j} \parallel E_{MK_{CH_j}}(ID_i \parallel ID_{CH_j} \parallel u \parallel T_1 \parallel T_2 \parallel X \parallel e_i)\}$ to the corresponding cluster head CH_j. Step 3. After receiving the message from the BS, the cluster head CH_j, decrypts the encrypted part of the message $D_{MK_{CH_j}}[E_{MK_{CH_j}}(ID_i \parallel ID_{CH_j} \parallel u \parallel T_1 \parallel T_2 \parallel X \parallel e_i)]$. Afterwards the CH_j checks if retrieved and received ID_i and ID_{CH_j} are equal and if $|T_2 - T_2^*| < \Delta T_2$. T_2^* is the current timestamp of the CH_j and ΔT_2 is the expected time interval for the transmission delay. If all verifications hold, the CH_j continues and computes $v = e_i \oplus X$, $w = h(v \parallel T_2)$ and checks if $w =? u$. If it holds the user U_i is authenticated by the CH_j. Otherwise the scheme terminates. Finally the CH_j computes the session key as $SK = h\left(ID_i \parallel ID_{CH_j} \parallel e_i \parallel T_1\right)$ and sends the acknowledgment to the user U_i. Step 4. After receiving the acknowledgment from the CH_j, the U_i can compute the session key $SK = h\left(ID_i \parallel ID_{CH_j} \parallel e_i \parallel T_1\right)$ and thus communicate securely with the CH_j.

F. Password change phase

If the user U_i wants to change the password, he can do that offline and individually. To manage the change, following steps are required. Step 1. U_i inserts the SC into a card reader and inputs the current and new password PW_i^{old}, PW_i^{new}. Afterwards the SC computes $RPW_i^* = h(y \parallel PW_i^{old})$, $M_1 = h(RPW_i^* \parallel X_A)$, $M_2 = h(y \parallel M_1)$ and compares $M_2 =? r_i$. If the verification does not hold, the user inputted an incorrect password and the phase terminates. Otherwise Step 2 follows. Step 2. The SC computes $M_3 = e_i \oplus M_1$, $M_4 = h(y \parallel PW_i^{new})$, $r_i' = h(y \parallel M_4)$, $M_5 = h(M_4 \parallel X_A)$ and $e_i' = M_3 \oplus M_5$. Step 3. At the end, the SC replaces the values r_i and e_i in the memory, with r_i' and e_i'.

G. Dynamic node addition phase

When an element (i.e., sensor node, cluster head) of the WSN needs to be deployed (e.g., changing a broken element or replacing a captured element) into the field after the initial pre-deployment and post-deployment phase, following is required. If a new sensor node S_i or a new cluster head CH_j is about to be additionally deployed into the deployment field, the BS assigns a unique identifier ID_{S_i} or ID_{CH_j}, and a randomly generated unique master key MK_{S_i} or MK_{CH_j}. The generated information is then loaded into the memory of the sensor node S_i or cluster head CH_j. Afterwards the elements can be deployed in the field, whereby the user U_i gets informed by the BS about the new addition to the network.

IV. COMMENTS ON THE FLAW AND REDUNDANCY OF DAS ET AL.'S SCHEME

This section highlights the flaw of Das et al.'s scheme [14] and shows why the scheme is inappropriate for real-life environment. Additionally, we highlight redundant parts of the scheme and explain why they are redundant. The flaw and redundant parts are as follows.

In Das et al.'s scheme, at the registration phase, the user U_i selects a random number y which is known only to him. While continuing with the registration process, the user also selects an identifier ID_i and a password PW_i. Afterwards, a computed masked password $RPW_i = h(y \parallel PW_i)$ is computed, using the secret random number y and the password PW_i. Next, the user U_i provides $\{RPW_i, ID_i\}$ to the BS, whereby the secret random number y is not provided. After receiving the information the BS computes among others $r_i = h(y \parallel x)$, whereby $x = h(RPW_A \parallel X_A)$. However, the BS cannot derive r_i, since y is a secret random number which is known only to the user U_i and it was not provided in the message $\{RPW_i, ID_i\}$ or in any other way to the BS. Therefore we conclude that Das et al.'s scheme has a flaw, hence the BS cannot know the value of y and cannot compute the parameter r_i. This flaw if further reflected in the scheme as follows. In the registration phase of Das et al.'s scheme, the BS generates a tamper-proof smart card SC with the following parameters $\{ID_i, y, X_A, r_i, e_i, \{(K_j, ID_{CH_j}) \mid 1 \leq j \leq m + m'\}\}$. Since the BS does not know the value of y, it cannot compute $r_i = h(y \parallel x)$. It is therefore infeasible for the BS to generate a smart card SC which such parameters. Additionally, the fault is linked further with the login phase of Das et al.'s scheme, where the SC tries to authenticate the user U_i by checking his inputted password PW_i'. The SC computes $RPW_i' = h(y \parallel PW_i')$. Again this is impossible, because the random number y cannot be stored in the SC as the BS was not in possession of the secret random number y while generated information was stored on the SC. In addition to the login phase, the SC computes $r_i' = h(y \parallel x')$, whereby $x' = h(RPW_i' \parallel X_A)$. Afterwards it verifies whether $r_i =? r_i'$ in order to verify the password, thus trying to find out if the user U_i entered a correct password. Once more, this verification is infeasible, hence r_i cannot be computed by the BS and stored into the SC as shown in the previous comments. Also r_i' cannot be computed, hence the SC cannot compute RPW_i' without the secret random number y. The fault is further linked with password change phase of Das et al.'s scheme, where the smart card SC computes $RPW_i^* = h(y \parallel PW_i^{old})$, whereby PW_i^{old} is the current password of the user U_i and was inputted by him/her along with a new password PW_i^{new}. As already presented, the SC cannot compute RPW_i^*, since the random number y cannot be stored in it, because the BS which was generating the SC cannot be in possession of the random number y. Therefore we conclude that the password change phase is infeasible.

In the authentication phase of Das et al.'s scheme, the cluster head CH_j tries to validate the user U_i by verifying $w =? u$. The value u is part of the encrypted message sent by the BS to the cluster head CH_j. The BS computes $u = h(Y \parallel T_2)$, whereby $Y = e_i \oplus h(ID_i \parallel X_s)$. After receiving the message $\{ID_i \parallel ID_{CH_j} \parallel E_{MK_{CH_j}}(ID_i \parallel ID_{CH_j} \parallel u \parallel T_1 \parallel T_2 \parallel X \parallel e_i)\}$ from the BS, the cluster head CH_j computes $w = h(v \parallel T_2)$, whereby $v = e_i \oplus X$. As it is noticeable, the cluster head CH_j computes w by using values e_i, X and T_2 which it got from the message of the BS. Furthermore, after computing w it compares w with u, which is also already contained in the message $\{ID_i \parallel ID_{CH_j} \parallel E_{MK_{CH_j}}(ID_i \parallel ID_{CH_j} \parallel u \parallel T_1 \parallel T_2 \parallel X \parallel e_i)\}$. We conclude that this part of authentication phase of Das et al.'s scheme is redundant, since it is an unnecessary verification of parameters which are all in the same encryption message.

V. Proposed Improved Scheme

This section proposes an improved dynamic password-based user authentication scheme for HWSNs to overcome the flaw and redundancy of Das et al.'s scheme [14]. We will not describe the pre-deployment, the post-deployment and the dynamic node addition phases of the proposed scheme since they are same as in Das et al.'s scheme. An overview of the scheme is depicted in Fig. 1.

A. Registration phase

The user authentication starts with the registration phase. For the user U_i to register successfully the following steps are required. Step 1. The user U_i selects an identifier ID_i, a password PW_i and a random number y which is known only to him/her. Using the random number y, the U_i computes a masked password $RPW_i = h(y \parallel PW_i)$ and then sends the values ID_i and RPW_i to the BS via a secure channel. Step 2. After receiving ID_i and RPW_i, the BS computes $f_i = h(ID_i \parallel X_s)$ using the secret information X_S which is known only to the BS. Using the secret information X_A which is shared between the U_i and the BS, the BS computes $x = h(RPW_i \parallel X_A)$ and $e_i = f_i \oplus x$. Step 3. For every initially deployed cluster head in the network $(CH_1, CH_2, \ldots, CH_m)$, the BS computes a combination $((K_j, ID_{CH_j}) \mid 1 \leq j \leq m)$. K_j is an encryption key computed as $K_j = E_{MK_{CH_j}}(ID_i, \parallel ID_{CH_j} \parallel X_S)$, using the master key MK_{CH_j} of a specific CH_j. Additionally, the BS computes another m' number of the combinations, whereby m' is the number of additionally prepared CHs for the option of dynamic addition of CHs. If afterwards a new cluster head (CH_{m+1}) is being deployed into the field, a user can already use the pre-computed combination $(K_{m+1}, ID_{CH_{m+1}})$ for the authentication process. Step 4. In the final step, the BS generates a smart card SC containing $\{ID_i, X_A, e_i, f_i, \{ \left(K_j, ID_{CH_j}\right) \mid 1 \leq j \leq m + m'\}\}$. Step 5. Finally, the user U_i adds the random number y into the smart card SC and thus ends the registration phase.

B. Login phase

In the login phase, following steps are performed. Step 1. The user U_i inserts his smart card SC into a card reader and inputs his password PW_i'. Step 2. The SC computes the masked password $RPW_i' = h(y \parallel PW_i')$, using the inputted password and the random number y which is already stored by the user U_i in the SC. Next, $x' = h(RPW_i' \parallel X_A)$ is computed using the stored secret information X_A and RPW_i'. In addition, the SC computes the initial $x = e_i \oplus f_i$ using the stored information e_i and f_i and compares $x =? x'$. If the verification does not hold, the user U_i has inputted an incorrect password and the scheme terminates. If the above verification holds, the BS computes $N_i = h(x' \parallel T_1)$, where T_1 is the system's timestamp. Step 3. For the user U_i to access real-time data from a specific cluster head, he/she needs to select the appropriate cluster head CH_j, his identifier ID_{CH_j} and the associated encryption key K_j from the list of all combinations already saved in the SC. Then the SC uses the K_j to encrypt a message $E_{K_j}(ID_i \parallel ID_{CH_j} \parallel N_i \parallel e_i \parallel T_1)$. Finally, the user U_i sends the message $\{ ID_i \parallel ID_{CH_j} \parallel E_{K_j}\left(ID_i \parallel ID_{CH_j} \parallel N_i \parallel e_i \parallel T_1\right) \}$ to the BS via a public channel.

C. Authentication phase

After the login phase, the BS has to authenticate the user U_i and so enable him to compute the session key SK and thus communicate securely with the cluster head CH_j. Following steps are required for a successful authentication. Step 1. After receiving the login request message from the user U_i, the BS firstly has to compute the encryption key in order to read the encrypted part of the login request message. This is done using the BS's secret information X_S and the values ID_i and ID_{CH_j}. Knowing the ID_{CH_j}, the BS can find the associated master key MK_{CH_j} of the appropriate cluster head CH_j. Thus the BS computes $K = E_{MK_{CH_j}}(ID_i \parallel ID_{CH_j} \parallel X_S)$. Having K, the BS can now decrypt the encrypted part of the login request message $D_K[E_{K_j}(N_i \parallel e_i \parallel T_1)]$. Step 2. When the login request message is decrypted successfully, the BS uses the current timestamp T_1^* and checks if $|T_1 - T_1^*| < \Delta T_1$, whereby ΔT_1 is the expected interval for the transmission delay. Furthermore, the BS checks if retrieved and received ID_i and ID_{CH_j} are equal. If the verifications do not hold the scheme terminates. Otherwise, the BS computes $Z = h(e_i \oplus h(ID_i \parallel X_s) \parallel T_1)$, using e_i, ID_i and T_1 from the login request message and its secret information X_S. Afterwards, the BS verifies $Z =? N_i$. If the verification does not hold, the scheme terminates. Otherwise, the BS acknowledges user U_i as a valid user and proceeds as follows. Step 3. Using the master key MK_{CH_j} of the appropriate cluster head CH_j as an encryption key, the BS encrypts the message $E_{MK_{CH_j}}(ID_i \parallel ID_{CH_j} \parallel T_1 \parallel T_2 \parallel e_i)$, whereby T_2 is the current timestamp of the system. After the message is constructed, the BS sends it to the appropriate cluster head CH_j via a public channel.

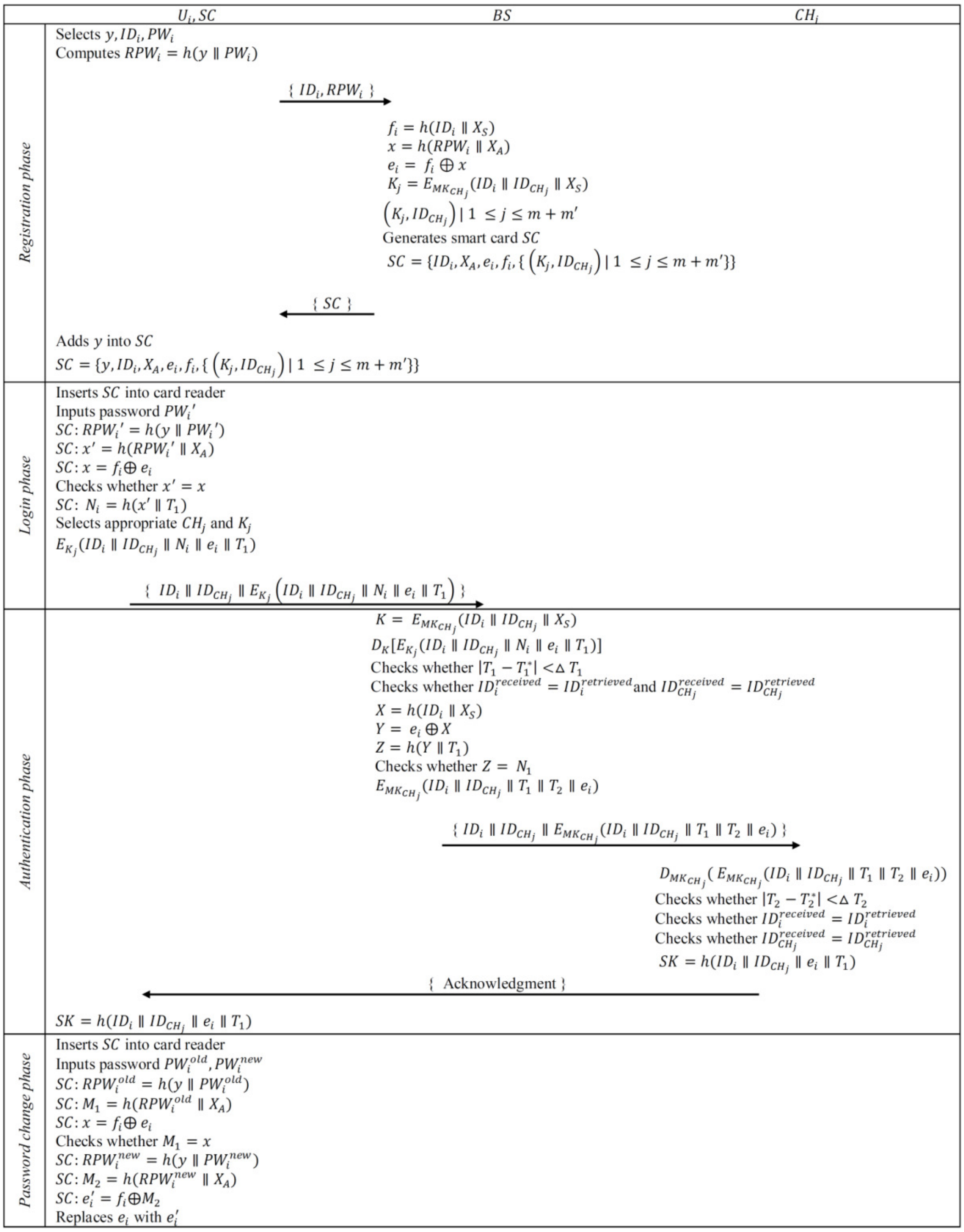

Fig. 1. Depiction of the proposed scheme through the phases and according to the communication between the actors of the WSN.

Step 4. After receiving the message $\{ID_i \parallel ID_{CH_j} \parallel E_{MK_{CH_j}}(ID_i \parallel ID_{CH_j} \parallel T_1 \parallel T_2 \parallel e_i)\}$ from the BS, the CH_j uses its master key MK_{CH_j} to decrypt the message $D_{MK_{CH_j}}(E_{MK_{CH_j}}(ID_i \parallel ID_{CH_j} \parallel T_1 \parallel T_2 \parallel e_i))$. It then checks if $|T_2 - T_2^*| < \Delta T_2$, whereby T_2^* is the current timestamp of the CH_j and ΔT_2 is the expected interval for the transmission delay. The BS also checks if retrieved and received ID_i and ID_{CH_j} are equal. If the verifications hold, the CH_j computes the session key $SK = h(ID_i \parallel ID_{CH_j} \parallel e_i \parallel T_1)$, using its own identifier ID_{CH_j} and the retrieved values ID_i, e_i and T_1. Otherwise the scheme terminates. Having computed the SK, the CH_j sends an acknowledgement to user U_i. Step 5. Finally, after the received acknowledgement, the user U_i can compute the session key $SK = h(ID_i \parallel ID_{CH_j} \parallel e_i \parallel T_1)$ with the values he/she is already in possession of. Using the secret session key SK, the user U_i can now communicate and securely access real-time data from the cluster head CH_j.

D. Password change phase

For a user U_i to change his/her password, no connection with the BS or any of the cluster heads CH_j is needed. The process can be done offline, using only the SC. The phase contains the following steps. Step 1. The user U_i inserts his/her SC into a card reader and inputs his/her old and new password PW_i^{old}, PW_i^{new}. Step 2. Using the random number y stored in the SC and the old password PW_i^{old}, the SC computes the masked password $RPW_i^{old} = h(y \parallel PW_i^{old})$. Additionally, using the secret information X_A, the SC computes $M_1 = h(RPW_i^{old} \parallel X_A)$. The SC then computes the initial $x = e_i \oplus f_i$ using the stored values e_i and f_i and compares $x =? M_1$. If the verification does not hold, the user U_i has inputted an incorrect password and the scheme terminates. Step 3. Otherwise, the SC starts the process of replacing the password, whereby the new masked password is computed $RPW_i^{new} = h(y \parallel PW_i^{new})$ using the new inputted password PW_i^{new}. Furthermore, the SC computes $M_2 = h(RPW_i^{new} \parallel X_A)$. Finally the new value $e_i' = f_i \oplus M_2$ is computed and replaced with the stored e_i in the memory of the SC.

Our proposed protocol not only eliminates the flaw but is also less computationally costly and thus more appropriate for use. In Section VII we demonstrate the advantages of our proposed protocol in comparison to competitive ones.

VI. Security Analysis And Discussion Of The Proposed Scheme

This section provides discussion and a security analysis of the proposed scheme. We show that our scheme overcomes all the practical flaws of Das et al.'s scheme and is equally resilient to various possible attacks.

A. *Flaw correction*

In our scheme, the BS, at the time of the registration, does not compute and store r_i into the smart card SC, but stores f_i, which is afterwards used as a verification token in the login and password change phase. Furthermore, the user U_i stores the secret random number y into the SC, hence neither the BS, nor any of CHs can know the value of y. In the authentication phase of our scheme, before sending a message to the CH, the BS does not encrypt the parameters u and X into the message, since they would be only needed if CH would verify w $=? u$, whereby $w = h((e_i \oplus X) \parallel T_2)$. We already described in in the comments of Section IV that this verification is redundant or an unnecessary verification of parameters which would all be in the same encryption message. Therefore u and X are removed along with the CH's computation of w and v.

B. *Replay attack*

Even if an attacker would intercept a login request message $\{ ID_i \parallel ID_{CH_j} \parallel E_{K_j}\left(ID_i \parallel ID_{CH_j} \parallel N_i \parallel e_i \parallel T_1\right) \}$ and try to replay it to the BS, the BS checks the freshness of the timestamps verifying $|T_1 - T_1^*| < \Delta T_1$. Moreover, even if the verification would hold and the BS would authenticate the attacker, he/she cannot compute the session key SK, since he/she cannot know the values e_i and T_1, which are encrypted with the encryption key K. Hence our scheme is resilient against replay attacks.

C. *Gateway node bypassing attack*

The proposed scheme can withstand the gateway node bypassing attack, because the user U_i and a cluster head CH_j need to establish a session key SK in order to communicate (request - reposnse) secrurely. To compute the SK the user U_i needs to register and authenticate with the BS.

D. *Stolen-verifier attack*

Stolen-verifier attack is an attack where an adversary steals a user's verifier from a server and tries to impersonate a legitimate user with the stolen verifier. Our proposed scheme is free from password tables or any kind of verifier tables, hence neither the BS nor the CHs keep them to authenticate the users, thus making the scheme resilient against stolen-verifier attack.

E. *Impersonation attack*

In an impersonation attack an adversary tries to impersonate a legitimate user by forging a valid login request. The adversary could forge the login request using some eavesdropped message or using information stored on the smart card. Since in our scheme the messages are encrypted, the adversary cannot forge a valid request message without knowing the encryption key K. Since the encryption key is computed using the secret information X_S which is known only to the BS it is impossible for an adversary to compute it. Furthermore, even if the adversary would steal a valid smart card and derive the encryption key K_j from it, he/she would not be able to compute N_i without the password PW_i of the user U_i. Without N_i the adversary cannot forge a valid login request, thus making the scheme resilient against the impersonation attack.

F. *Offline and online password guessing attack*

In an offline password guessing attack [25] an adversary eavesdrops the communication over a public channel between a legitimate user and the authentication server. He/She then uses the eavesdropped message and tries to generate a valid password by using a brute force or dictionary attack and compare it with the message from the legitimate user. For an adversary to use an offline password guessing attack in our proposed scheme, he/she would first need to have a user's smart card. Moreover, messages sent over a public channel are in our proposed scheme protected using an symmetric encryption key K. Additionally, the password PW_i in our proposed scheme can only be found hidden inside the parameters $e_i = f_i \oplus h(h(y \parallel PW_i) \parallel X_A)$ and $N_i = h(h(h(y \parallel PW_i') \parallel X_A) \parallel T_1)$, thus making it computationally infeasible to extract it due to the one-way property of the hash function. In an online password guessing attack an adversary tries to find a valid password by attempting to login or authenticate online. To use this attack the adversary would need to have a valid smart card, whereby it is assumed that the smart card itself would block the password guessing after multiple wrong password inputs. Therefore, we can conclude that our proposed scheme is resilient against offline or online password guessing attacks.

G. *Smart card breach attack*

Although we assume that a smart card is tamper-resistant and cannot be breached, we consider a scenario where a legitimate user's smart card is being stolen or lost and eventually found and somehow cracked by an adversary. This would mean that the adversary obtained the information $\{y, ID_i, X_A, e_i, f_i, \{ \left(K_j, ID_{CH_j}\right) | \ 1 \le j \le m + m'\}\}$ from the SC. Fortunately, the adversary cannot use the retrieved information from the SC to impersonate a legitimate user U_i, since he/she needs to know the U_i's password PW_i in order to successfully accomplish an authentication. Furthermore, there is no feasible way for an adversary to obtain the PW_i from $e_i = f_i \oplus h(h(y \parallel PW_i) \parallel$

X_A) due to the one-way property of a hash function. There is also no feasible way for an adversary to crack the encryption key K, since he/he does not know the secret information X_S, which is known only to the BS. Therefore we can conclude that the scheme is resilient against smart card breach attack.

H. Password change attack

If a legitimate user U_i wants to change the password PW_i, he/she can accomplish that offline, using its smart card SC and without contacting the BS, as described in the *Password change phase* of the proposed scheme. Thus for an adversary to change the password of the user U_i, he/she needs to be in the possession of U_i's smart card. Furthermore, if an adversary could come into the possesion of a legitimate user's smart card, he/she would need to know the old password PW_i^{old} of the U_i in order to change it. As we already described earlier, our scheme can withstand the smart card breach attack, thus making it impossible for an attacker to accomplish a password change attack.

I. Many logged-in users with the same login-id attack

As Das et al.'s scheme can withstand the many logged-in users with the same login-in attack, also can our proposed scheme. For a user to be able to login, he/she needs his smart card SC, whereby every SC has a random number y stored in it. So even if two or more users have the same login creditencials (ID_i, PW_i), their computed masked password $RPW_i = h(y \parallel PW_i)$ will be different.

J. Privileged insider attack

For a privileged-insider attack [26] to take place, a privileged person who can access a server (e.g., administrator or system manager), could use his/her privileges to obtain a password of a user (e.g., from a password table or from a login request message) and then try to impersonate the same user on some other server, where the user could also be registered. In our case the server is the BS, but as already described in *Stolen-verifier and password guessing attack*, our scheme is free from password tables, thus making it impossible for anyone to obtain a password from the BS. Furthermore, even if a privileged insider of the BS would monitor the login request from the user, he/she cannot obtain his/her password, since he/she does not send the password PW_i in plaintext, but rather in form of a computed masked password $RPW_i = h(y \parallel PW_i)$. Because the password is concatenated with the random number y and hashed with a one-way hash function it is computationally infeasible for an adversary to obtain the password, thus making the scheme secure against the privileged-insider attack.

K. DoS attack

Denial-of-service attack [27] is useless against our proposed scheme since acknowledgement about a successful authentication from the BS is being sent over the CH to the user U_i.

VII. PERFORMANCE ANALYSIS AND COMPARISON

This section summarizes the performance and functionality of our proposed scheme and compares it with some recent and related user authentication schemes for WSN. In Table II we compare the functionality of our proposed scheme with other related schemes. The comparison demonstrates that our scheme can achieve the same functionalities as Das et al.'s scheme, therefore much more than other schemes.

TABLE II. FUNCTIONALITY COMPARISON.

Functionalities	Our proposed protocol	[14]	[16]	[17]	[13]	[12]	[18]
Supports password change	Yes	Yes	Yes	Yes	Yes	No	No
Mutual authentication	Yes	Yes	No	No	Yes	Yes	Yes
Resilient against DoS attack	Yes	Yes	No	No	Yes	Yes	No
Resilient against node capture attack	Yes	Yes	Yes	No	No	Yes	No
Session key between user and node	Yes	Yes	No	No	Yes	No	No
Supports dynamic node addition	Yes	Yes	No	No	No	No	No

Furthermore, Table III shows the computational-cost comparison of our scheme and other schemes. We summarized only the registration, login and authentication phases, since they are the important ones for user authentication. It can be seen that our scheme requires less computations (i.e., four hashing operations less) than Das et al.'s scheme, whereby both ours and Das et al.'s are more computational-costly than other schemes. However, additional encryption/decryption operations in our and Das et al.'s scheme are worth the additional functionalities which are derived.

TABLE III. COMPUTATIONAL COST COMPARISON.

Authentication scheme	Registration phase	Login + authentication phase
Our proposed scheme	$3T_h + (m + m')T_E$	$7T_h + 3T_E + 2T_D$
Das, Sharma [14]	$4T_h + (m + m')T_E$	$10T_h + 3T_E + 2T_D$
Huang, Chang [16]	$4T_h$	$11T_h$
He, Gao [17]	$6T_h$	$11T_h$
Vaidya, Makrakis [13]	$5T_h$	$13T_h$
Fan, Ping [12]	$6T_h$	$19T_h$
Chen and Shih [28]	$3T_h$	$10T_h$

VIII. CONCLUSIONS

This paper shows that because of a serious flaw, Das et al.'s dynamic password-based user authentication scheme for HWSN is inappropriate for implementation in real-life environment. Moreover, we present some redundant parts which unnecessarily slow the scheme down. To overcome the flaw and redundancy of Das et al.'s scheme, we proposed an enhanced dynamic password-based user authentication scheme for HWSN to remedy these practical weaknesses. The scheme which we proposed satisfies all the requirements for a HSWN user authentication scheme and is robust for a real-life environment. Furthermore, it can also withstand various attacks without losing any functionality of Das et al.'s scheme, thus retains its advantages and is less computationally-costly (i.e., four hashing operations less ($4T_h$)).

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