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ITSSAKA-MS: An Improved Three-Factor Symmetric-Key Based Secure AKA Scheme for Multi-Server Environments

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ABSTRACT A variety of three-factor smart-card based schemes, specifically designed for telecare medicine information systems (TMIS) are available for remote user authentication. Most of the existing schemes for TMIS are customarily proposed for the single server-based environments and in a single-server environment. Therefore, there is a need for patients to distinctly register and login with each server to employ distinct services, so it escalates the overhead of keeping the cards and memorizing the passwords for the users. Whereas, in a multi-server environment, users only need to register once to resort various services for exploiting the benefits of a multi-server environment. Recently, Barman *et al.* proposed an authentication scheme for e-healthcare by employing a fuzzy commitment and asserted that the scheme can endure many known attacks. Nevertheless, after careful analysis, this paper presents the shortcoming related to its design. Furthermore, it proves that the scheme of Barman *et al.* is prone to many attacks including: server impersonation, session-key leakage, user impersonation, secret temporary parameter leakage attacks as well as its lacks user anonymity. Moreover, their scheme has the scalability issue. In order to mitigate the aforementioned issues, this work proposes an amended three-factor symmetric-key based secure authentication and key agreement scheme for multi-server environments (ITSSAKA-MS). The security of ITSSAKA-MS is proved formally under automated tool AVISPA along with a security feature discussion. Although, the proposed scheme requisites additional communication and computation costs. In contrast, the informal and automated formal security analysis indicate that only proposed scheme withstands several known attacks as compared to recent benchmark schemes.

INDEX TERMS Authentication and key-agreement (AKA), AVISPA tool, e-healthcare, fuzzy commitment scheme, multi-server authentication, telecare medicine information system (TMIS).

I. INTRODUCTION

The use of information and communication technologies (ICT) is increasing day by day not only for the entertainment and related leisure purposes rather its' becoming a part and parcel of daily life. People are now benefiting through a large number of quality services including e-Health/telemedicine, remote surveillance, online shopping, online banking, and online education etc. With the broad availability of the Internet everywhere and with the cheaper mobile devices, telemedicine and the e-Healthcare services are in the reach to the patients, directly despite being in remote areas [1], [2]. Moreover, e-Health can substitute the traditional clinical medical services [3], [4]. By using TMIS, the physician can access and monitor the live medical condition of the patients within no time by using open channel [5]. It becomes very crucial to block an adversary from deducing the patient's delicate information.

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Furthermore, as the adaption of e-Healthcare increases, the need of patient-privacy should be the first priority as all the communication is taking place through public channel [6], [7]. To prevent various threats, an authentication scheme can be implemented to ensure that TMIS is only accessed by legitimate users [8]–[11]. Recently, Wu *et al.* [12] introduced a two-factor authentication scheme by employing smart-card and password for TMIS. Debiao *et al.* [13] identified that Wu *et al.*'s scheme is prone to insider attack, impersonation attack, and the stolen smart-card attack. He *et al.* designed an other scheme to solve the flaws of [12]. Zhu [14] also introduced RSA-cryptosystem based authentication scheme. Many other researchers [15]–[18] presented various schemes using password and smart-card, which were later proved weak against one or other attack. Recently, in numerous studies, many researchers proposed three-factor authentication schemes to enhance the security and to ensure user privacy by combining ID/password, biometric (e.g.fingerprint, iris) and smart-card [19]–[24]. Furthermore, some other schemes compromised the users privacy by sending the identity of the user over the insecure channel, directly to the server [12]–[14], [25], [26]. Nevertheless, the privacy of the user should be insured in order to keep the identity secret from the illegal users and privacy is now being taken as a part and parcel of authentication schemes [27], [28]. To ensure user privacy/anonymity Pu *et al.* [29] presented an elliptic curve cryptography (ECC) based authentication scheme, but the computation, communication and storage demand in Pu *et al.*'s scheme is very high. An authentication based on dynamic ID with performance efficiency was proposed by Chen *et al.* [30]. After careful cryptanalysis, it is proved by Jiang *et al.* [31] that Chen *et al.*'s scheme is unable to ensure user anonymity and presented a scheme to overcome the flaw. In contrast, Kumari *et al.* [32] found that Jiang *et al.*s' [31] scheme is prone to password guessing attack, session-key disclosure attack, Denial-of-Service (DoS) attack and user impersonation attack. Kumari *et al.* [32] presented an enhanced scheme to overcome the before-mentioned attacks. Chang and Chen [33] proposed another three-factor authentication scheme for multi-server environment. However, Lin *et al.* [34] and Mishra *et al.* [35] established that Chuang-Chang's scheme is unsafe towards several attacks like insider attack, Denial-of-Service (DoS) attack, user impersonation attack, server spoofing attack and lacks user anonymity. Another authentication scheme was proposed by Mishra *et al.* for expert systems. Nevertheless, Wang *et al.* [36] & Lu *et al.* [37] proved that Mishra *et al.*'s scheme is prone to forgery attack, DoS attack, replay attack as well as lacks user anonymity and perfect forward secrecy.

In 2019, Barman *et al.* [5] presented a three-factor authentication scheme for e-Healthcare in the multi-server environment by employing fuzzy commitment and stated that the scheme can cope with prominent attacks. But, the carefully analysis conducted in this paper exposes several weaknesses of Barman *et al.*'s scheme. This manuscript depicts that [5] suffers from design faults, and is prone to stolen verifier attack, which leads to session-key leakage, user and server impersonation attack, secret temporary parameters leakage; moreover, the Barman *et al.*'s scheme works in absence of user anonymity. Therefore, an improved three-factor symmetric-key based secure authentication and key agreement scheme for multi-server environments (ITSSAKA-MS) is proposed in this paper. Rest of the paper presentation is as follows:

The attack model employed in this paper is outlined in Subsection I-A. Review and cryptanalysis of Barman *et al.*'s scheme is conducted in Section II and Section III, respectively. In Section IV different phases of the proposed ITSSAKA-MS are discussed. The security analysis of the proposed ITSSAKA-MS is performed in Section V. In Section VI performance analysis of the ITSSAKA-MS is furnished and compared with various schemes. Paper is finally concluded in Section VII.

A. ADVERSARIAL MODEL

In this manuscript, the standard adversarial model is taken into account as stated in [38]–[44] where following considerations are assumed as the power of the adversary $\mathcal{U_A}$:

1) $\mathcal{U_A}$ can listen the messages exchanged through public channel. $\mathcal{U_A}$ have the capability to listen, replay, alter, abolish or can send forges messages.
2) $\mathcal{U_A}$ can be a dishonest system user or can be an outsider.
3) $\mathcal{U_A}$ can extract information stored into his/stolen smart-card by performing power analysis [38], [40] or from leaked data [41].
4) $\mathcal{U_A}$ can be a privileged and legitimate insider, which can expose the verifier table stored in the database of the RC [45]–[48].
5) $\mathcal{U_A}$ can not steal the private key of the RC.

II. REVIEW OF THE SCHEME OF BARMAN *et al.*

This section presents the review of the scheme of Barman *et al.* The three phases of the scheme are described in following subsections:

A. REGISTRATION PROCESS

Registrations of each of the server and patient are explained in following subsections:

1) SERVER REGISTRATION PROCESS

All the medical servers (MS_j) need to register themselves with RC. A MS_j chooses and transmits an identity SID_j to RC. RC computes $W_j = h(SDI_j||K_{RC})$, for j^{th} medical server using its secret key K_{RC} and sends W_j to medical server.

2) PATIENT REGISTRATION PROCESS

In order to register with the RC and avail medical services, every patient/user say U_i selects an identity (PID_i), password (PW_i), transformation-key (T_{P_i}) respectively and imprints his/her fingerprint-biometric (BM_i). A cancellable template ($C_{T_i} = f(BM_i, T_{P_i})$) is generated with a T_{P_i} using a transformation function $f(.)$ from the users BM_i. Following are the steps involved in the patients registration process:

1) An error encoding technique ψ_{enc} is utilized to alter the arbitrary picked key K into the code-word $K_{CW} = \psi_{enc}(K)$ and saves it into $LTK_i = K_{CW} \oplus C_{T_i}$.
2) U_i sends a registration request containing PID_i, PWD_i to RC, where $PWD_i = h(PID_i||K||PW_i)$.
3) Upon receiving registration request from U_i, RC calculates $A_j = PWD_i \oplus h(PID_i||W_j)$ and $P_j = PWD_i \oplus h(SID_j||W_j)$.
4) RC saves the variables $\{SID_j, A_j, P_j, h(.)\}$ into the SC_i and $\{PID_i, h(PWD_i||W_j)\}$ into the database.
5) U_i calculates the $f_i = h(PID_i||PWD_i||C_{T_i})$ and saves $\{LTK_i, T_{P_i}, h(K), f(.), f_i, \psi_{dec}(), \psi_{enc}()\}$ into the smart-card.

The SC_i finally holds the subsequent parameters $\{\langle A_j, SID_j, P_j\rangle \mid (1 \leq j \leq m + m'), T_{P_i}, h(.), LTK_i, f_i, h(K), f(.), \psi_{enc}(), \psi_{dec}()\}$.

B. LOGIN AND KEY-ESTABLISHMENT PROCESS

In this phase U_i gets authenticated and a session key is shared among the U_i and S_j by executing following steps:

1) U_i enters the SC_i and provides the credentials containing PID_i, PW_i and biometric BM_i^*. Smart-card SC_i computes $C_{T_i}^* = f(BM_i^*, T_{P_i})$, using the transformation function $f(.)$. SC_i regenerates the $K^* = \psi_{dec}(LTK_i \oplus C_{T_i}^*) = \psi_{dec}(K_{CW}^*)$. SC_i confirms $h(K^*) \overset{?}{=} h(K)$, if incorrect session terminates, else continues. SC_i picks R_{rand_1}, T_1 and calculates $PWD_i^* = h(PID_i||K^*||PW_i), f_i^* = h(PID_i||PWD_i^*||C_{T_i}^*)$ and checks whether $f_i^* \overset{?}{=} f_i$, if inaccurate session terminates, if not, it proceeds. SC_i calculates the subsequent: $V_1 = A_j \oplus PWD_i^* = h(PID_i||W_j)$, $V_2 = P_j \oplus PWD_i^* = h(SID_j||W_j)$, $V_3 = PID_i \oplus V_2$, $V_4 = V_1 \oplus R_{rand_1}$, $V_5 = h(V_1||R_{rand_1}||T_1)$. SC_i finally sends the login request containing $\langle T_1, V_4, V_3, V_5\rangle$ to MS_j.
2) Upon getting the login message from U_i, MS_j confirms the condition $\mid T_c - T_1 \mid \leq \triangle T$ to verify the timeliness of the timestamp T_1, if true continue else session terminates.MS_j computes $V_6 = h(SID_j||W_j)$, $V_7 = V_3 \oplus V_6 = PID_i$, $V_8 = h(V_7 \,||\, W_j) = h(PID_i \,||\, W_j)$, $V_9 = V_4 \oplus V_8 = R_{rand_1}$, $V_{10} = h(V_8 \,||\, V_9 \,||\, T_1) = h(h(ID_i||W_j)||R_{rand_1}||T_1)$. MS_j picks the arbitrary nonce R_{rand_2} and the present timestamp T_2 if $V_{10} \overset{?}{=} V_5$ is true, else terminates the session. MS_j computes $V_{11} = R_{rand_2} \oplus h(V_8||R_{rand_1}) = R_{rand_2} \oplus h(h(PID_i||W_j)||R_{rand_1})$, $SK_{ij} = h(V_6|| V_8|| V_9|| R_{rand_2}|| T_2) = h(h(SID_j\,||W_j) \,||\, h(PID_i \,||\, W_j) \,||\, R_{rand_1} \,||\, R_{rand_2} \,||\, T_2)$, $V_{12} = h(SK_{ij} \,||\, V_8 \,||\, V_9 \,||\, T_2) = h(SK_{ij} \,||\, h(PID_i \,||\, W_j) \,||\, R_{rand_1} \,||\, T_2)$. MS_j transmits the message containing $\langle T_2, V_{12}, V_{11}\rangle$ to U_i via open channel.
3) U_i validates the condition $\mid T_c - T_2 \mid \leq \triangle T$ to verify the validity of the T_2, if false session terminates else continues and U_i computes: $V_{13} = h(V_1||R_{rand_1}) \oplus R_{rand_1} \oplus V_{11}$, $SK_{ij} = h(V_1 \,||V_2 \,||R_{rand_1} \,||V_{13} \,||T_2)$, $V_{14} = h(SK_{ij}||V_1||R_{rand_1}||T_2)$. U_i checks the condition $V_{12} \overset{?}{=} V_{14}$, if false session is terminated. SC_i generates the new timestamp and calculates: $V_{15} = h(SK_{ij}||V_1||V_{13}||T_3)$ and transmits the message containing $\langle V_{15}, T_3\rangle$ to MS_j at time T_3. Upon getting the message from U_i, the server calculates $V_{16} = h(SK_{ij}||V_8||R_{rand_2}||T_3)$, if $\mid T_c - T_3 \mid \leq \triangle T$. MS_j checks the condition $V_{16} \overset{?}{=} V_{15}$, if true, session-key SK_{ij} is established among the MS_j and U_i, so that they can communicate securely.

III. CRYPTANALYSIS OF THE SCHEME OF BARMAN *et al.*

In this section, we demonstrate some of the critical weaknesses of the scheme of Barman *et al.* It is to substantiate here that a privileged insider $\mathcal{U_A}$ having access to RC can impersonate as a legitimate U_i and can launch other attacks under the capabilities mentioned in adversarial model presented in Section I-A:

A. DESIGN FAULTS

Barman *et al.*'s scheme suffers from design fault [49], after login user sends the message $\langle T_1, V_3, V_4\ , V_5\rangle$ to a medical server (MS_j), as it can be observed that the request message does not include the server (SID_j) identity/ address, while there are $j(j : 1 \leq j \leq m + m')$ servers. Therefore, for moving further, following two are the possibilities:

Case 1: The message is broadcasted, so every server receives it and the intended server processes it completely. In such case, each server partly processes the request, which can cause, unnecessary computation on each server and can cause delay in processing other legitimate requests and hence degrade the quality of service.

Case 2: Alternatively, the absence of server address/identity in request message can be treated as a typo. In this case, the scheme can complete working normally but has severe security weaknesses, explained in subsequent subsections.

B. STOLEN VERIFIER AND USER ANONYMITY VIOLATION ATTACK

After successfully authenticating the U_i, SC_i transmits the message $\langle V_3, V_4, V_5, SID_j, T_1\rangle$ to MS_j considering III-A in Subsection III-A this message also includes servers identity/address. The message sent by SC_i is transferring over the public channel so a legitimate but wicked user ($U_{\mathcal{A}}$) of the system can intercept it and can compute users identity as follow:

1) The $U_{\mathcal{A}}$ extracts the value P_j from his own smart-card through power-analysis [39], [40] and computes $h(SID_j||W_j)$ as it is the same for all the users by adopting the following procedure:

$$\mathcal{Z_A} = P_j = (h(SID_j||W_j) \oplus PWD_A) \oplus PWD_A \quad (1)$$

$$\mathcal{Z_A} = h(SID_j||W_j) for\ 1 \leq j \leq m + M' \quad (2)$$

2) The $U_{\mathcal{A}}$ waits for the U_i to initiate a login request consisting of $\langle V_3, V_4, V_5, SID_j, T_1\rangle$ where:

$$V_3 = PID_i \oplus h(SID_j||W_j) \tag{3}$$

3) Then $U_{\mathcal{A}}$ computes the following:

$$PID_i = \mathcal{Z}_{\mathcal{A}} \oplus V_3 \tag{4}$$

where PID_i is the identity of U_i and stays similar for all sessions, therefore $U_{\mathcal{A}}$ has successfully launched the traceability attack. Also, SID_j and corresponding key W_j are stored in the verifier table on the RC. So a privileged insider can access this table [50] and can compute the corresponding P_j to launch the traceability attack.

C. USER IMPERSONATION ATTACK

Let $U_{\mathcal{A}}$ be a legit user of the system and knows the identity of another legal user U_i. Following procedure can be adopted by $U_{\mathcal{A}}$ to impersonate as a U_i:

1) The $U_{\mathcal{A}}$ fetches W_j corresponding to SID_j from RC's verifier table [51], picks an arbitrary nonce $R^{\mathcal{A}}_{rand_1}$ and calculates:

$$V_1^{\mathcal{A}} = h(PID_i||W_j) \tag{5}$$
$$V_2^{\mathcal{A}} = h(SID_j||W_j) \tag{6}$$
$$V_3^{\mathcal{A}} = PID_i \oplus V_2^{\mathcal{A}} \tag{7}$$
$$V_4^{\mathcal{A}} = V_1^{\mathcal{A}} \oplus R^{\mathcal{A}}_{rand_1} \tag{8}$$

2) $U_{\mathcal{A}}$ generates the current timestamp and computes:

$$V_5^{\mathcal{A}} = h(V_1^{\mathcal{A}}||R^{\mathcal{A}}_{rand_1}||T_1^{\mathcal{A}}) \tag{9}$$

3) Finally, $U_{\mathcal{A}}$ sends the message containing $\langle V_3^{\mathcal{A}}, V_4^{\mathcal{A}}, V_5^{\mathcal{A}}, T_1^{\mathcal{A}}\rangle$

4) The server MS_j gets the message forged by the $U_{\mathcal{A}}$, MS_j checks the freshness of time-stamp $T_1^{\mathcal{A}}$, as it is fresh, hence $U_{\mathcal{A}}$ passes this test.

5) MS_j now computes:

$$V_6 = h(SID_j||W_j) \tag{10}$$
$$V_7 = V_3^{\mathcal{A}} \oplus V_6 \tag{11}$$
$$V_8 = h(h(V_7||W_j)) \tag{12}$$
$$V_9 = V_4^{\mathcal{A}} \oplus V_8 = R^{\mathcal{A}}_{rand_1} \tag{13}$$
$$V_{10} = h(V_8||V_9||T_1^{\mathcal{A}}) \tag{14}$$

6) MS_j now verifies the equality:

$$V_{10} \stackrel{?}{=} V_5^{\mathcal{A}} \tag{15}$$

7) MS_j considers $U_{\mathcal{A}}$ as genuine U_i if Eq. 15 holds and process the next steps to complete the authentication process. It can be clearly seen that Eq. 15 holds, as V_8 computed by MS_j in Eq. 12 is identical to $V_1^{\mathcal{A}}$ calculated by the $U_{\mathcal{A}}$ in Eq. 5. Similarly, V_9 computed in Eq 13 is also the same $R^{\mathcal{A}}_{rand_1}$ generated by $U_{\mathcal{A}}$. Therefore, $U_{\mathcal{A}}$ has successfully launched impersonation attack using the stolen verifier.

D. SECRET TEMPORARY PARAMETER LEAKAGE

1) As described in Subsection III-B and III-C, $U_{\mathcal{A}}$ being insider knows the identity of U_i and secret-key of server W_j, and computes:

$$V_1^{\mathcal{A}} = h(PID_i||W_j) \tag{16}$$

2) $U_{\mathcal{A}}$ can now extract the random number R_{rand_1} in the following way:

$$R_{rand_1} = V_4 \oplus V_1^{\mathcal{A}} \tag{17}$$

Leakage of users random number leads to the server impersonation attack as described in the next subsection.

E. SESSION-KEY LEAKAGE AND SERVER IMPERSONATION ATTACK

$U_{\mathcal{A}}$ intercepts the message $\langle V_{11}, V_{12}, T_2\rangle$ from server to user and generates its own message in the following way:

1) As described in Subsection III-B and III-C, that $U_{\mathcal{A}}$ can generate the value $h(SID_j \oplus W_j)$, and $U_{\mathcal{A}}$ also knows the identity of the U_i so he/she computes:

$$V_6^{\mathcal{A}} = h(SID_j||W_j) \tag{18}$$
$$V_7^{\mathcal{A}} = PID_i \oplus V_6^{\mathcal{A}} \tag{19}$$
$$V_8^{\mathcal{A}} = h(V_7^{\mathcal{A}}||W_j) \tag{20}$$
$$V_9^{\mathcal{A}} = V_4 \oplus V_8^{\mathcal{A}} \tag{21}$$

2) $U_{\mathcal{A}}$ selects an arbitrary nonce $R^{\mathcal{A}}_{rand_2}$, the present timestamp $T_2^{\mathcal{A}}$ and calculates:

$$V_{11}^{\mathcal{A}} = h(V_8^{\mathcal{A}}||R_{rand_1}) \oplus R^{\mathcal{A}}_{rand_2} \tag{22}$$
$$SK_{ij} = h(V_6^{\mathcal{A}}||V_8^{\mathcal{A}}||V_9^{\mathcal{A}}||R^{\mathcal{A}}_{rand_2}||T_2^{\mathcal{A}}) \tag{23}$$
$$V_{12}^{\mathcal{A}} = h(SK_{ij}||V_8^{\mathcal{A}}||V_9^{\mathcal{A}||T_2^{\mathcal{A}}}) \tag{24}$$

Finally, $U_{\mathcal{A}}$ sends the message containing $\langle V_{11}^{\mathcal{A}}, V_{12}^{\mathcal{A}}, T_2^{\mathcal{A}}\rangle$ to U_i.

3) U_i receives the message forged by the $U_{\mathcal{A}}$, and examines the novelty of time-stamp $T_2^{\mathcal{A}}$, as it is fresh, hence $U_{\mathcal{A}}$ passes this test.

4) Now, U_i computes:

$$V_{13} = V_{11}^{\mathcal{A}} \oplus h(V_1||R_{rand_1}) \oplus R_{rand_1} \tag{25}$$
$$SK_{ij} = h(V_1||V_2||R_{rand_1}||V_{13}||T_2^{\mathcal{A}}) \tag{26}$$
$$V_{14} = h(SK_{ij}||V_1||R_{rand_1}||T_2^{\mathcal{A}}) \tag{27}$$

5) U_i now verifies:

$$V_{12} \stackrel{?}{=} V_{14} \tag{28}$$

6) U_i considers $U_{\mathcal{A}}$ as genuine MS_j if Eq. 28 holds and process the next steps to complete the authentication process. It can be clearly seen that Eq. 28 holds, as SK_{ij} calculated by U_i in Eq. 26 is identical to that calculated by $U_{\mathcal{A}}$ in Eq. 23. Similarly, V_1 is also the same as $V_8^{\mathcal{A}}$ computed by $U_{\mathcal{A}}$ in Eq. 20. Therefore, $U_{\mathcal{A}}$ has successfully launched server impersonation attack using the stolen verifier.

TABLE 1. Notation guide.

Symbols	Representations
U_i, PID_i, PWD_i	The patients name, unique personal identity and password
$Gen(.), Rep(.)$	Probabilistic generation and deterministic reproduction functions of fuzzy extractor, respectively
SC_i, PWD_i	The smart-card and pseudo-random-password U_i
RC, K_{RC}	The registration centre, and its secret key
S_j, SID_j, S_{priv_j}	The server, its unique identity and secret key
t, σ_i, τ_i	Error tolerance threshold, Biometric secret-key & public reproduction parameter, respectively
SK_{ij}	Session-key between U_i and S_j
$T, \triangle T$	Timestamp, Maximum allowable transmission delay
$i \overset{?}{=} j$	Checks if i equals to j
$h(.), \oplus, \|\|$	Hash function, Bitwise XOR and concatenation operators
$\mathcal{A}, \mathcal{U}_{\mathcal{A}}, \mathcal{I}$	Adversary symbols

Server (S_j)	Registration centre (RC)
Selects identity SID_j $\xrightarrow[(S_j \rightarrow RC\ via\ secure\ channel)]{\langle SID_j \rangle}$	
	Compute $S_{priv_j} = h(SID_j\|\|K_{RC})$ $\xleftarrow[(S_j \leftarrow RC\ via\ secure\ channel)]{\langle S_{priv_j} \rangle}$
Save S_{priv_j}	

FIGURE 1. Server registration.

IV. PROPOSED SCHEME

This section manifests the improved three-factor symmetric-key based secure AKA scheme for multi-server environments (ITSSAKA-MS), specifically proposed to vanquish the defects exist in [5]. The proposed scheme consists of three phases which are further divided into sub-phases. The notation utilized in the proposed scheme are depicted in Table 1. The scheme is described in the subsequent subsections:

A. REGISTRATION PROCESS

This phase explains the procedure of registering the users and servers:

1) SERVER REGISTRATION PROCESS

All of the medical servers $MS_j(1 \leq j \leq m + m')$ in the proposed scheme have to register with the registration center (RC), where m are the currently registered servers and m' are the servers which may be registered in the future. For registration as presented in Figure 1, each server $S_j(S_j : 1 \leq j \leq m)$ selects it's identity SID_j and sends it to the RC and the RC computes $S_{priv_j} = h(SID_j||K_{RC})$ and sends S_{priv_j} to S_j, which saves it in its' database.

2) USER REGISTRATION PROCESS

All of the users U_i need to register with the RC in order to avail the services. With respect to Figure 2, U_i and RC performs these steps to complete the registration:

RG1: User chooses his/her PID_i, PWD_i and imprints BIO_i, computes $HID_i = h(PID_i)$ and sends registration request containing HID_i to RC.

User (U_i)	Registration centre (RC)
Selects PID_i, PWD_i, imprint BIO_i and compute $HID_i = h(PID_i)$ $\xrightarrow[(U_i \rightarrow RC\ via\ secure\ channel)]{\langle HID_i \rangle}$	
	Selects a random number R_{rand_1}, and temporary identity $TPID_i$ Compute $Auth_i = h(K_{RC}\|\|HID_i\|\|R_{rand_1})$ $K_i = h(HID_i\|\|R_{rand_1})$ $R_i = E_{K_{RC}\{Auth_i, R_{rand_1}, HID_i\}}$ Store $\{K_i, R_i, TPID_i\}$ into the SC_i $\xleftarrow[(U_i \leftarrow RC\ via\ secure\ channel)]{\langle Smart-card \rangle}$
Computes $Gen(BIO_i) = (\sigma_i, \tau_i)$ $A_i = h(PID_i\|\|PWD_i\|\|\sigma_i)$ $R_i^{'} = R_i \oplus h(PWD_i\|\|\sigma_i)$ $K_i^{'} = K_i \oplus h(PWD_i\|\|\sigma_i)$ $TPID_i^{'} = TPID_i \oplus h(PWD_i\|\|\sigma_i)$ Replace $\{R_i, K_i, TPID_i\}$ with $\{R_i^{'}, K_i^{'}, TPID_i^{'}\}$ *Finally* SC_i *contains* $\{A_i, K_i^{'}, R_i^{'}, TPID_i^{'}, h(.), Gen(.), Rep(.), \tau_i, t\}$	

FIGURE 2. User registration.

RG2: RC Selects R_{rand_1} and a temporary identity $TPID_i$. RC Compute $Auth_i = h(K_{RC}||HID_i||R_{rand_1})$, $R_i = E_{K_{RC}}(Auth_i, R_{rand_i}, HID_i)$, $K_i = h(HID_i||R_{rand_1})$. Finally, RC stores $\{K_i, R_i, TID_i\}$ into the SC_i and transmits it to the U_i via secure channel.

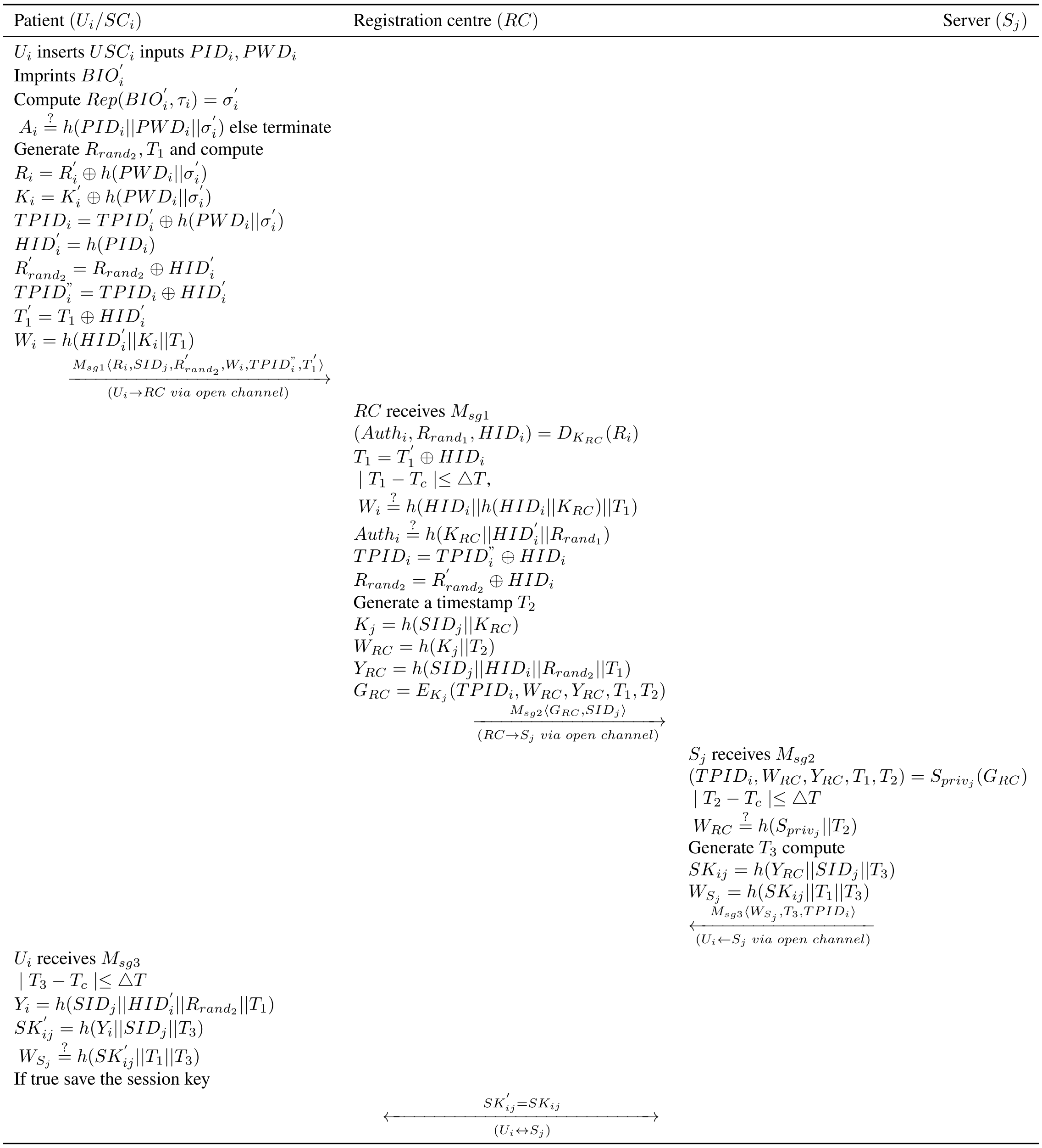
RG3: User compute $Gen(BIO_i) = (\sigma_i, \tau_i)$, $A_i = h(PID_i||PWD_i||\sigma_i)$, $R_i' = R_i \oplus h(PWD_i||\sigma_i)$, $K_i' = K_i \oplus h(PWD_i||\sigma_i)$, $TPID_i' = TPID_i \oplus h(PWD_i||\sigma_i)$. Replaces R_i, K_i, TID_i with R_i', K_i', TID_i' and stores $\{R_i', K_i', TID_i', h(.), Gen(.), Rep(.), \tau_i, t\}$.

B. LOGIN AND KEY-ESTABLISHMENT PROCESS

Following are the steps performed by U_i to login to MS_j as discussed in Figure 3:

LA1: User U_i inserts SC_i, inputs PID_i, PWD_i, imprints his/her BIO_i'. U_i now computes $Rep(BIO_i', \tau_i) = \sigma_i'$, checks if $A_i \overset{?}{=} h(PID_i||PWD_i||\sigma_i')$, terminate the request if it is in-equal. U_i generates R_{rand_2}, T_1 and computes $R_i = R_i' \oplus h(PWD_i||\sigma_i')$, $K_i = K_i' \oplus h(PWD_i||\sigma_i')$, $TPID_i = TPID_i' \oplus h(PWD_i||\sigma_i')$, $HID_i' = h(PID_i)$, $R'_{rand_2} = R_{rand_2} \oplus HID_i'$, $SID_j' = SID_j \oplus HID_i'$ $TPID_i' = TPID_i \oplus HID_i'$, $W_i = h(HID_i'||T_1)$. U_i now transmits the $M_{sg1} = \langle R_i, SID_j', R_{rand_2}, W_i, TPID_i, T_1 \rangle$ to RC.

LA2: RC receives M_{sg1}, checks the condition $| T_1 - T_c | \leq \triangle T$, if true computes $(Auth_i, R_{rand_i}, HID_i) = D_{K_{RC}}(R_i)$, and checks $W_i \overset{?}{=} h(HID_i||T_1)$, and $Auth_i \overset{?}{=} h(K_{RC} ||HID_i'||R_{rand_1})$, terminates if any of these or both are not valid. RC now computes $TPID_i = TPID_i' \oplus HID_i$, $R_{rand_2} = R'_{rand_2} \oplus HID_i$, $SID_j = SID_j' \oplus HID_i$. RC generates a timestamp T_2 and computes $K_j = h(SID_j||K_{RC})$, $W_{RC} = h(Key_j||T_2)$, $Y_{RC} = h(SID_j||HID_i||R_{rand_2}||T_1)$,



Patient (U_i/SC_i) | Registration centre (RC) | Server (S_j)

U_i inserts USC_i inputs PID_i, PWD_i
Imprints $BIO_i^{'}$
Compute $Rep(BIO_i^{'}, \tau_i) = \sigma_i^{'}$
$A_i \overset{?}{=} h(PID_i||PWD_i||\sigma_i^{'})$ else terminate
Generate R_{rand_2}, T_1 and compute
$R_i = R_i^{'} \oplus h(PWD_i||\sigma_i^{'})$
$K_i = K_i^{'} \oplus h(PWD_i||\sigma_i^{'})$
$TPID_i = TPID_i^{'} \oplus h(PWD_i||\sigma_i^{'})$
$HID_i^{'} = h(PID_i)$
$R_{rand_2}^{'} = R_{rand_2} \oplus HID_i^{'}$
$TPID_i^{"} = TPID_i \oplus HID_i^{'}$
$T_1^{'} = T_1 \oplus HID_i^{'}$
$W_i = h(HID_i^{'}||K_i||T_1)$

$$\xrightarrow[(U_i \rightarrow RC\ via\ open\ channel)]{M_{sg1}\langle R_i, SID_j, R_{rand_2}^{'}, W_i, TPID_i^{"}, T_1^{'}\rangle}$$

RC receives M_{sg1}
$(Auth_i, R_{rand_1}, HID_i) = D_{K_{RC}}(R_i)$
$T_1 = T_1^{'} \oplus HID_i$
$| T_1 - T_c |\leq \triangle T,$
$W_i \overset{?}{=} h(HID_i||h(HID_i||K_{RC})||T_1)$
$Auth_i \overset{?}{=} h(K_{RC}||HID_i^{'}||R_{rand_1})$
$TPID_i = TPID_i^{"} \oplus HID_i$
$R_{rand_2} = R_{rand_2}^{'} \oplus HID_i$
Generate a timestamp T_2
$K_j = h(SID_j||K_{RC})$
$W_{RC} = h(K_j||T_2)$
$Y_{RC} = h(SID_j||HID_i||R_{rand_2}||T_1)$
$G_{RC} = E_{K_j}(TPID_i, W_{RC}, Y_{RC}, T_1, T_2)$

$$\xrightarrow[(RC \rightarrow S_j\ via\ open\ channel)]{M_{sg2}\langle G_{RC}, SID_j\rangle}$$

S_j receives M_{sg2}
$(TPID_i, W_{RC}, Y_{RC}, T_1, T_2) = S_{priv_j}(G_{RC})$
$| T_2 - T_c |\leq \triangle T$
$W_{RC} \overset{?}{=} h(S_{priv_j}||T_2)$
Generate T_3 compute
$SK_{ij} = h(Y_{RC}||SID_j||T_3)$
$W_{S_j} = h(SK_{ij}||T_1||T_3)$

$$\xleftarrow[(U_i \leftarrow S_j\ via\ open\ channel)]{M_{sg3}\langle W_{S_j}, T_3, TPID_i\rangle}$$

U_i receives M_{sg3}
$| T_3 - T_c |\leq \triangle T$
$Y_i = h(SID_j||HID_i^{'}||R_{rand_2}||T_1)$
$SK_{ij}^{'} = h(Y_i||SID_j||T_3)$
$W_{S_j} \overset{?}{=} h(SK_{ij}^{'}||T_1||T_3)$
If true save the session key

$$\xleftrightarrow[(U_i \leftrightarrow S_j)]{SK_{ij}^{'} = SK_{ij}}$$

FIGURE 3. Login and Key-establishment.

$G_{RC} = E_{K_j}(TID_i, W_{RC}, Y_{RC}, T_1, T_2)$. RC sends the $M_{sg2}\langle G_{RC}, SID_j\rangle$ to the medical server MS_j.

LA3: MS_j receives M_{sg2} from RC and computes $(TID_i, W_{RC}, Y_{RC}, T_1, T_2) = D_{Key_j}(G_{RC})$. RC now validates the timeliness of the message by the condition $| T_2 - T_c |\leq \triangle T$ and checks $W_{RC} \overset{?}{=} h(MS_{priv_j}||T_2)$. On successful validations, MS_j generates timestamp T_3 and computes $SK_{ij} = h(Y_{RC}||SID_j||T_3)$, $W_{MS_j} = h(SK_{ij}||T_1||T_3)$, MS_j sends message $M_{sg3}\langle W_{MS_j}, T_3, TID_i\rangle$ directly to U_i.

LA4: User U_i receives M_{sg3} and confirms the the freshness of the message by the condition $| T_3 - T_c |\leq \triangle T$. User U_i computes $Y_i = h(SID_j||HID_i^{'}||R_{rand_2}||T_1)$, $SK_{ij}^{'} = h(Y_i||SID_j||T_3)$, $W_{MS_j} \overset{?}{=} h(SK_{ij}^{'}||T_1||T_3)$, If true saves the session key for future communication.

C. UPDATE PROCESS

This phase contains two sub-phases namely i) password and biometric update phase, ii) new user addition, revocation and re-registration phase.

1) PASSWORD AND BIOMETRIC UPDATE PROCESS

To decrease the communication and computation cost, this phase is performed without the involvement of the RC. Following are the actions committed in this phase:

PBU 1: U_i inputs his/her SC_i, enters the old PID_i^{old}, PWD_i^{old} and imprints BIO_i^{old}.

PBU 2: SC_i computes $Rep(BIO_i^{old}, \tau_i) = \sigma_i^{old}$ and checks $A_i^{old} \overset{?}{=} h(PID_i^{old}||PWD_i^{old}||\sigma_i^{old})$, if true continues else terminate the process.

PBU 3: SC_i prompts the U_i to provide novel password PWD_i^{new} and biometric BIO_i^{new} and computes $A_i = h(PID_i^{old}||PWD_i^{new}||\sigma_i^{new})$, $R_i^{new} = R_i' \oplus h(PWD_i^{old}||\sigma_i^{old}) \oplus h(PWD_i^{new}||\sigma_i^{new}) = R_i \oplus h(PWD_i^{new}||\sigma_i^{new})$, $k_i^{new} = k_i' \oplus h(PWD_i^{old}||\sigma_i^{old}) \oplus h(PWD_i^{new}||\sigma_i^{new}) = K_i \oplus h(PWD_i^{new}||\sigma_i^{new})$ and $TPID_i^{new} = TPID_i' \oplus h(PWD_i^{old}||\sigma_i^{old}) \oplus h(PWD_i^{new}||\sigma_i^{new}) = TPID_i \oplus h(PWD_i^{new}||\sigma_i^{new})$

PBU 4: SC_i replaces the parameters $\{A_i, K_i', R_i'\}$ with $\{A_i^{new}, K_i^{new}, R_i^{new}$. SC_i finally contains the following parameters $\{A_i^{new}, K_i^{new}, R_i^{new}, TPID_i^{new}, h(.), Gen(.), Rep(.), \tau_i^{new}, t\}$

2) NEW USER ADDITION, REVOCATION AND RE-REgistration PROCESS

If a legal user has misplaced the SC_i, stolen by an adversary or some novel user needs to register with the system this can be accomplished in the following manner:

NUARR 1: U_i^{new} enters the identity PID_i^{new} (old user may enter the same old or new identity) and transmits the registration request containing $HID_i = h(PID_i^{new})$ to RC via secure channel.

NUARR 2: RC selects the temporary-identity $TPID_i^{new}$ for U_i and computes the following $Auth_i^{new} = h(K_{RC}||HID_i^{new}||R_{rand_1}^{new})$, $K_i^{new} = h(HID_i^{new}||R_{rand_1}^{new})$ and $R_i^{new} = E_{K_{RC}}(Auth_i^{new}, R_{rand_1}^{new}, HID_i^{new})$. Finally, RC stores $\{K_i^{new}, R_i^{new}, TPID_i^{new}\}$ into the smart-card SC_i^{new} and then transmits the SC_i^{new} to U_i^{new} over the private/secure channel.

NUARR 3: U_i^{new} receives the the smart-card imprints the biometric BIO_i^{new} and computes $Gen(BIO_i^{new}) = (\sigma_i^{new}, \tau_i^{new})$, $A_i^{new} = h(PID_i^{new}||\ PWD_i^{new}\ ||\sigma_i^{new})$, $R_i' = R_i^{new} \oplus h(PWD_i^{new}||\sigma_i^{new})$, $K_i' = K_i^{new} \oplus h(PWD_i^{new}||\sigma_i^{new})$ and $TPID_i' = TPID_i^{new} \oplus h(PWD_i^{new}||\sigma_i^{new})$.

NUARR 4: SC_i^{new} replaces the R_i^{new}, K_i^{new}, $TPID_i^{new}$ with $R_i', K_i', TPID_i'$. Smart-card finally contains the following parameters $\{A_i^{new}, K_i', R_i', TPID_i', h(.), Gen(.), Rep(.), \tau_i^{new}, t\}$.

V. SECURITY ANALYSIS

This portion elaborates the formal and informal security discussion:

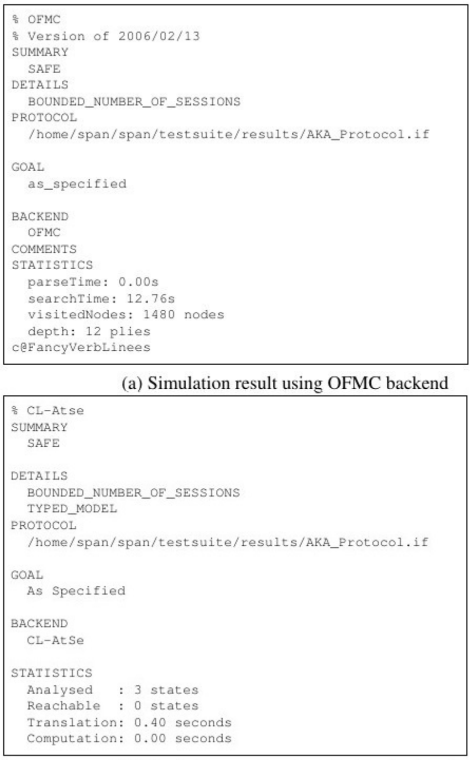
A. AUTOMATED FORMAL SECURITY VERIFICATION THROUGH AVISPA

This section demonstrates that the scheme can withstand the man-in-the-middle and replay attack verified through widely used AVISPA simulation tool [52]. AVISPA simulation can be performed in the subsequent steps:

Step 1: The role oriented High Level schemes Specification Language (HLPSL) [52] is used to implement the scheme, which is then interpreted into Intermediate Format (IF) through HLPSL2IF translator.

Step 2: Than the translated IF is provided to Output Format (OF) to check either the scheme is secure or not.

The simulation results shown in Figure 4a and Figure 4b exhibit that the proposed scheme is as per to the design properties, and can stand against the man-in-the-middle and replay attacks. In the OFMC backend, a total of 1480 nodes were examined in 12.76 seconds with the depth of 12 piles. The CL-AtSe backend analyzed 3 states the interpretation and computation taken for this backend are 0.40 seconds and 0.00 seconds, individually.



```
% OFMC
% Version of 2006/02/13
SUMMARY
  SAFE
DETAILS
  BOUNDED_NUMBER_OF_SESSIONS
PROTOCOL
  /home/span/span/testsuite/results/AKA_Protocol.if

GOAL
  as_specified

BACKEND
  OFMC
COMMENTS
STATISTICS
  parseTime: 0.00s
  searchTime: 12.76s
  visitedNodes: 1480 nodes
  depth: 12 plies
c@FancyVerbLinees
```

(a) Simulation result using OFMC backend

```
% CL-Atse
SUMMARY
  SAFE

DETAILS
  BOUNDED_NUMBER_OF_SESSIONS
  TYPED_MODEL
PROTOCOL
  /home/span/span/testsuite/results/AKA_Protocol.if

GOAL
  As Specified

BACKEND
  CL-AtSe

STATISTICS
  Analysed   : 3 states
  Reachable  : 0 states
  Translation: 0.40 seconds
  Computation: 0.00 seconds
```

(b) Simulation result using CL-Atse backend

FIGURE 4. Simulation result of the AVISPA tool.

B. SECURITY DISCUSSION

The subsection provides a brief discussion on security features provision of the proposed ITSSAKA-MS:

1) USER ANONYMITY

In proposed ITSSAKA-MS, the user sends $M_{sg1}\langle R_i, SID_j', R_{rand_2}, W_i, TPID_i, T_1\rangle$, out of all the sent parameter only $TPID_i$ is related to user identity and it is alias identity stored in smart card, using this alias identity or anyother parameter sent on public channel may not benefit the attacker $\mathcal{A}$ to reveal original identity of the user, eve if $\mathcal{A}$ steals the smart-card and tries to recover the identity of the patient, to do this he/she needs to know PID_i, PWD_i of the user. Also hashed-identity is stored in A_i, but to extract it $\mathcal{A}$ needs to know the secret-key of RC. Addition to this U_i's identity is never shared with the server, neither is send openly over the public channel. Hence the scheme provides anonymity.

2) PRIVILEGED INSIDER ATTACK

During the registration process identity of the U_i is secured by hash-functions one-way property, so an insider cannot guess the U_i's identity. Also no verifier-table is stored on the RC, so an insider cannot extract any info. Additionally, if an insider steals the smart-card and tries to extract the U_i's password or identity, yet this is not possible because they are in hashed form. Hence, the said attack is not possible.

3) OFFLINE PASSWORD GUESSING ATTACK

Suppose an adversary $\mathcal{A}$ steals the smart-card of a legal user U_i, and tries to extract the password from $A_i = h(PID_i||PWD_i||\sigma_i)$ and to be successful, $\mathcal{A}$ needs the knowledge of PID_i and σ_i. Therefore, the offline password guessing attack is not conceivable in the proposed scheme.

4) IMPERSONATION ATTACK

A User (U_i) or a server (S_j) may try to impersonate as an adversary $\mathcal{A}$ in the subsequent ways:

a: USER IMPERSONATION ATTACK

Suppose $U_{\mathcal{A}}$ is a valid but dishonest user and may try to impersonate as a legal user U_i. $U_{\mathcal{A}}$ may generate its own random number $R^{\mathcal{A}}_{rand_2}$ and current time-stamp $T_1^{\mathcal{A}}$. Next he/she tries to compute $R^{\mathcal{A}'}_{rand_2} = R^{\mathcal{A}}_{rand_2} \oplus HID_i$, $W_i^{\mathcal{A}} = h(HID_i'||K_i||T_1^{\mathcal{A}})$, $TPID_i^{\mathcal{A}'} = TPID_i \oplus HID_i$ in order to initiate a genuine login request message. However, $U_{\mathcal{A}}$ needs the knowledge of PID_i and K_i to impersonate as a U_i and form a legal message, so the scheme is secure against the said attack.

b: RESISTS SERVER IMPERSONATION ATTACK

An intruder $\mathcal{A}$ may impersonate as an authentic server S_j towards U_i. To do this $\mathcal{A}$ generates the timestamp $T_3^{\mathcal{A}}$ and has to compute $SK_{ij}^{\mathcal{A}} = h(Y_{RC}||SID_j||T_3^{\mathcal{A}})$, $W_{S_j}^{\mathcal{A}} = h(SK_{ij}^{\mathcal{A}}||T_1||T_3^{\mathcal{A}})$. To produce a legal message $\mathcal{A}$ should have the knowledge of Y_{RC} and T_1. Hence, the said attack is not possible.

5) MUTUAL AUTHENTICATION

The RC authenticates the user on validation of three conditions: 1) the freshness of timestamp, 2)$W_i \overset{?}{=} h(HID_i||h(HID_i||K_{RC})||T_1)$, and 3) $Auth_i \overset{?}{=} h(K_{RC}|| HID_i'||R_{rand_1})$. The verification of these 3 dependent conditions require the knowledge of K_{RC}, HID_i and R_{rand_1}. In similar way, S_j authenticates RC on validation of two conditions: 1) the freshness of timestamp, and 2) $W_{RC} \overset{?}{=} h(S_{priv_j}||T_2)$, both of these are also dependent on each other and on the knowledge of S_{priv_j}. Similarly, only valid and legal S_j can generate $M_{sg3}\langle W_{S_j}, T_3, TPID_i\rangle$ as described in V-B4b. Hence, the entities of the proposed scheme can mutually authenticate each other.

6) REPLAY ATTACK

Random nonce and timestamp are generated in each session to stop the replay attack in our scheme. If an intruder $\mathcal{A}$ intercepts the messages $\langle M_{sg1}, M_{sg2}, M_{sg3}\rangle$ during the login and authentication phase and tries to replay it, the attacker presence can be checked by checking the freshness of the timestamp. Also, timestamp is hashed with other parameters making it hard for the $\mathcal{A}$ to replay the old message.

TABLE 2. Comparison of functionality features.

Scheme→ ↓Features	Chaudhry [7]	Reddy et al. [53]	Irshad et al. [54]	Barman et al. [5]	Our
$F\#1$	✓	✓	✓	×	✓
$F\#2$	✓	✓	✓	✓	✓
$F\#3$	✓	✓	✓	✓	✓
$F\#4$	✓	✓	✓	✓	✓
$F\#5$	✓	✓	✓	✓	✓
$F\#6$	✓	✓	✓	✓	✓
$F\#7$	✓	✓	✓	×	✓
$F\#8$	×	✓	–	✓	✓
$F\#9$	×	✓	✓	✓	✓
$F\#10$	✓	✓	✓	×	✓
$F\#11$	×	✓	×	✓	✓
$F\#12$	✓	✓	✓	×	✓

Note: $F\#1$:User anonymity; $F\#2$:Provision of three-factor security; $F\#3$:Security against replay attack; $F\#4$:Secure against insider attack; $F\#5$:Protection against off-line password guessing attack; $F\#6$:Secure against stolen smart-card attack; $F\#7$:Protection against user impersonation attack; $F\#8$:Secure against Denial-of-service attack; $F\#9$:Provide perfect forward secrecy; $F\#10$:Mutual authentication; $F\#11$: Provision of smart-card revocation, $F\#12$:Server impersonation, where $F\#i$ is the i^{th} compared feature.

7) MAN-IN-THE-MIDDLE ATTACK

Assume an intruder $\mathcal{A}$ captures the message $M_{sg1}\langle R_i, SID_j, R'_{rand_2}, W_i, TPID_i', T_1\rangle$ and generates its own login message $M_{sg1}^{\mathcal{A}}\langle R_i^{\mathcal{A}}, SID_j^{\mathcal{A}}, R^{\mathcal{A}}_{rand_2}, W_i^{\mathcal{A}}, TPID_i^{\mathcal{A}}, T_1^{\mathcal{A}}\rangle$, but to do this $\mathcal{A}$ needs to know HID_i, R_{rand_2} and K_i. In the same way $\mathcal{A}$ needs to know Y_{RC} and T_1 to generate the message M_{sg3}, so said attack cannot be employed against the proposed attack.

8) STOLEN SMART-CARD ATTACK

Assume an attacker $\mathcal{A}$ steals the smart-card of a legal user U_i and tries to extract his/her PWD_i or PID_i. However, because of hash functions one-way property these parameters cannot be guessed, also $\mathcal{A}$ needs to know σ_i to correctly guess the PWD_i. Hence scheme is secure against the stolen smart-card attack.

VI. PERFORMANCE ANALYSIS

This section evaluates the proposed scheme with regard to computation, communication costs and security features provision concerning other multi-server authentication schemes.

A. FUNCTIONALITY COMPARISON

The Table 2 depicts the merits and demerits of of the proposed scheme associated to related schemes [5], [7], [53], [54]. Different schemes lack various security features. In contrast, our scheme fulfills all the necessary security requirements and is secure against various attacks in multi-server environment.

B. COMPUTATION COST ANALYSIS

For computation costs comparison, different operation timings [55] are depicted in the Table 3. Table 4 depicts that though, the cost of the proposed scheme is slightly higher than [5], [7], [54] and same as [53], but it is evident that the

TABLE 3. Approximate time required for various operations.

Notation	Description	computation time
T_h	$Hash\ function$	$0.0023ms$
T_m	$ECC\ point\ multiplication$	$0.0046ms$
T_{spm}	$Symmetric\ enc/dec$	$2.226ms$
T_{fe}	$Fuzzy\ extractor\ function$	$2.226ms$

TABLE 4. Comparison of computation costs.

Scheme	User	RC	Server	Time (ms)
[7]	5T$_h$	7T$_h$+2T$_{sym}$	12T$_h$	≈4.4796ms
[53]	6T$_h$+1T$_m$	9T$_h$+3T$_m$	15T$_h$ $+ 4T_m$	≈8.9385ms
[54]	8T$_h$	13T$_h$+2T$_{spm}$	21T$_h$+2T$_{spm}$	≈0.0575ms
[5]	3T$_h$+1Tf$_e$	11T$_h$	14T$_h$+1T$_{fe}$	≈2.2582ms
Our	6T$_h$+1T$_{fe}$	2$_{spm}$+6T$_h$	3T$_h$+1$_{spm}$	≈8.9385ms

TABLE 5. Comparison of communication costs.

Scheme	# of bits
Chaudhry et al. [7]	1024
Reddy et al. [53]	1280
Irshad et al. [54]	864
Barman et al. [5]	1116
Proposed	2144

proposed scheme is robust and more secure than the other schemes.

C. COMMUNICATION COST ANALYSIS

The Table 5 shows the communication costs of different schemes in multi-server environment. We assumed that the hash digest (SHA-1), user identity, elliptic curve crypto-based point (x_p, y_p), arbitrary number and timestamp requires respectively $160-bits$, $160-bits$, $320-bits$, $160-bits$, and $32-bits$. The proposed scheme bears an average computational cost of 2144-bits, which is slightly greater than then the other related and compared schemes [5], [7], [53], [54]; but it come up with more security features as compared to other related schemes.

VII. CONCLUSION

In this paper, we have critically analyzed the some shortcomings including vulnerabilities against user impersonation, secret key reveal, lack of anonymity and design flaws of the scheme of Barman *et al.* proposed specifically for multi-server environments and usable in telecare medical information systems. In contrast, our study presents an improved three-factor symmetric-key based secure authenticated key agreement scheme for multi-server environments (ITSSAKA-MS). The security of ITSSAKA-MS is proved formally through automated tool AVISPA. Moreover, the security discussion argued the robustness of ITSSAKA-MS against the known attacks. The performance analysis is presented keeping the communication and computation costs as metrics. The ITSSAKA-MS incurred slightly additional computation and communication costs, mainly to provide the better security as compared to the recent schemes.

REFERENCES

[1] Y. Zhang, L. Sun, H. Song, and X. Cao, "Ubiquitous WSN for healthcare: Recent advances and future prospects," *IEEE Internet Things J.*, vol. 1, no. 4, pp. 311–318, Aug. 2014.

[2] U. Gogate and J. Bakal, "Refining healthcare monitoring system using wireless sensor networks based on key design parameters," in *Information and Communication Technology for Intelligent Systems*. Singapore: Springer, 2019, pp. 341–349.

[3] S. Gritzalis, C. Lambrinoudakis, D. Lekkas, and S. Deftereos, "Technical guidelines for enhancing privacy and data protection in modern electronic medical environments," *IEEE Trans. Inf. Technol. Biomed.*, vol. 9, no. 3, pp. 413–423, Sep. 2005.

[4] M. S. Farash, O. Nawaz, K. Mahmood, S. A. Chaudhry, and M. K. Khan, "A provably secure RFID authentication protocol based on elliptic curve for healthcare environments," *J. Med. Syst.*, vol. 40, no. 7, p. 165, Jul. 2016.

[5] S. Barman, H. P. H. Shum, S. Chattopadhyay, and D. Samanta, "A secure authentication protocol for multi-server-based E-healthcare using a fuzzy commitment scheme," *IEEE Access*, vol. 7, pp. 12557–12574, 2019.

[6] S.-H. Li, C.-Y. Wang, W.-H. Lu, Y.-Y. Lin, and D. C. Yen, "Design and implementation of a telecare information platform," *J. Med. Syst.*, vol. 36, no. 3, pp. 1629–1650, Jun. 2012.

[7] S. A. Chaudhry, H. Naqvi, and M. K. Khan, "An enhanced lightweight anonymous biometric based authentication scheme for TMIS," *Multimedia Tools Appl.*, vol. 77, no. 5, pp. 5503–5524, Mar. 2018.

[8] K. Mahmood, J. Arshad, S. A. Chaudhry, and S. Kumari, "An enhanced anonymous identity-based key agreement protocol for smart grid advanced metering infrastructure," *Int. J. Commun. Syst.*, vol. 32, no. 16, p. e4137, Nov. 2019.

[9] A. Ghani, K. Mansoor, S. Mehmood, S. A. Chaudhry, A. U. Rahman, and M. N. Saqib, "Security and key management in IoT-based wireless sensor networks: An authentication protocol using symmetric key," *Int. J. Commun. Syst.*, vol. 32, no. 16, p. e4139, Nov. 2019.

[10] S. Hussain and S. A. Chaudhry, "Comments on 'biometrics-based privacy-preserving user authentication scheme for cloud-based industrial Internet of Things deployment,'" *IEEE Internet Things J.*, vol. 6, no. 6, pp. 10936–10940, Dec. 2019.

[11] B. A. Alzahrani, S. A. Chaudhry, A. Barnawi, A. Al-Barakati, and T. Shon, "An anonymous device to device authentication protocol using ECC and self certified public keys usable in Internet of Things based autonomous devices," *Electronics*, vol. 9, no. 3, p. 520, Mar. 2020.

[12] Z.-Y. Wu, Y.-C. Lee, F. Lai, H.-C. Lee, and Y. Chung, "A secure authentication scheme for telecare medicine information systems," *J. Med. Syst.*, vol. 36, no. 3, pp. 1529–1535, Jun. 2012.

[13] H. Debiao, C. Jianhua, and Z. Rui, "A more secure authentication scheme for telecare medicine information systems," *J. Med. Syst.*, vol. 36, no. 3, pp. 1989–1995, Jun. 2012.

[14] Z. Zhu, "An efficient authentication scheme for telecare medicine information systems," *J. Med. Syst.*, vol. 36, no. 6, pp. 3833–3838, Dec. 2012.

[15] M.-S. Hwang and L.-H. Li, "A new remote user authentication scheme using smart cards," *IEEE Trans. Consum. Electron.*, vol. 46, no. 1, pp. 28–30, Feb. 2000.

[16] M. Sandirigama, A. Shimizu, and M. T. Noda, "Simple and secure password authentication protocol (SAS)," *IEICE Trans. Commun.*, vol. 83, no. 6, pp. 1363–1365, 2000.

[17] H. Arshad and M. Nikooghadam, "An efficient and secure authentication and key agreement scheme for session initiation protocol using ECC," *Multimedia Tools Appl.*, vol. 75, no. 1, pp. 181–197, 2016.

[18] Z. Zhang, Q. Qi, N. Kumar, N. Chilamkurti, and H.-Y. Jeong, "A secure authentication scheme with anonymity for session initiation protocol using elliptic curve cryptography," *Multimedia Tools Appl.*, vol. 74, no. 10, pp. 3477–3488, May 2015.

[19] S. Challa, A. K. Das, V. Odelu, N. Kumar, S. Kumari, M. K. Khan, and A. V. Vasilakos, "An efficient ECC-based provably secure three-factor user authentication and key agreement protocol for wireless healthcare sensor networks," *Comput. Electr. Eng.*, vol. 69, pp. 534–554, Jul. 2018.

[20] C.-T. Li and M.-S. Hwang, "An efficient biometrics-based remote user authentication scheme using smart cards," *J. Netw. Comput. Appl.*, vol. 33, no. 1, pp. 1–5, Jan. 2010.

[21] H. Arshad and M. Nikooghadam, "Three-factor anonymous authentication and key agreement scheme for telecare medicine information systems," *J. Med. Syst.*, vol. 38, no. 12, p. 136, Dec. 2014.

[22] K. Srivastava, A. K. Awasthi, S. D. Kaul, and R. C. Mittal, "A hash based mutual RFID tag authentication protocol in telecare medicine information system," *J. Med. Syst.*, vol. 39, no. 1, p. 153, Jan. 2015.

[23] K. Mansoor, A. Ghani, S. Chaudhry, S. Shamshirband, S. Ghayyur, and A. Mosavi, "Securing IoT-based RFID systems: A robust authentication protocol using symmetric cryptography," *Sensors*, vol. 19, no. 21, p. 4752, Nov. 2019.

[24] S. A. Chaudhry, T. Shon, F. Al-Turjman, and M. H. Alsharif, "Correcting design flaws: An improved and cloud assisted key agreement scheme in cyber physical systems," *Comput. Commun.*, vol. 153, pp. 527–537, Mar. 2020.

[25] J.-Y. Liu, A.-M. Zhou, and M.-X. Gao, "A new mutual authentication scheme based on nonce and smart cards," *Comput. Commun.*, vol. 31, no. 10, pp. 2205–2209, Jun. 2008.

[26] X. Xu, P. Zhu, Q. Wen, Z. Jin, H. Zhang, and L. He, "A secure and efficient authentication and key agreement scheme based on ECC for telecare medicine information systems," *J. Med. Syst.*, vol. 38, no. 1, p. 9994, Nov. 2013.

[27] D. He, N. Kumar, S. Zeadally, A. Vinel, and L. T. Yang, "Efficient and privacy-preserving data aggregation scheme for smart grid against internal adversaries," *IEEE Trans. Smart Grid*, vol. 8, no. 5, pp. 2411–2419, Sep. 2017.

[28] C. Lin, D. He, N. Kumar, K.-K.-R. Choo, A. Vinel, and X. Huang, "Security and privacy for the Internet of drones: Challenges and solutions," *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 64–69, Jan. 2018.

[29] Q. Pu, J. Wang, and R. Zhao, "Strong authentication scheme for telecare medicine information systems," *J. Med. Syst.*, vol. 36, no. 4, pp. 2609–2619, Aug. 2012.

[30] H.-M. Chen, J.-W. Lo, and C.-K. Yeh, "An efficient and secure dynamic ID-based authentication scheme for telecare medical information systems," *J. Med. Syst.*, vol. 36, no. 6, pp. 3907–3915, Dec. 2012.

[31] Q. Jiang, J. Ma, Z. Ma, and G. Li, "A privacy enhanced authentication scheme for telecare medical information systems," *J. Med. Syst.*, vol. 37, no. 1, pp. 1–8, Feb. 2013.

[32] S. Kumari, M. K. Khan, and R. Kumar, "Cryptanalysis and improvement of a privacy enhanced scheme for telecare medical information systems,'" *J. Med. Syst.*, vol. 37, no. 4, pp. 1–11, Aug. 2013.

[33] M.-C. Chuang and M. C. Chen, "An anonymous multi-server authenticated key agreement scheme based on trust computing using smart cards and biometrics," *Expert Syst. Appl.*, vol. 41, no. 4, pp. 1411–1418, Mar. 2014.

[34] H. Lin, F. Wen, and C. Du, "An improved anonymous multi-server authenticated key agreement scheme using smart cards and biometrics," *Wireless Pers. Commun.*, vol. 84, no. 4, pp. 2351–2362, Oct. 2015.

[35] D. Mishra, A. K. Das, and S. Mukhopadhyay, "A secure user anonymity-preserving biometric-based multi-server authenticated key agreement scheme using smart cards," *Expert Syst. Appl.*, vol. 41, no. 18, pp. 8129–8143, Dec. 2014.

[36] C. Wang, X. Zhang, and Z. Zheng, "Cryptanalysis and improvement of a biometric-based multi-server authentication and key agreement scheme," *PLoS ONE*, vol. 11, no. 2, Feb. 2016, Art. no. e0149173.

[37] Y. Lu, L. Li, X. Yang, and Y. Yang, "Robust biometrics based authentication and key agreement scheme for multi-server environments using smart cards," *PLoS ONE*, vol. 10, no. 5, May 2015, Art. no. e0126323.

[38] T. S. Messerges, E. A. Dabbish, and R. H. Sloan, "Examining smart-card security under the threat of power analysis attacks," *IEEE Trans. Comput.*, vol. 51, no. 5, pp. 541–552, May 2002.

[39] T. Eisenbarth, T. Kasper, A. Moradi, C. Paar, M. Salmasizadeh, and M. T. M. Shalmani, "On the power of power analysis in the real world: A complete break of the keeloq code hopping scheme," in *Proc. Annu. Int. Cryptol. Conf.* Berlin, Germany: Springer, 2008, pp. 203–220.

[40] P. Kocher, J. Jaffe, and B. Jun, "Differential power analysis," in *Proc. Annu. Int. Cryptol. Conf.* Berlin, Germany: Springer, 1999, pp. 388–397.

[41] D. Dolev and A. Yao, "On the security of public key protocols," *IEEE Trans. Inf. Theory*, vol. IT-29, no. 2, pp. 198–208, Mar. 1983.

[42] D. He, N. Kumar, and J.-H. Lee, "Privacy-preserving data aggregation scheme against internal attackers in smart grids," *Wireless Netw.*, vol. 22, no. 2, pp. 491–502, Feb. 2016.

[43] M. N. Aman, K. C. Chua, and B. Sikdar, "Mutual authentication in IoT systems using physical unclonable functions," *IEEE Internet Things J.*, vol. 4, no. 5, pp. 1327–1340, Oct. 2017.

[44] M. N. Aman and B. Sikdar, "ATT-auth: A hybrid protocol for industrial IoT attestation with authentication," *IEEE Internet Things J.*, vol. 5, no. 6, pp. 5119–5131, Dec. 2018.

[45] D. Wang and P. Wang, "Two birds with one stone: Two-factor authentication with security beyond conventional bound," *IEEE Trans. Dependable Secure Comput.*, vol. 15, no. 4, pp. 708–722, Aug. 2018.

[46] C.-M. Chen and W.-C. Ku, "Stolen-verifier attack on two new strong-password authentication protocols," *IEICE Trans. Commun.*, vol. 85, no. 11, pp. 2519–2521, 2002.

[47] D. He, N. Kumar, M. K. Khan, L. Wang, and J. Shen, "Efficient privacy-aware authentication scheme for mobile cloud computing services," *IEEE Syst. J.*, vol. 12, no. 2, pp. 1621–1631, Jun. 2018.

[48] C.-M. Chen, K.-H. Wang, K.-H. Yeh, B. Xiang, and T.-Y. Wu, "Attacks and solutions on a three-party password-based authenticated key exchange protocol for wireless communications," *J. Ambient Intell. Hum. Comput.*, vol. 10, no. 8, pp. 3133–3142, Aug. 2019.

[49] Z. Ali, A. Ghani, I. Khan, S. A. Chaudhry, S. H. Islam, and D. Giri, "A robust authentication and access control protocol for securing wireless healthcare sensor networks," *J. Inf. Secur. Appl.*, vol. 52, Jun. 2020, Art. no. 102502.

[50] S. A. Chaudhry, M. T. Khan, M. K. Khan, and T. Shon, "A multiserver biometric authentication scheme for tmis using elliptic curve cryptography," *J. Med. Syst.*, vol. 40, no. 11, 2016, Art. no. 230.

[51] Z. Ali, S. A. Chaudhry, M. S. Ramzan, and F. Al-Turjman, "Securing smart city surveillance: A lightweight authentication mechanism for unmanned vehicles," *IEEE Access*, vol. 8, pp. 43711–43724, 2020.

[52] A. Armando, D. Basin, J. Cuellar, M. Rusinowitch, and L. Viganò, "Avispa: Automated validation of Internet security protocols and applications," ERCIM News Jan. 2006, vol. 64.

[53] A. G. Reddy, E.-J. Yoon, A. K. Das, V. Odelu, and K.-Y. Yoo, "Design of mutually authenticated key agreement protocol resistant to impersonation attacks for multi-server environment," *IEEE Access*, vol. 5, pp. 3622–3639, 2017.

[54] A. Irshad, S. A. Chaudhry, S. Kumari, M. Usman, K. Mahmood, and M. S. Faisal, "An improved lightweight multiserver authentication scheme," *Int. J. Commun. Syst.*, vol. 30, no. 17, p. e3351, Nov. 2017.

[55] H. H. Kilinc and T. Yanik, "A survey of SIP authentication and key agreement schemes," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 2, pp. 1005–1023, 2nd Quart., 2014.

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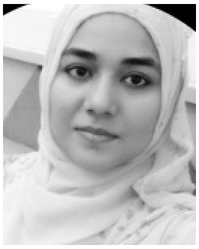

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