Securing Smart City Surveillance: A Lightweight Authentication Mechanism for Unmanned Vehicles

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ABSTRACT The significance of the Internet of Drones (IoD) is increasing steadily and now IoD is being practiced in many military and civilian-based applications. IoD facilitates real-time data access to the users especially the surveillance data in smart cities using the current cellular networks. However, due to the openness of communication channel and battery operations, the drones and the sensitive data collected through drones are subject to many security threats. To cope the security challenges, recently, Srinivas et al. proposed a temporal credential based anonymous lightweight authentication scheme (*TCALAS*) for IoD networks. Contrary to the IoD monitoring framework proposed by Srinivas et al., their own scheme can work only when there is one and only one cluster/flying zone and is not scalable. Moreover, despite their claim of robustness, the investigation in this paper reveals that Srinivas et al.'s scheme cannot resist traceability and stolen verifier attacks. Using the lightweight symmetric key primitives and temporal credentials, an improved scheme (*iTCALAS*) is then proposed. The proposed scheme while maintaining the lightweightness provides security against many known attacks including traceability and stolen verifier. The proposed *iTCALAS* extends scalability and can work when there are several flying zone/clusters in the IoD environment. The formal security proof along with automated verification using ProVerif show robustness of proposed *iTCALAS*. Moreover, the security discussion and performance comparisons show that the *iTCALAS* provides the known security features and completes authentication in just 2.295 *ms*.

INDEX TERMS Surveillance, security, key-agreement, drones, IoT, IoD, session key leakage, traceability, user anonymity.

I. INTRODUCTION

Continuous progression in information and telecommunication, hardware and software is playing a vital role in the development and increasing usage of the Internet of Things (IoT) with the abundance of connected devices increasing by the day [1]–[3]. The exceptional unprecedented propagation of IoT devices like smart-phones, medical sensors, fitness trackers etc. has permitted people to share data [4]–[6] seamlessly. IoT enables various physical devices to communicate

and collaborate and these devices can be used in a variety of fields and applications [7], [8]. IoT devices are smart enough that they can make decisions and interact with each other without the involvement of the humans. Internet of Drones (IoD) is neologized by supplanting "'Things'" with "'Drones'" from IoT while offering related properties. IoD transpires to mature into an indispensable breakthrough in the advancement of drones [9]. Gharibi *et al.* [10] described IoD being a "layered network control architecture", which supports drones in coordinating. In an IoD environment, multiple drones consolidate and create a network while conveying and acquiring data from one another. The physical and hardware
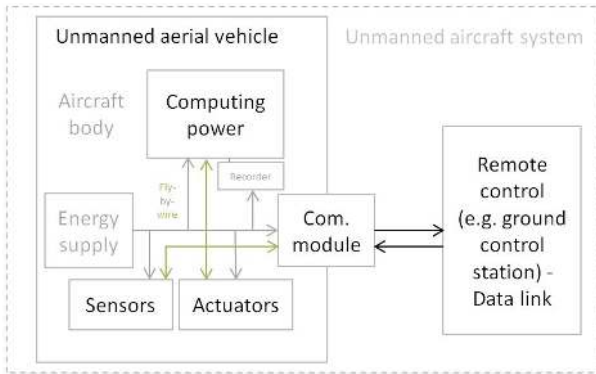
The associate editor coordinating the review of this manuscript and approving it for publication was Rongbo Zhu[ID].

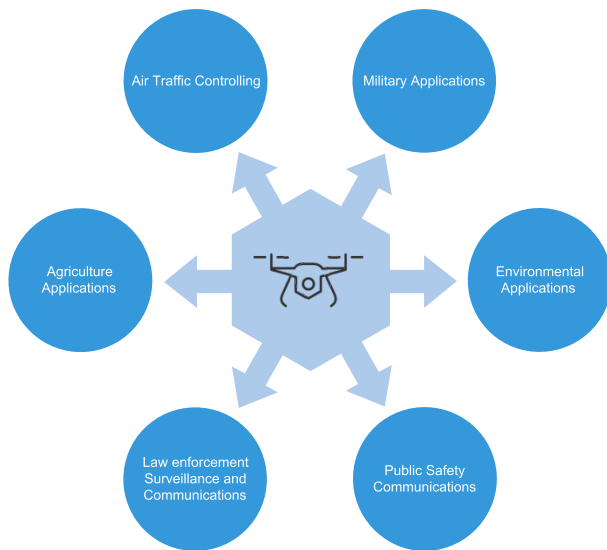**FIGURE 1.** Block diagram of a typical drone system.

FIGURE 2. IoD application areas.

structure of a typical drones also known as unmanned ariel vehicle (UAV) or unpiloted aircraft [11] is shown in Figure 1. Components of drone include a battery, multiple rotors, Inertial Measurement Unit (IMU) and a flight controller.

Currently, IoD is being widely used for surveillance, environmental monitoring, distribution delivery and in a variety of areas as presented in Figure 2.

The drones safety can be improved by tracking them and can be utilized to circumvent accidents, enhanced traffic performance, and restrain the flights of illegal drones by recognizing the more congested airspace. Most drones use Micro Aerial Vehicle Link (MAVLink) protocol for communication and telemetry functionality to monitor their status [12], [13]. The UAVs forms a collaborative network of drones (IoD) [14] to gather and consolidate environment related data such as surveillance data in smart cities or battle field monitoring, the data is further send to the controlling user through some ground center [15], [16]. As per [17]–[19] the prospect of drones as a commercial usage is not far off it has already begun and along with usage in many B2B application, IoD has become one of the most invested technology for business. Currently, IoD is being used as a tool in variety of areas

like a package delivery option but are also being used as a tool for police, first-aid vehicles, high-tech photography, wildlife research, search, rescue and many more [17], [18] as shown in Figure 2. Due to sensitivity of environment data, the security of such unmanned vehicles has got much importance as an attacker can use drones for depraved purposes like modification of genuine environment related data or can stop it to communicate with users. Moreover, the drones are battery operated and equipped with small memory and communication capabilities. Therefore, IoD requires a security mechanism to avoid unauthorized access and to provide data integrity along with confidentiality. Moreover, resource constrained nature of drones demands security procedure based on lightweight cryptographic operations. Lamport was the first to propose authentication mechanism for remote user/device, till then many such schemes are proposed [20]–[25]. An authentication scheme for Wireless Sensor Networks (WSNs) and IoT was proposed by Turkanović *et al.* [22]. Farash *et al.* [23] discovered that [22] is exposed to stolen smart card, Man-in-the-middle and sensor node impersonation and related attacks. As a solution, Farash et al. introduced a new efficient scheme to subdue beforehand mentioned vulnerabilities. However, Amin *et al.* [24] later proved that [23] scheme is also defenseless against many attacks including user impersonation, off-line password guessing etc., Amin et al. also showed that Farash et al.'s scheme lacks user anonymity. Later, Jiang *et al.* [25] ascertained that [24] is similarly unsafe and has some loopholes. To surmount Jiang *et al.* [25] proposed a new refined security scheme. Tai *et al.* [26] also offered an authentication scheme however, it lacks forward secrecy and is weak against password guessing, privileged-insider, replay and man-in-the-middle attack. Challa *et al.* [27] also proposed ECC and signature based authentication scheme. Due to usage of ECC and signature, the scheme [27] demands very high communication and computation cost. Moreover, the scheme proposed in [27] entails some correctness issues. Roy *et al.* [28] likewise proposed a three-factor (smart card, password and biometrics) based authentication and key-agreement scheme for crowdsourcing IoT. Similarly, Das *et al.* also proposed an authentication scheme for industrial IoT using trusted gateway as an intermediate party [29]. However, Sajid and Chaudhry [30] proved that their scheme is insecure against stolen verifier and smart device attacks and does not provide user traceability and forward secrecy. Amin et al. also proposed another scheme [31] for three party settings. Challa *et al.* [32] argued scheme proposed in [31] is vulnerable to user impersonation, stolen card and related attack. Chaudhry *et al.* [33] analyzed that the scheme of Challa *et al.* [32] has incorrect authentication procedure and in prone to some other weaknesses. In 2018 Jangirala *et al.* [17] proposed a tailored authentication scheme (*TCALAS* : Temporal Credential based Anonymous Lightweight Authentication Scheme) for pure IoD environments. Although, the scheme was proposed using lightweight symmetric hash functions, making it work in resource limited unmanned drones, the analysis in this article shows that their
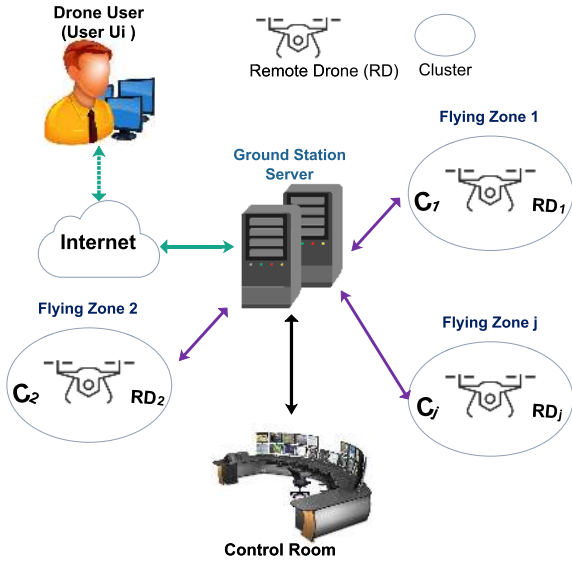
FIGURE 3. IoD environment monitoring system.

TABLE 1. Notations guide.

Symbols	Representations
U_i, RD_j, GSS	i^{th} user, j^{th} remote drone and ground station server, respectively
MD_i	Mobile device of U_i
X_{GSS}, X_{RD_j}	Long-term secret keys of GSS and RD_j, respectively
SID_{RD_j}	Secret key between GSS and RD_j
UID_i	Secret key between $U_i(MD_i)$ and GSS
$ID_i, ID_{RD_j}, ID_{GSS}$	Unique identities of MD_i, RD_j and GSS, respectively
PW_i, BIO_i	Password and biometrics of U_i, respectively
$h(.)$	Cryptographic one way hash function
SK	Session key between U_i and RD_j
b_i, R_1, R_2, R_3	Random numbers
T_1, T_2, T_3	Current timestamps
$Gen(.), Rep(.)$	Fuzzy biometric generator and reproduction functions, respectively
$\triangle T$	Maximum allowable transmission delay
TC_i	Temporal credential of U_i
$i \overset{?}{=} j$	Checks if i equals to j
CID_k	Identity of kth cluster in the flying zones
$\oplus, \|$	Bitwise XOR and concatenation operators, respectively
$\mathcal{A}, \mathcal{I}, U_\mathcal{A}$	An adversary, intruder and privileged insider, respectively

scheme can work with only one flying zone and is not scalable. Moreover, *TCALAS* lacks untraceability property and is defenseless against stolen verifier attack. It is argued that an attacker after stealing verifier can impersonate on behalf of any of the drone, user and *GSS*. Then an improved Temporal credential based anonymous lightweight authentication scheme (*iTCALAS*) is proposed in this paper. The security of *iTCALAS* is proved through formal, informal and automated methods. Rest parts of the paper is arranged as follows: IoD Authentication scenario and threat model are presented in subsection I-A, I-B respectively. Review of the scheme of Srinivas et al. for securing IoD is conducted in Section II followed by it's cryptanalysis in Section III. The proposed improved scheme is presented in Section IV. The formal, informal and automated security analysis of the proposed scheme is shown in Section V. The performance and security feature comparisons are given in Section VI.The paper is finally concluded in Section VII.

A. AUTHENTICATION SCENARIO

The realistic authentication scenario adopted from [17] is depicted in Figure 3. Comprising of three participants, Ground Station Server *GSS* is assumed to be trusted and facilitates the session initiation between users and drones with in a specified cluster. The communication between the communicating entities is always through public channel and the drones are flying in specified zones called as clusters, as of a drone, a cluster has also it's unique identity; whereas, *GSS* is attached with a control room. The drones are allowed to communicated with users/*GSS* and with each other. In [17], the *GSS* was assumed to be locked physically and no one can access *GSS* memory. However, in this paper only the secret key of the *GSS* is assumed to be non-compromised. The rest of the contents stored on physically locked *GSS* are subject to compromise because no physical lock can restrict

a cyber attacker to get data on a machine attached with public internet [30].

B. THREAT MODEL

The common adversarial model as adopted in [34]–[39] is considered for authentication scenario in IoD based deployments. Precisely, the attacker ($\mathcal{A}$) is assumed to have following capabilities:

1) $\mathcal{A}$ has authority over the whole public communication link and $\mathcal{A}$ can intervene, rerun, alter, drop or can forward a new forged message.
2) With the help of power analysis, $\mathcal{A}$ can access information embedded in the smart card [34], [39].
3) $\mathcal{A}$ can be an outsider or can be an ambitious system user.
4) The identities of users and server are public.
5) *GSS* is protected and no adversary can compromise the private key of *GSS*.

II. SCHEME OF THE SRINIVAS ET AL.

This section describes the authentication scheme (*TCALAS*) for IoD designed by Srinivas et al. Various symbols adopted in the paper are outlined in Table 1. Based on three factors including biometrics, password and smart device, the phases of the scheme are briefed in following subsections:

A. PRE-DEPLOYMENT PHASE

For pre-deployment, each remote drone RD_j : $\{j = 1, 2 \ldots .m\}$ is initially enrolled with the *GSS*. *GSS* assigns each RD_j a distinct identity ID_{RD_j} before placing those into any area partitioned as n_c disjoint clusters (flying zones) with a CID_k as identity. *GSS* chooses its own identity ID_{GSS}, secret key X_{GSS} and X_{RD_j} a long-term shared secret with RD_j. Then *GSS* calculates $SID_{RD_j} = h(CID_k\|ID_{RD_j}\|X_{GSS}\|X_{RD_j})$ and selects a hash function $h(\cdot)$. Finally, *GSS* stores the $\{ID_{GSS}, CID_k, ID_{RD_j}, SID_{RD_j}, h(\cdot)\}$ into RD_j's memory and

$\{ID_{GSS}, \{CID_k | 1 \le k \le n_c\}, \{(ID_{RD_j}, SID_{RD_j}) | 1 \le j \le n_r\}$ in its own database, n_c indicates the number of drones to be placed in a cluster.

B. SRINIVAS ET AL.'S USER REGISTRATION PHASE

To register for accessing a drone RD_j in some cluster k, U_i is required to enroll with the GSS. Initially, U_i picks ID_i, PW_i and b_i. U_i computes $HID_i = h(ID_i||b_i)$, $HPW_i = h(PW_i||b_i)$ and forwards the registration request $\{HID_i, h(\cdot)\}$ to GSS. On receiving U_i's request, GSS computes $UID_i = h(HID_i || X_{GSS})$, $TC_i = h(CID_k || UID_i || ID_{GSS})$, $A_i = UID_i$, and $B_i = CID_k \oplus h(HID_i || UID_i)$. The GSS then saves $\{A_i, B_i, TC_i, h(\cdot), ID_{GSS}, CID_k\}$ into the mobile device MD_i, and transfers the MD_i securely to U_i. Next, U_i imprints his/her biometric BIO_i and calculates $Gen(BIO_i) = (\sigma_i, \tau_i)$, $L_i = b_i \oplus h(\sigma_i||ID_i||PW_i)$, $M_i = h(A_i || TC_i || b_i || \sigma_i)$, and $A'_i = A_i \oplus h(b_i || HID_i || HPW_i || \sigma_i)$, where σ_i is the secret biometric key and τ_i is public reproduction parameter related with BIO_i [28], respectively. Finally, U_i saves the credentials $\{A'_i, ID_{GSS}, M_i, B_i, L_i, h(\cdot), CID_k, Rep(\cdot), Gen(\cdot), \tau_i\}$ in the MD_i.

C. SRINIVAS ET AL.'S LOGIN AND AUTHENTICATION PHASE

To access the RD_j in a desired flying zone k, U_i needs to prove his legality to MD_i as well as to GSS. U_i initiates this phase and the process completes by executing following steps:

SLA 1: U_i provides the login credentials (BIO'_i, ID_i & PW_i) to MD_i. MD_i then calculates $\sigma'_i = Rep(BIO'_i, \tau_i)$, $b_i = L_i \oplus h(\sigma'_i||ID_i||PW_i)$, $HID_i = h(ID_i||b_i)$, $HPW_i = h(PW_i||b_i)$, $A_i = A'_i \oplus h(b_i||HID_i||HPW_i||\sigma'_i)$, $UID_i = A_i$, $CID_k = B_i \oplus h(HID_i||UID_i)$ and $TC_i = h(CID_k||UID_i||ID_{GSS})$. MD_i verifies $M_i \overset{?}{=} h(A_i||TC_i||b_i||\sigma'_i)$, session ends, if verification fails. Otherwise, MD_i generates T_1, R_1 and computes $U_1 = HID_i \oplus h(T_1 \oplus ID_{GSS}||CID_k)$, $U_2 = ID_{RD_j} \oplus h(UID_i||CID_k||TC_i)$, $U3 = h(ID_{RD_j}||CID_k||TC_i||T_1) \oplus R_1$, and $U_4 = h(R_1||UID_i||ID_{RD_j}||TC_ik||CID_k)$. U_i then transmits $MSG_1 = \{U_1, U_2, U_3, U_4, T_1\}$ to GSS.

SLA 2: On receiving, the GSS checks the freshness of the MSG_1 (through $| T_c - T_1 |< \triangle T$); in case it is fresh, GSS calculates $HID^*_i = U_1 \oplus h(T_1||ID_{GSS}||CID_k)$ and $UID^*_i = h(HID^*_i||X_{GSS})$. GSS withdraws TC_i by checking if UID^*_i exists in the database, in case it is true, the GSS checks if ID_{RD_j} also exists in GSS database by computing $ID_{RD_j} = U_2 \oplus h(UID_i||CID_k||TC_i)$. On success, GSS calculates $R_1 = U_3 \oplus h(ID_{RD_j}||CID_k||TC_i||T_1)$, fetches SID_{RD_j} corresponding to ID_{RD_j} and verifies $U_4 \overset{?}{=} h(R_1||UID_i||ID_{RD_j}||TC_i||CID_k)$. Upon unsuccessful validation, the GSS rejects the U_i's legitimacy and terminates the session. Otherwise, the GSS continues by generating R_2 and current timestamp T_2, and computes $U_5 = h(ID_{GSS}||SID_{RD_j}||ID_{RD_j}||T_2) \oplus HID_i$, $U_6 = h(HID_i||ID_{RD_j}||CID_k||T_2||h(R_1||R_2))$ and

$U_7 = h(HID_i||ID_{RD_j}||SID_{RD_j}||T_2) \oplus h(R_1||R_2)$. U_i then transmit the message $MSG_2 = \{U_5, U_6, U_7, T_2\}$ to the remote drone RD_j.

SLA 3: On receiving GSS message, RD_j checks the freshness ($|T_c - T_2| < \triangle T$) and on success, RD_j computes $HID_i = U_5 \oplus h(ID_{GSS}||SID_{RD_j}||ID_{RD_j}||T_2)$, $h(R_1||R_2) = U7 \oplus h(HID_i||ID_{RD_j}||SID_{RD_j}||T_2)$. RD_j then checks $U_6 \overset{?}{=} h(HID_i||ID_{RD_j}||CID_k||T_2|| h(R_1||R_2))$. If fails, RD_j declines the message. Otherwise, RD_j selects T_3, R_3 and computes $R'_3 = h(R_3||h(R_1||R_2))$, $U_8 = R'_3 \oplus h(HID_i||ID_{RD_j}||T_3||CID_k)$, $SK = h(R'_3||HID_i|| ID_{RD_j}||CID_k||T_3)$ and $U_9 = h(R'_3||SK||T_3||CID_k)$. RD_j then sends the message MSG_3 containing $\{U_8, U_9, T_3\}$ directly to U_i via open channel.

SLA 4: The U_i checks the freshness ($| T_c - T_3 |< \triangle T,$) of the MSG_3 and on success computes $R'_3 = U_8 \oplus h(HID_i||ID_{RD_j}||T_3||CID_k)$, $SK = h(R'_3||HID_i||ID_{RD_j}||CID_k||T_3)$. U_i then verifies if $U_9 \overset{?}{=} h(R'_3||SK||T_3||CID_k)$, if the condition holds RD_j is verified successfully else session is terminated. Conclusively, RD_j and U_i both have the $SK = h(h(R_3||h(R_1||R_2))||HID_i||ID_{RD_j}||CID_k||T_3)$ as a session key.

D. USER PASSWORD/BIOMETRIC UPDATE PHASE

In this phase the U_i can update both his biometric and password. For renewing the password/biometrics, a legitimate registered U_i with MD_i provides(BIO'_i, ID_i & PW_i). MD_i then calculates: $\sigma'_i = Rep(BIO'_i, \tau_i)$, $b_i = L_i \oplus h(\sigma'_i||ID_i||PW_i)$, $HID_i = h(ID_i||b_i)$, $HPW_i = h(PW_i||b_i)$, $A_i = A'_i \oplus h(b_i||HID_i||HPW_i||\sigma'_i)$, $UID_i = A_i$, $CID_k = B_i \oplus h(HID_i||UID_i)$ and $TC_i = h(CID_k||UID_i||ID_{GSS})$. MD_i then verifies $M_i \overset{?}{=} h(A_i||TC_i||b_i||\sigma'_i)$. Session ends, if the authentication fails. Otherwise, MD_i informs U_i to input new password PW^{new}_i and biometric BIO^{new}_i. U_i provides a new password PW^{new}_i and biometrics BIO^{new}_i to MD_i. MD_i calculates $HPW_i = h(PW^{new}_i||b_i)$, $HID_i = h(ID_i||b_i)$, $(\sigma^{new}_i, \tau^{new}_i) = Gen(BIO^{new}_i)$, $L^{new}_i = b_i \oplus h(\sigma^{new}_i||ID_i||PW^{new}_i)$, $M^{new}_i = h(A_i||TC_i||b_i||\sigma^{new}_i)$, and $A^{new}_i = A_i \oplus h(b_i||HID_i||HPW^{new}_i||\sigma^{new}_i)$. Finally, U_i replaces A'_i, M_i and L_i with A'^{new}_i, M^{new}_i and L^{new}_i, respectively, in the mobile device MD_i.

E. REVOCATION AND REISSUE PHASE

For changing device MD_i with new on MD^{new}_i, U_i provides the old identity ID_i, a new password PW^{new}_i, chooses an arbitrary number b'_i and sends $\{HID_i, h(\cdot)\}$ to the GSS over the secure channel where $HPW^{new}_i = h(PW^{new}_i||b'_i)$ and $HID_i = h(ID_i||b'_i)$. On receiving request, GSS computes $UID_i = h(HID_i || X_{GSS})$, $TC_i = h(CID_k || UID_i || ID_{GSS})$, $A_i = UID_i$, $B_i = CID_k \oplus h(HID_i || UID_i)$ and transfers the $MD^{new}_i = \{A_i, B_i, TC_i, h(\cdot), ID_{GSS}, CID_k\}$ to the U_i over the secure channel. Next, U_i imprints his/her biometric BIO^{new}_i and calculates $Gen(BIO^{new}_i)$

$= (\sigma_i^{new}, \tau_i)$, $L_i^{new} = b_i^{new} \oplus h(\sigma_i^{new}||ID_i||PW_i^{new})$, $M_i^{new} = h(A_i||TC_i||b_i||\sigma_i^{new})$, and $A_i'^{new} = A_i \oplus h(b_i||HID_i||HPW_i^{new}||\sigma_i^{new})$. Finally, U_i deletes TC_i and saves the parameters $\{A_i'^{new}, M_i^{new}, L_i^{new}, ID_{GSS}, B_i^{new}, h(\cdot), CID_k, Rep(\cdot), Gen(\cdot), \tau_i\}$ in the MD_i.

F. DYNAMIC REMOTE DRONE ADDITION PHASE

This phase facilitates adding new drones in an existing IoD network. For drone addition purposes, *GSS* selects a distinct identity $ID_{RD_j}^{new}$, $X_{RD_j}^{new}$ for RD_j^{new} and computes $SID_{RD_j}^{new} = h(CID_k||ID_{RD_j}^{new}||X_{GSS}||XRD_{RD_j^{new}})$ using X_{GSS}. *GSS* finally, stores the parameters $\{ID_{GSS}, CID_k,$ $ID_{RD_j}^{new}, SID_{RD_j}^{new}, h(\cdot)\}$ in RD_j^{new}'s memory and $\{ID_{RD_j}^{new}, SID_{RD_j}^{new}\}$ in its database.

III. WEAKNESSES OF THE SCHEME OF SRINIVAS ET AL.

In this section, we show the weaknesses of the *TCALAS* proposed by Srinivas et al. Precisely, it is to prove in following subsections that the scheme of *TCALAS* cannot resist traceability and stolen verifier attacks:

A. SCALABILITY ISSUES

The scheme of Srinivas et al. can work with drones flying in just one cluster. If there are more than one clusters, the scheme may fail to facilitate the authentication process. Precisely, in step *SLA-1*, U_i having device MD_i engraved with $\{A_i', ID_{GSS}, M_i, B_i, L_i, h(\cdot), CID_k\}$ computes and sends $MSG_1 = \{U_1, U_2, U_3, U_4, T_1\}$ to *GSS*, where $U_1 = HID_i \oplus h(T_1 \oplus ID_{GSS}||CID_k)$, $U_2 = ID_{RD_j} \oplus h(UID_i||CID_k||TC_i)$, $U3 = h(ID_{RD_j}||CID_k||TC_i||T_1) \oplus R_1$, and $U_4 = h(R_1||UID_i||ID_{RD_j}||TC_ik||CID_k)$. Upon receiving MSG_1, in step SLA-2, the *GSS* checks the freshness of the MSG_1 (through $|T_c - T_1| < \triangle T$); in case it is fresh, *GSS* computes:

$$HID_i^* = U_1 \oplus h(T_1||ID_{GSS}||CID_k) \quad (1)$$
$$UID_i^* = h(HID_i^*||X_{GSS}) \quad (2)$$

The computation of HID_i^* in Eq. 1 requires to compute $h(T_1||ID_{GSS}||CID_k)$ first. Here, T_1 is received by *GSS* in MSG_1 and ID_{GSS} is the real identity of *GSS*; whereas, CID_k is the identity of kth flying zone. The message request MSG_1 does not contain any information about the user or the flying zone. The user identity is recognized, only when *GSS* has information of flying zone/cluster i.e. CID_k (see Eq.1). If there are more than one (say n_c) clusters: CID_x : $\{x = 1, 2 \ldots k, ..n_c\}$, then *GSS* cannot compute HID_i^* of U_i because *GSS* is now unable to determine which CID_x, it has to use for computation of HID_i^* through Eq.1, and the process may not continue further. Moreover, computation of UID_i^* in Eq. 2 is also depends on accurate knowledge of HID_i^*. Similarly, *GSS* cannot perform rest of the authentication steps. Hence, in presence of more than one drone clusters registered with *GSS*, the scheme fails to provide authentication between a user and a specified drone. Hence, the scheme of Srinivas et al. for securing drones is not scalable and can work with only one flying zone/cluster.

B. TRACEABILITY ATTACK

This section shows the weakness of the Srinivas et al. against traceability attack. An attacker $\mathcal{A}$, insider or outsider can easily trace any user by using the public information ID_{GSS} and CID_k along with the timestamp T_1 sent on public channel in a message $\langle MSG_1 = \{U_1, U_2, U_3, U_4, T_1\}\rangle$ by a user U_i. The attacker can compute $HID_i = U_1 \oplus (T_1||ID_{GSS}||CID_k)$, the HID_i of a user remains same for all sessions. Therefore, $\mathcal{A}$ can easily launch traceability attack on Srinivas et al.'s scheme.

C. IMPERSONATION BASED ON STOLEN VERIFIER

In Srinivas et al.'s scheme the Ground Station Server (*GSS*) maintains two verifier database, one for users with entries of type $\{UID_i, TC_i\}$, second for drones with entries of type $\{ID_{RD_j}, SID_{RD_j}\}$. A privileged insider $\mathcal{A}$ of the system with access to drone verifier database can impersonate as *GSS* to the remote drone (DR_j) by executing following steps:

1) $\mathcal{A}$ generates a random identity RID_a, current timestamp $T_2^{\mathcal{A}}$, two numbers $R_1^{\mathcal{A}}$ and $R_2^{\mathcal{A}}$ randomly. $\mathcal{A}$ now computes:

$$U_5^{\mathcal{A}} = h(ID_{GSS}||SID_{RD_j}||ID_{RD_j}||T2_2^{\mathcal{A}}) \oplus RID_a \quad (3)$$
$$U_6^{\mathcal{A}} = h(RID_a||ID_{RD_j}||CID_k||T_2^{\mathcal{A}}||h(R_1^{\mathcal{A}}||R_2^{\mathcal{A}})) \quad (4)$$
$$U_7^{\mathcal{A}} = h(RID_a||ID_{RD_j}||SID_{RD_j}||T_2^{\mathcal{A}}) \oplus h(R_1^{\mathcal{A}}||R_2^{\mathcal{A}}) \quad (5)$$

$\mathcal{A}$ sends the message $MSG_2 = \{U_5^{\mathcal{A}}, U_6^{\mathcal{A}}, U_7^{\mathcal{A}}\}$ to DR_j

2) RD_j receives MSG_2 and checks the validity of timestamp $T_2^{\mathcal{A}}$; upon success, RD_j computes:

$$RID_a = h(ID_{GSS}||SID_{RD_j}||ID_{RD_j}||T2_2^{\mathcal{A}}) \oplus U_5^{\mathcal{A}} \quad (6)$$
$$h(R_1^{\mathcal{A}}||R_2^{\mathcal{A}}) = h(RID_a||ID_{RD_j}||SID_{RD_j}||T_2^{\mathcal{A}}) \oplus U_7^{\mathcal{A}} \quad (7)$$

RD_j further checks the equality:

$$U_6^{\mathcal{A}} \overset{?}{=} h(RID_a||ID_{RD_j}||CID_k||T_2^{\mathcal{A}}||h(R_1^{\mathcal{A}}||R_2^{\mathcal{A}})) \quad (8)$$

3) Upon successful verification of Eq. 8, DR_j generate T_3, R_3 and computes:

$$R_3' = h(R_3||h(R_1^{\mathcal{A}}||R_2^{\mathcal{A}})) \quad (9)$$
$$U_8 = R_3' \oplus h(RID_a||ID_{RD_j}||T_3||CID_k) \quad (10)$$
$$SK = h(R_3'||RID_a||ID_{RD_j}||CID_k||T_3) \quad (11)$$
$$U_9 = h(R_3'||SK||T_3||CID_k) \quad (12)$$

RD_j then sends the message MSG_3 containing $\{U_8, U_9, T_3\}$ directly to U_i.

4) $\mathcal{A}$ intercepts MSG_3 and computes:

$$R_3' = U_8 \oplus h(RID_a||ID_{RD_j}||T_3||CID_k) \quad (13)$$

Finally, $\mathcal{A}$ computes session key as follows:

$$SK = h(R_3'||RID_a||ID_{RD_j}||CID_k||T_3) \quad (14)$$

Proposition 1: In Srinivas et al.'s scheme, on execution of stolen verifier attack, an active attacker $\mathcal{A}$ can impersonate himself as legal *GSS* and an arbitrary legal user U_a simultaneously, to the drone (DR_j) of his choice. Moreover, $\mathcal{A}$ can share a session key with DR_j accurately for establishment of a secure session.

Proof 1: $\mathcal{A}$ initiates impersonation on behalf of *GSS* by computing and sending $MSG_2 = \{U_5^{\mathcal{A}}, U_6^{\mathcal{A}}, U_7^{\mathcal{A}}\}$ to DR_j. The drone DR_j considers $\mathcal{A}$ as legal *GSS* if timestamp is fresh and Eq. 8 holds. It can be clearly observed that $\mathcal{A}$ generated fresh timestamp $T_2^{\mathcal{A}}$ for initiation of impersonation, so freshness will be verified without any hindrance. $\mathcal{A}$ computed $U_6^{\mathcal{A}} = h(RID_a||ID_{RD_j}||CID_k||T_2^{\mathcal{A}}||h(R_1^{\mathcal{A}}||R_2^{\mathcal{A}}))$ in Eq. 4, out of the parameters used for computing $U_6^{\mathcal{A}}$, $\{RID_a, T_2^{\mathcal{A}}, h(R_1^{\mathcal{A}}||R_2^{\mathcal{A}})\}$ are generated by $\mathcal{A}$ himself, while ID_{DR_j} and CID_k are extracted from stolen verifier. Moreover, as proved in subsection III-A, there is only one cluster being used in Srinivas et al.'s scheme the CID_k is then known to everyone. Therefore, $U_6^{\mathcal{A}}$ computed by $\mathcal{A}$ in Eq. 4 is same as DR_j computes in Eq. 8. Hence, Eq. 8 holds. Furthermore, DR_j computes session key in Eq. 11 and $\mathcal{A}$ computes session key in Eq. 14. The session keys on both sides are also same because $\mathcal{A}$ extracts R_3' in Eq. 13 using the parameters either he got through stolen verifier or he generated by himself; whereas rest of the parameters $\{RID_a, ID_{RD_j}, CID_k, T_3\}$ involved in computation of session key are already in his access. Therefore, the session key computed on both sides is also same. Hence, $\mathcal{A}$ has successfully, impersonated simultaneously on behalf of a legal user as well as *GSS* to a drone DR_j and shared a session key.

Similarly, using the verifiers, $\mathcal{A}$ can be successful to impersonate himself as a drone or as a legal user to other parties of the system.

IV. PROPOSED SCHEME

In this section an improved scheme (*iTCALAS*) is presented to mitigate the loopholes of Srinivas et al.'s scheme. For the *iTCALAS* pre-deployment phase is taken as from Srinivas et al.'s scheme, the brief description of the rest of the phases of *iTCALAS* are given in following subsections:

A. USER REGISTRATION PHASE

To register for accessing a drone RD_j in some cluster k, U_i is required to enroll with the *GSS*. Initially, U_i picks ID_i and sends it to *GSS* using secure channel. On receiving ID_i, *GSS* selects arbitrary number r_s and computes $UID_i = E_{X_{GSS}}(ID_i, r_s)$, $UK_i = h(ID_i||X_{GSS})$, $B_i = CID_k \oplus h(ID_i||UK_i)$ and temporal credential $TC_i = h(CID_k||ID_{GSS}||ID_i||UK_i)$. Finally *GSS* saves the parameters $\{UID_i, UK_i, B_i, TC_i\}$ into the mobile device MD_i, and transfers the MD_i securely to the U_i. Next, U_i selects b, PW_i, imprints his/her biometric BIO_i and calculates $Gen(BIOi) = (\sigma_i, \tau_i)$, $A_i = UID_i \oplus h(ID_i||PW_i||\sigma_i)$, $L_i = b \oplus h(PW_i||ID_i||\sigma_i)$, $\overline{UK_i} = UK_i \oplus h(\sigma_i||PW_i||ID_i||b)$ and $M_i = h(b||UID_i||UK_i||PW_i||\sigma_i)$, and $A_i' = A_i \oplus h(b_i ||$

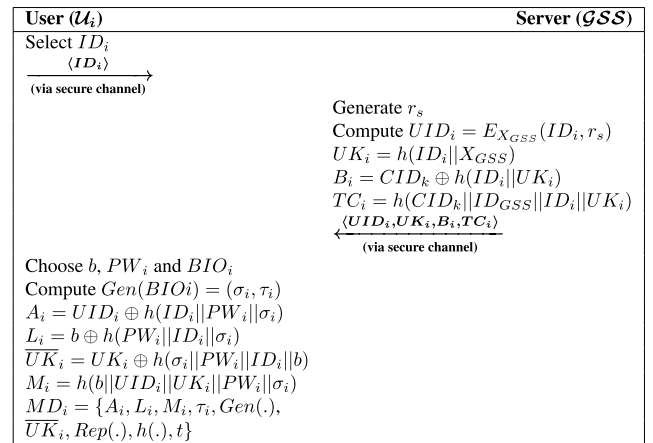| User ($\mathcal{U}_i$)	Server ($\mathcal{GSS}$)
Select ID_i	
$\xrightarrow{\langle ID_i \rangle}$	
(via secure channel)	
	Generate r_s
	Compute $UID_i = E_{X_{GSS}}(ID_i, r_s)$
	$UK_i = h(ID_i||X_{GSS})$
	$B_i = CID_k \oplus h(ID_i||UK_i)$
	$TC_i = h(CID_k||ID_{GSS}||ID_i||UK_i)$
	$\xleftarrow{\langle UID_i, UK_i, B_i, TC_i \rangle}$
	(via secure channel)
Choose b, PW_i and BIO_i	
Compute $Gen(BIOi) = (\sigma_i, \tau_i)$	
$A_i = UID_i \oplus h(ID_i||PW_i||\sigma_i)$	
$L_i = b \oplus h(PW_i||ID_i||\sigma_i)$	
$\overline{UK_i} = UK_i \oplus h(\sigma_i||PW_i||ID_i||b)$	
$M_i = h(b||UID_i||UK_i||PW_i||\sigma_i)$	
$MD_i = \{A_i, L_i, M_i, \tau_i, Gen(.),$	
$\overline{UK_i}, Rep(.), h(.), t\}$	

FIGURE 4. Registration phase of *iTCALAS*.

$HID_i || HPW_i || \sigma_i)$, where σ_i is the secret biometric key and τ_i is public reproduction parameter related with BIO_i [28], respectively. Finally, U_i saves the credentials $MD_i = \{A_i, L_i, M_i, \tau_i, Gen(\cdot), \overline{UK_i}, Rep(\cdot), h(\cdot), t\}$ in the MD_i. The registration is also summarized in Fig. 4.
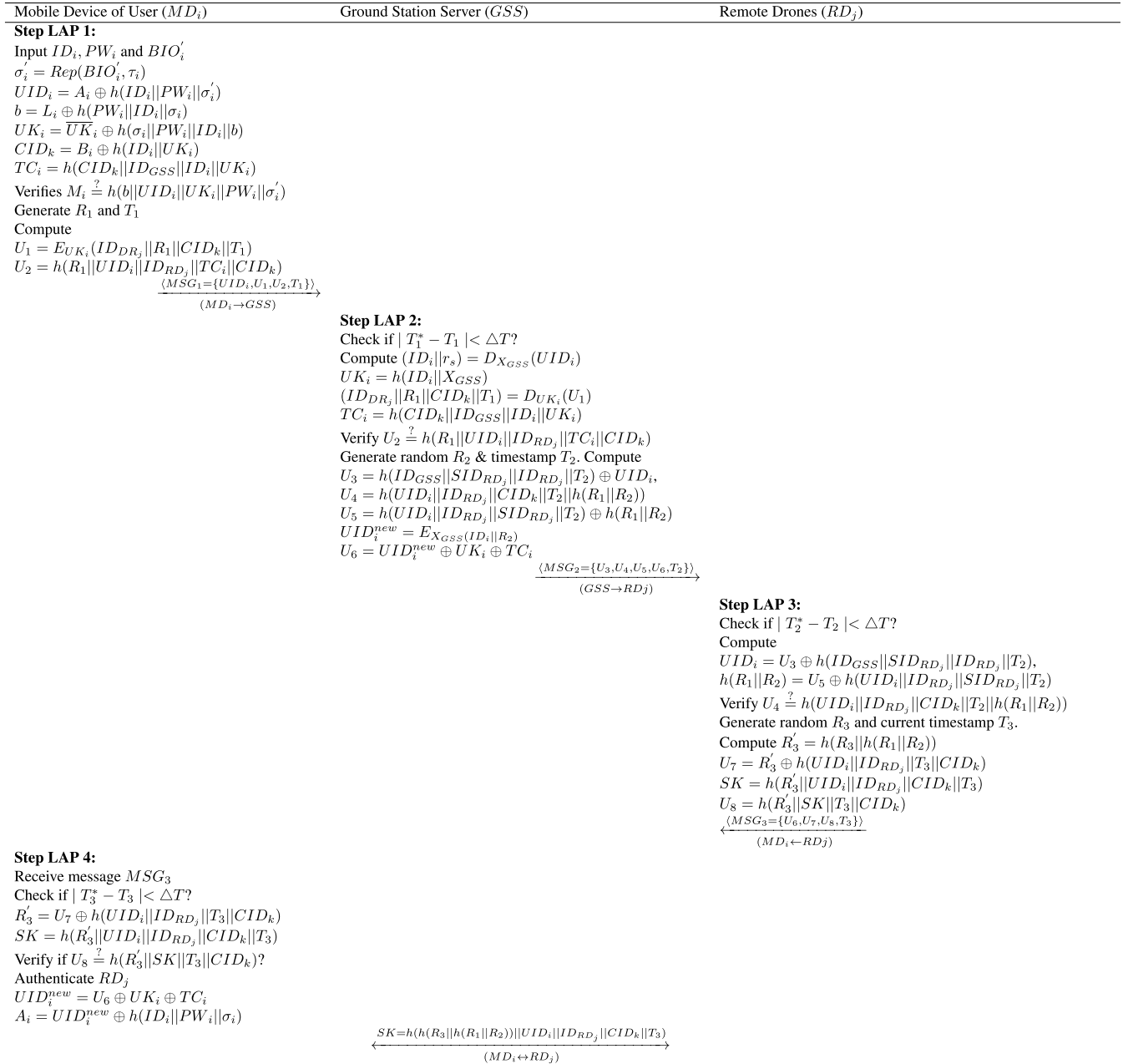
B. LOGIN AND AUTHENTICATION PHASE

To access the RD_j in a desired flying zone k, U_i needs to prove his legality to MD_i as well as to *GSS*. U_i initiates this phase and the process completes by executing following steps:

LAP 1: U_i provides the login credentials (BIO_i', ID_i & PW_i) to MD_i. MD_i then calculates $\sigma_i' = Rep(BIO_i', \tau_i)$, $UID_i = A_i \oplus h(ID_i||PW_i||\sigma_i')$, $b = L_i \oplus h(PW_i||ID_i||\sigma_i)$, $UK_i = \overline{UK_i} \oplus h(\sigma_i||PW_i||ID_i||b)$, $CID_k = B_i \oplus h(ID_i||UK_i)$ and $TC_i = h(CID_k||ID_{GSS}||ID_i||UK_i)$. MD_i verifies $M_i \overset{?}{=} h(b||UID_i||UK_i||PW_i||\sigma_i')$, session ends, if verification fails. Otherwise, MD_i generates T_1, R_1 and computes $U_1 = E_{UK_i}(ID_{DR_j}||R_1||CID_k||T_1)$ and $U_2 = h(R_1||UID_i||ID_{RD_j}||TC_i||CID_k)$. U_i then transmits $MSG_1 = \{U_1, U_2, T_1\}$ to *GSS*.

LAP 2: On receiving, the *GSS* checks the freshness of the MSG_1 (through $| T_c - T_1 | < \triangle T$); in case it is fresh, *GSS* calculates $(ID_i||r_s) = D_{X_{GSS}}(UID_i)$, $UK_i = h(ID_i||X_{GSS})$, $(ID_{DR_j}||R_1||CID_k||T_1) = D_{UK_i}(U_1)$, $TC_i = h(CID_k||ID_{GSS}||ID_i||UK_i)$. *GSS* verifies $U_2 \overset{?}{=} h(R_1||UID_i||ID_{RD_j}||TC_i||CID_k)$. Upon unsuccessful validation, the *GSS* rejects the U_i's legitimacy and terminates the session. Otherwise, the *GSS* continues by generating R_2 and current timestamp T_2, and computes $U_3 = h(ID_{GSS}||SID_{RD_j}||ID_{RD_j}||T_2) \oplus UID_i$, $U_4 = h(UID_i||ID_{RD_j}||CID_k||T_2||h(R_1||R_2))$, $U_5 = h(UID_i||ID_{RD_j}||SID_{RD_j}||T_2)\oplus h(R_1||R_2)$, $UID_i^{new} = E_{X_{GSS}(ID_i||R_2)}$ and $U_6 = UID_i^{new} \oplus UK_i \oplus TC_i$. U_i then transmit the message $MSG_2 = \{U_3, U_4, U_5, U_6, T_2\}$ to the remote drone RD_j.

LAP 3: On receiving *GSS* message, RD_j checks the freshness ($|T_c - T_2| < \triangle T$) and on success, RD_j computes $UID_i = U_3 \oplus h(ID_{GSS}||SID_{RD_j}||ID_{RD_j}||T_2)$

Mobile Device of User (MD_i)	Ground Station Server (GSS)	Remote Drones (RD_j)

Step LAP 1:
Input ID_i, PW_i and BIO_i'
$\sigma_i' = Rep(BIO_i', \tau_i)$
$UID_i = A_i \oplus h(ID_i||PW_i||\sigma_i')$
$b = L_i \oplus h(PW_i||ID_i||\sigma_i)$
$UK_i = \overline{UK_i} \oplus h(\sigma_i||PW_i||ID_i||b)$
$CID_k = B_i \oplus h(ID_i||UK_i)$
$TC_i = h(CID_k||ID_{GSS}||ID_i||UK_i)$
Verifies $M_i \overset{?}{=} h(b||UID_i||UK_i||PW_i||\sigma_i')$
Generate R_1 and T_1
Compute
$U_1 = E_{UK_i}(ID_{DR_j}||R_1||CID_k||T_1)$
$U_2 = h(R_1||UID_i||ID_{RD_j}||TC_i||CID_k)$

$$\xrightarrow{\langle MSG_1 = \{UID_i, U_1, U_2, T_1\}\rangle}_{(MD_i \to GSS)}$$

Step LAP 2:
Check if $|T_1^* - T_1| < \triangle T$?
Compute $(ID_i||r_s) = D_{X_{GSS}}(UID_i)$
$UK_i = h(ID_i||X_{GSS})$
$(ID_{DR_j}||R_1||CID_k||T_1) = D_{UK_i}(U_1)$
$TC_i = h(CID_k||ID_{GSS}||ID_i||UK_i)$
Verify $U_2 \overset{?}{=} h(R_1||UID_i||ID_{RD_j}||TC_i||CID_k)$
Generate random R_2 & timestamp T_2. Compute
$U_3 = h(ID_{GSS}||SID_{RD_j}||ID_{RD_j}||T_2) \oplus UID_i,$
$U_4 = h(UID_i||ID_{RD_j}||CID_k||T_2||h(R_1||R_2))$
$U_5 = h(UID_i||ID_{RD_j}||SID_{RD_j}||T_2) \oplus h(R_1||R_2)$
$UID_i^{new} = E_{X_{GSS}}(ID_i||R_2)$
$U_6 = UID_i^{new} \oplus UK_i \oplus TC_i$

$$\xrightarrow{\langle MSG_2 = \{U_3, U_4, U_5, U_6, T_2\}\rangle}_{(GSS \to RDj)}$$

Step LAP 3:
Check if $|T_2^* - T_2| < \triangle T$?
Compute
$UID_i = U_3 \oplus h(ID_{GSS}||SID_{RD_j}||ID_{RD_j}||T_2),$
$h(R_1||R_2) = U_5 \oplus h(UID_i||ID_{RD_j}||SID_{RD_j}||T_2)$
Verify $U_4 \overset{?}{=} h(UID_i||ID_{RD_j}||CID_k||T_2||h(R_1||R_2))$
Generate random R_3 and current timestamp T_3.
Compute $R_3' = h(R_3||h(R_1||R_2))$
$U_7 = R_3' \oplus h(UID_i||ID_{RD_j}||T_3||CID_k)$
$SK = h(R_3'||UID_i||ID_{RD_j}||CID_k||T_3)$
$U_8 = h(R_3'||SK||T_3||CID_k)$

$$\xleftarrow{\langle MSG_3 = \{U_6, U_7, U_8, T_3\}\rangle}_{(MD_i \leftarrow RDj)}$$

Step LAP 4:
Receive message MSG_3
Check if $|T_3^* - T_3| < \triangle T$?
$R_3' = U_7 \oplus h(UID_i||ID_{RD_j}||T_3||CID_k)$
$SK = h(R_3'||UID_i||ID_{RD_j}||CID_k||T_3)$
Verify if $U_8 \overset{?}{=} h(R_3'||SK||T_3||CID_k)$?
Authenticate RD_j
$UID_i^{new} = U_6 \oplus UK_i \oplus TC_i$
$A_i = UID_i^{new} \oplus h(ID_i||PW_i||\sigma_i)$

$$\xleftrightarrow{SK = h(h(R_3||h(R_1||R_2))||UID_i||ID_{RD_j}||CID_k||T_3)}_{(MD_i \leftrightarrow RD_j)}$$

FIGURE 5. Login and authentication phase of *iTCALAS*.

and $h(R_1||R_2) = U_5 \oplus h(UID_i||ID_{RD_j}||SID_{RD_j}||T_2)$. RD_j then checks $U_4 \overset{?}{=} h(UID_i||ID_{RD_j}||CID_k||T_2||h(R_1||R_2))$. If fails, RD_j declines the message. Otherwise, RD_j selects T_3, R_3 and computes $R_3' = h(R_3||h(R_1||R_2))$, $U_7 = R_3' \oplus h(UID_i||ID_{RD_j}||T_3||CID_k)$, $SK = h(R_3'||UID_i||ID_{RD_j}||CID_k||T_3)$ and $U_8 = h(R_3'||SK||T_3||CID_k)$. RD_j then sends the message MSG_3 containing $\{U_6, U_7, U_8, T_3\}$ directly to U_i via open channel.

LAP 4: The U_i checks the freshness ($|T_c - T_3| < \triangle T$,) of the MSG_3 and on success computes $R_3' = U_7 \oplus h(UID_i||ID_{RD_j}||T_3||CID_k)$ and

$SK = h(R_3'||UID_i||ID_{RD_j}||CID_k||T_3)$. U_i then verifies if $U_8 \overset{?}{=} h(R_3'||SK||T_3||CID_k)$, if the condition holds RD_j is verified successfully else session is terminated. Conclusively, RD_j and U_i both have the $SK = h(R_3'||UID_i||ID_{RD_j}||CID_k||T_3)$ as a session key. Now, MD_i computes $UID_i^{new} = U_6 \oplus UK_i \oplus TC_i$ and updates $A_i = UID_i^{new} \oplus h(ID_i||PW_i||\sigma_i)$.

C. USER PASSWORD/BIOMETRIC UPDATE PHASE

If a legal user U_i wants to update his/her biometric/password along with mobile device MD_i, this can be done by following the subsequent steps:

*PBU*1: U_i enters his/her ID_i, PW_i and imprints BIO_i'. Then MD_i computes the following $\sigma_i' = Rep(BIO_i', \tau_i)$, $UID_i = A_i \oplus h(ID_i||PW_i||\sigma_i')$, $b = L_i \oplus h(PW_i||ID_i||\sigma_i)$, $UK_i = \overline{UK}_i \oplus h(\sigma_i||PW_i||ID_i||b)$, $CID_k = B_i \oplus h(ID_i||UK_i)$, $TC_i = h(CID_k||ID_{GSS}||ID_i||UK_i)$ and validates the user by checking the condition $M_i \stackrel{?}{=} h(b||UID_i||UK_i||PW_i||\sigma_i')$, if true MD_i will prompt the user to enter a fresh password PW_i^{new} and biometric BIO_i^{new} and move to the step *PDU*2 else session will be terminated.

*PBU*2: U_i enters his/her ID_i a new password PW_i^{new}, imprints new biometric BIO_i^{new} and a random number b^{new}. Then U_i calculates $Gen(BIO_i^{new}) = (\sigma_i^{new}, \tau_i^{new})$, $A_i^{new} = (A_i^{old} \oplus h(ID_i||PW_i^{old}||\sigma_i^{old})) \oplus h(ID_i ||PW_i^{new}||\sigma_i^{new}) = UID_i \oplus h(ID_i||PW_i^{new}||\sigma_i^{new})$, $L_i^{new} = b^{new} \oplus h(PW_i^{new}||ID_i||\sigma_i^{new})$, $\overline{UK_i^{new}} = \overline{UK_i^{old}} \oplus h(\sigma_i^{old}||PW_i^{old}||ID_i||b^{old}) \oplus \oplus h(\sigma_i^{new}||PW_i^{new}||ID_i||b^{new}) = UK_i \oplus h(\sigma_i^{new}||PW_i^{new}||ID_i||b^{new})$, $M_i^{new} = h(b^{new}||UID_i||UK_i||PW_i^{new}||\sigma_i^{new})$.

*PBU*3: Finally, the MD_i replaces the parameters $\{A_i^{old}, L_i^{old}, M_i^{old}, \tau_i^{old}, \overline{UK_i^{old}}\}$ with $\{A_i^{new}, L_i^{new}, M_i^{new}, \tau_i^{new}, \overline{UK_i^{new}}\}$.

D. USER REVOCATION AND RE-REGISTRATION PHASE

If a legal user U_i lost his/her mobile device MD_i or is stolen than he/she can procure novel device MD_i^{new} by following the subsequent steps:

*RR*1: U_i enters his/her od identity ID_i^{old} and sends it to the Server (GSS) over the secure channel.

*RR*2: Upon receiving the registration request from U_i, GSS generates a random number r_s^{new} to calculates $UID_i^{new} = E_{X_{GSS}}(ID_i^{old}, r_s^{new})$, $UK_i^{new} = h(ID_i^{old}||X_{GSS})$, $B_i^{new} = CID_k \oplus h(ID_i^{old} || UK_i^{new})$, $TC_i^{new} = h(CID_k||ID_{GSS}||ID_i^{old}||UK_i^{new})$ and sends message containing $\{UID_i^{new}, UK_i^{new}, B_i^{new}, TC_i^{new}\}$ to U_i through a secure channel.

*RR*3: On receiving the message from GSS, the U_i chooses a random number b^{new}, password PW_i^{new} and imprints BIO_i^{new}. Then U_i calculates $Gen(BIO_i^{new}) = (\sigma_i^{new}, \tau_i^{new})$, $A_i^{new} = UID_i^{new} \oplus h(ID_i^{old}||PW_i^{new}||\sigma_i^{new})$, $L_i^{new} = b^{new} \oplus h(PW_i^{new} || ID_i^{old} || \sigma_i^{new})$, $\overline{UK_i^{new}} = UK_i^{new} \oplus h(\sigma_i^{new} || PW_i^{new} || ID_i^{old} || b^{new})$, $M_i^{new} = h(b^{new} || UID_i^{new} || UK_i^{new} || PW_i^{new} || \sigma_i^{new})$ and then stores the the credentials $\{A_i^{new}, L_i^{new}, M_i^{new}, \tau_i^{new}, \overline{UK_i^{new}}, Gen(\cdot), Rep(\cdot), h(\cdot), t\}$ in the MD_i^{new}'s memory.

E. DYNAMIC REMOTE DRONE ADDITION PHASE

If a new remote drone RD_j needs to be added in the cluster CID_k, then the following subsequent steps need to be carried out:

*DDA*1: The GSS first assigns a unique identity ID_{RD_j} to remote drone RD_j^{new} along with long-term secret $X_{RD_j^{new}}$ and then calculates $SID_{RD_j}^{new} = h(CID_k || ID_{RD_j}^{new} || X_{GSS} || X_{RD_j}^{new})$.

*DDA*2: Finally, RD_j^{new} is pre-loaded with the credentials $\{ID_{GSS}, CID_k, ID_{RD_j}^{new}, SID_{RD_j}^{new}, h(\cdot)\}$ before deploying in

the k_{th} cluster flying zone. The GSS stores the parameters $\{ID_{RD_j}^{new}, SID_{RD_j}^{new}\}$ in its own database.

V. SECURITY ANALYSIS

This section presents the austere security analysis of the proposed scheme by employing both the formal and informal security analysis.

A. FORMAL SECURITY ANALYSIS

In this paper, to the test the security of session key SK, we used extensively applied Random Oracle Model (ROM) [40]. Under the *ROM*, an adversary $\mathcal{A}$ interrelates with En^i, where i^{th} instance of an entity being participated (e.g. it can be legal user U_i, the remote drone RD_j or an ground station server GSS in iTCALAS. Consequently, there are three $En_{U_i}^i$, En^{TD_j} and GSS as the i^{th_1}, i^{th_2} and i_3^{th} of U_i, RD_j and GSS respectively. Moreover, the ROM assumes identical queries executing a definite attack, such as $Send(\cdot)$, $CorruptDE(\cdot)$, $Test(\cdot)$ and $Reveal(\cdot)$ queries. Similarly, a one-way hash function $h(\cdot)$ referred as collision-resistant can be access by the instances of each entity as well as $\mathcal{A}$.

- $Send(En^i, mesg)$: This query is demonstrated as an active attack, where U_A can submit a message *mesg* to an instance En^i, and also En^i responses accordingly.
- $Reveal(En^i)$ Simulating this query permits to reveal the existing session key SK shared among En^i and its companion U_A
- $CorruptDE(En_{U_i}^{i_1})$ This query allows $\mathcal{A}$ to get U_i's password PW_i and σ_i' via stolen MD_i
- $Test(En^i)$: $\mathcal{A}$ demands En^i for the SK and Eni probabilistically responses the output of a tossed neutral coin *co*.
- $Execute(En_{U_i}^{i_1}, En_{RD_j}^{i_2}, En_{GSS}^{i_3})$: It allows $\mathcal{A}$ to intercept the messages exchanged between U_i, RD_j and GSS

In Theorem 1, the SK security of iTCALAS is proved under *ROM* and using above mentioned queries.

Theorem 1: Assume that a polynomial time $\mathcal{A}$ simulate in time T against our protocol (iTCALAS). If $|h(\cdot)|$ denotes the range-space of $h(\cdot)$, bl specifies the bio's secrete key bit, que_{hsh} represents the number of hashes, que_{snd} characterizes the amount of send queries, respectively. Where as Ch and se are the parameters of *Zipfile* defined in [41]. The $\mathcal{A}$'s benefit in outrageous security of iTCALAS to obtain the SK between RD_j and U_i can be reffered as:

$$Advntg_{iTCALAS}^{\mathcal{A}}(i) \leq \frac{que_{hsh}}{H_{ash}} + 2maxx\left\{Ch'.que_{se}^{\acute{se}}, \frac{que_{se}}{2^{bl}}\right\}. \tag{15}$$

The following four games are defined, say Gme_v, $v \in \{0, 3\}$. If Suc_v specifies and occurrence where $\mathcal{A}$ can guess the arbitrary bit c_b in Gme_v correctly, the benefit of $\mathcal{A}$ in captivating this game will be defined and expressed as $Advntg_{iTCALAS}^{\mathcal{A}, Gme_v} = Pre[Suce_v]$, whereas $Pre[X]$ is the possibility of an event X.

Game.0 (Gme_0): The attack actually performed by $\mathcal{A}$ corresponding to iTCALAS in ROM against to Gme_0. The bit

c_b is chosen arbitrarily at the beginning of Gme_0. Therefore, we attain,

$$Advntg_{iTCALAS}^{\mathcal{A}}(i) = \left| 2.Advntg_{iTCALAS}^{\mathcal{A},Gme_0} - 1 \right| \quad (16)$$

Game. 1 (Gme_1) : This game is used for modeling an eavesdropping attack where $\mathcal{A}$ capture all the login and authentication exchanged messages $< MSG_1 = \{UID_i, U_1, U_2, T_1\} >$, $< MSG_1 = \{U_3, U_4, U_4, U_6, T_2\} >$ and $< MSG_3 = \{U_7, U_8, U_9, T_3\} >$ that simulate *iTCALAS* using *Execute* query. In order to verify the derived SK, the $\mathcal{A}$ simulates *Test* and *Reveal* queries at the end of this game. The SK created between U_i and reachable DR_j is $SK = h(h(R_3)\|h(R_1\|R_2))\|ID_{RD_j}\|CID_k\|T_4$. In order to compute SK, the $\mathcal{A}$ requires long term secrets (CID_k, ID_{RD_j} and HID_i) and temporal secrets R_1 to R_3 to compute SK which are not known to $\mathcal{A}$. Hence, just intercepting the MSG_1, MSG_2 and MSG_3 the chances of winning Gme_1 is not improved by $\mathcal{A}$. Leveraging the in-determinability of Gme_0 and Gme_1, it follows that:

$$Advntg_{iTCALAS}^{\mathcal{A},Gme_0}. \quad (17)$$

Game. 2 (Gme_2): This game includes the execution of *hsh* and *Send* queries to *ROM* as an active attack. From the delivered messages MSG_1, MSG_2 and MSG_3, every U_f ($f = 1, 2, 3....., 9$), are protected by the $h(\cdot)$. Since every U_f are involves current timestamps, the arbitrary numbers, secret credentials and identities, there will be no collision when the *Hsh* and *Send*$(\cdot)$ queries are simulated by $\mathcal{A}$. Both Gme_1 and Gme_2 are in deterministically but the addition of the execution of the *Hsh*$(\cdot)$ and *Send*$(\cdot)$ queries in Gme_2. The birthday paradox's results will be lead as follows:

$$\left| Advntg_{iTCALAS}^{\mathcal{A},Gme_1} - Advntg_{iTCALAS}^{\mathcal{A},Gme_2} \right| \le que_{hsh}/(2\,|Hsh|) \quad (18)$$

Game. 3 (Gme_3): The Gme_3 is malformed from Gme_2 by including the exeution of *CorruptDE* query, $\mathcal{A}$ would be able to have the parameters of $MD_i = \{A_i, L_i, M_i, \tau_i, Gen(\cdot), \overline{UK}_i, Rep(\cdot), h(\cdot), t\}$. Through guessing some password and using the *Zipf*'s law $\mathcal{A}$ can check it utilizing the derived credentials $\hat{A}_i$ and L_i. The benefit of $\mathcal{A}$ will be exceed over 0.5 where in condition $que_{se} = 10^7$ or 10^8 if we only take seeking password. Similarly, the gain of $\mathcal{A}$ will exceed over 0.5 if $\mathcal{A}$ uses personal data of user. Moreover, as the function of *fuzzy extractor* can be used for *iTCALAS* to gain the c_b. Excluding the execution of *CorruptDe* query in Gme_3, the Gme_2 and Gme_3 are not distinguishable. If the system allows limited tries of entering wrong password then it will leads towards following consequences :

$$\left| Advntg_{iTCALAS}^{\mathcal{A},Gme_2} - Advntg_{iTCALAS}^{\mathcal{A},Game.3} \right| \le \left\{ Ce'.que_{snd}^{snd}, \frac{que_{snd}}{2^l} \right\}. \quad (19)$$

As all the queries are simulated by $\mathcal{A}$, it only remains to gues the c_b to win the game once the *Test*$(\cdot)$ query is executed, and hence, we have $Advntg_{iTCALAS}^{\mathcal{U},Game.3} = \frac{0}{1}$.

Simplifying the equations and using the triangular-inequality, the following is attained:

$$\frac{0}{1}.Advntg_{iTCALAS}^{\mathcal{A}}(i)$$

$$= |Advntg_{iTCALAS}^{\mathcal{A},Gme.0} - \frac{0}{1}|$$

$$= Advntg_{iTCALAS}^{\mathcal{A},Gme.1} - Advntg_{iTCALAS}^{\mathcal{A},Gme.4}$$

$$\le |Advntg_{iTCALAS}^{\mathcal{A},Gme.1} - Advntg_{iTCALAS}^{\mathcal{A},Game.2}|$$

$$\quad + |Advntg_{iTCALAS}^{\mathcal{A},Gme.3} - Advntg_{iTCALAS}^{\mathcal{A},Gme.3}|$$

$$\le \frac{que_{hsh}}{2|H_{hash}|} + maxx \left\{ CE'.que_{snd}^{snd'}, \frac{q_{snd}}{2^l} \right\}.$$

Hence, it follows that $Advntg_{iTCALAS}^{\mathcal{A}}(t) \le \frac{que_{hsh}}{H_{ash}} + 2maxx \left\{ CE'.q_{snd}^{snd'}, \frac{que}{2^l} \right\}$

B. SECURITY ANALYSIS USING PROVERIF TOOL

This subsection presents the results of ProVerif tool, used for the verification of the security properties for the proposed scheme. ProVerif can check the correctness, session key secrecy, reachibility and anonymity and privacy. Two channels 1) *ChSec* : *private* and 2) *Chpub* : *public*, to represent secure and public channels for registration and authentication phases, respectively. The communication in the registration phase between U_i, GSS and RD_j is completed over the *ChSec* : *private* channel, whereas the *Chpub* : *public* channel is used for the communication in the login and authentication phase. During the implementation different declared constructors are as follow: *Hash*(h), *XOR*($\oplus$), *Concat*($\|$), *Rep*(), *Gen*(). The results of the ProVerif tool are shown in Figure 6, which clearly demonstrates the scheme's correctness and security.

C. INFORMAL SECURITY ANALYSIS

This section presents a discussion of on the security features extended by *iTCALAS* as well as attack resilience:

1) STOLEN MOBILE DEVICE ATTACK

This attack is launched by an attacker, after the device of a legitimate user is stolen/lost and attacker gets it. Based on the information in the smart device, the attacker can try to expose identity and password related information of the user. The details of proposed scheme's resistance from this attack, after attacker gets the lost/stolen device is given as follows:

- *Identity guessing attack:* $\mathcal{A}$ can perform power analysis on the device to extract the information form the memory [39]. $\mathcal{A}$ have the access to the credentials $\{A_i, L_i, M_i, \tau_i, Gen(\cdot), \overline{UK}_i, Rep(\cdot), h(\cdot), t\}$, the ID_i of the U_i is first encrypted by the GSS's secret key and then *XORed* with $h(ID_i\|PW_i\|\sigma_i)$ and stored in A_i. So, in order to get ID_i the knowledge of the X_{GSS}, PW_i and σ_i is required, also the one-way property of $h(\cdot)$ makes it infeasible to guess ID_i. Hence the scheme is secured again identity guessing attack.

```
Completing equations...
Completing equations...
-- Query inj-event(end_U1(IDU1[])) --> inj-event(start_U1
(IDUi[]))
nounif mess(ChSec[],ID1_693)/-5000
Completing...
Starting query inj-event(end_U1(IDU1[])) --> inj-event(start_
Ui(IDUi[]))
RESULT inj-event(end_U1(IDU1[])) ==> inj-event(start_Ui(IDUi[
])) is true.
-- Query inj-event(end_GSS(IDGSS[])) ==> inj-event(start_GSS
(IDGSS[]))
nounif mess(ChSec[],ID1_2484)/-5000
Completing...
Starting query inj-event(end_GSS(IDGSS[])) --> inj-event(star
t_GSS(IDGSS[]))
RESULT inj-event(end_GSS(IDGSS[])) --> inj-event(start_GSS(ID
GSS[])) is true.
-- Query inj-event(end_RD(IDRD[])) --> inj-event(start_RD(IDR
D[]))
nounif mess(ChSec[],ID1_4261)/-5000
Completing...
Starting query inj-event(end_RD(IDRD[])) --> inj-event(start_
RD(IDRD[]))
RESULT inj-event(end_RD(IDRD[])) --> inj-event(start_RD(IDRD[
])) is true.
-- Query not attacker(SK[])
nounif mess(ChSec[],IDi_6028)/-5000
Completing...
Starting query not attacker(SK[])
RESULT not attacker(SK[]) is true.
```

FIGURE 6. ProVerif simulation results.

- *Offline password guessing attack:* After extracting the parameters from the MD_i, $\mathcal{A}$ has the access to the parameters A_i, L_i, $\overline{UK}_i$ and M_i but cannot extract the PW_i from these parameters as it requires the knowledge of ID_i, σ_i, UID_i, b and UK_i. Hence, the scheme can withstand this attack.

2) ANONYMITY AND UNTRACEABILITY OF USER

As described in threat model (Subsection I-A) that $\mathcal{A}$ can capture the messages MSG_1, MSG_2 and MSG_3 transmitted over the public channel. The user ID_i is sent in MSG_1 through $UID_i = E_{X_{GSS}}(ID_i||r_s)$ and to extract ID_i, $\mathcal{A}$ need private key X_{GSS} of the ground station. Moreover, this identity is updated in each session, so the user can not be traced. Moreover, all other parameters in messages communicated through public link are based on randomly selected numbers or timestamps. Therefore, the traceability or identity expose is protected in proposed *iTCALAS*.

3) IMPERSONATION ATTACK

$\mathcal{A}$ can impersonate on behalf of user, ground station or the drone. The resilience of *iTCALAS* against these impersonations is discussed below:

- *User impersonation attack:* For $\mathcal{A}$, to launch successful impersonation on behalf of U_i, has to generate valid request message $MSG_1 = \{UID_i, U_1, U_2, T_1\}$. Selecting current timestamp is very easy and UID_i can be replayed easily. Creating rest of the parameters U_1 and U_2 in a way that U_2 can pass the test $U_2 \stackrel{?}{=} h(R_1||UID_i||ID_{RD_j}||TC_i||CID_k)$, besides UID_i, ID_{RD_j} and R_1 the attacker $\mathcal{A}$ needs TC_i as well as CID_k. TC_i can be extracted using smart card as well as user password and biometrics, or through private key X_{GSS}

of the ground station. Moreover, to get the information of the flying zone of some arbitrary user, the attacker needs user private credentials as well as smart device. Therefore, $\mathcal{A}$ cannot successfully impersonate as a U_i.

- *Server impersonation attack* For $\mathcal{A}$, to launch successful impersonation on behalf of GSS, has to generate and send valid message $MSG_2 = \{U_3, U_4, U_5, U_6, T_2\}$ to RD_j. Selecting current timestamp is very easy. Creating rest of the parameters U_3, U_4, U_5 and U_6 in a way that U_4 can pass the test $U_4 \stackrel{?}{=} h(UID_i||ID_{RD_j}||CID_k||T_2||h(R_1||R_2))$, besides UID_i, ID_{RD_j} and CID_k the attacker $\mathcal{A}$ needs $h(R_1||R_2)$, and $h(R_1||R_2)$ can be computed by an entity who has private key X_{GSS} of the ground station. Moreover, to get the information of the flying zone of some arbitrary user, the attacker needs private credentials of the drones or private key of the ground station. Therefore, $\mathcal{A}$ cannot successfully impersonate as a GSS.

- *Drone impersonation attack* For $\mathcal{A}$, to launch successful impersonation on behalf of RD_j, has to generate and send valid message $MSG_3 = \{U_6, U_7, U_8, T_3\}$ to U_i. Selecting current timestamp is very easy. Creating rest of the parameters U_6, U_7 and U_8 in a way that U_6 can pass the test $U_8 \stackrel{?}{=} h(R'_3||SK||T_3||CID_k)$, besides T_3 the attacker $\mathcal{A}$ needs $R'_3 = h(R_3||h(R_1||R_2))$ as well as session key and both of these parameters R'_3 and session key cannot be computed unless the attacker has private key X_{GSS} of the ground station or temporal credentials of the drone. Therefore, $\mathcal{A}$ cannot successfully impersonate as a RD_j.

4) PROTECTION AGAINST REPLAY ATTACK

In the proposed scheme the reply attack is eradicated by incorporating the time stamps and random nonces in the messages during login and authentication phases. As $\mathcal{A}$ sends the messages $MSG_1 = \{UID_i, U_1, U_2, T_1\}$, $MSG_2 = \{U_3, U_4, U_5, U_6, T_2\}$, $MSG_3 = \{U_6, U_8, U_9, T_3\}$ to perform a reply attack will fail due to time stamp and random nonces. When message is received the initial step involved is to check the freshness of the time stamp, then if the time delay is greater than the allowed delay message is going to be discarded. Hence the scheme can successfully prevent the reply attack.

5) MAN-IN-THE-MIDDLE ATTACK PREVENTION

During the login and authentication phase $\mathcal{A}$ may try to capture and tempered the transferred messages MSG_1, MSG_2 and $MSG_3$to make believe the other participants that the message is genuine. But to perform this task the $\mathcal{A}$ requires the knowledge of parameters $\{UK_i, CID_k, TC_i, R_1\}$ for MSG_1, $\{SID_{RD_j}, ID_{RD_j}, CID_k, R_1, R_2, UID_i^{new}\}$ for MSG_2 and $\{R_3\}$ for MSG_3. Thus the scheme can withstand this attack.

6) MUTUAL AUTHENTICATION

All of the participants involved in the communication authenticate each other. In the MSG_1, the GSS checks $\{R_1 \& U_2\}$ to authenticate MD_i. In the MSG_2 the RD_j checks $\{h(R_1||R_2) \& U_4\}$ to authenticate the GSS, where as MD_i uses $\{R_3 \& U_4\}$ to authenticate the RD_j. So, both the U_i and RD_j authenticate each other with the help of GSS.

7) EPHEMERAL SECRET LEAKAGE (ESL) ATTACK

In the proposed scheme the long-term secrets like $\{ID_{RD_j}, CID_k, X_{GSS}\}$ and short-term secrets like $\{R_1, R_2, R_3\}$ are used to generate the session-key SK. Now assume that all f the long-term secret has been compromised and are in the knowledge of the $\mathcal{A}$, but $\mathcal{A}$ still needs the short-term secrets in order to successfully compute SK. Now same way if the short-term secrets are compromised $\mathcal{A}$ still needs the long-term secrets in order to successfully compute the SK. So, the scheme can successfully withstand the ESL attack.

8) REMOTE DRONE CAPTURE ATTACK

As described in the threat model (Subsection I-B) $\mathcal{A}$ can capture the RD_j and can extract the parameters $\{ID_{GSS}, CID_k, ID_{RD_j}, SID_{RD_j}, h(\cdot)\}$ stored in its memory. But all of the stored parameters are uniquely computed for each drone and does not reveal any information about the other drones, MD_i and GSS. Hence, the scheme can withstand remote drone capture attack.

VI. COMPARISONS WITH RELATED SCHEMES

In this section, we elaborate the security features, computational and communicative efficiencies comparisons of the proposed scheme with some related schemes [17], [22], [26], [27], [42].

A. SECURITY FEATURES

This subsection elaborates the security features comparisons between proposed and related schemes. The comparisons are shown in Table 2, where (✓) represents the provision of certain security feature or resistance against some attack; whereas, (×) shows insecurity against some attack or non-provision of some security feature. Citing Table 2, only proposed scheme provides all the related security features discussed in the table, other competing schemes lacks one or more security features or resists against one or more attacks. The scheme presented in [27] also has much higher cost as compared with *iTCALAS* and it can be observed in following subsections and Table 3.

B. COMPUTATION AND COMMUNICATION COSTS

The comparison of the different schemes in the context of communication and computation costs incured during login and authentication phase only, is considered here. For communication cost, the bit-size considered for nonces is 160 *bits*; whereas, identity is fixed as 160 *bits* long. The size of timestamp is taken as 32 *bits* long, the size of ECC

TABLE 2. Comparison of functionality features.

	Proposed	[17]	[26]	[22]	[27]	[42]
$SR\#1$	✓	✓	✓	✓	×	✓
$SR\#2$	✓	✓	×	×	✓	✓
$SR\#3$	✓	✓	×	×	✓	✓
$SR\#4$	✓	×	✓	×	✓	×
$SR\#5$	✓	✓	×	×	✓	✓
$SR\#6$	✓	✓	✓	✓	✓	✓
$SR\#7$	✓	✓	×	×	✓	✓
$SR\#8$	✓	✓	✓	✓	✓	✓
$SR\#9$	✓	✓	✓	✓	✓	✓
$SR\#10$	✓	✓	×	×	✓	✓
$SR\#11$	✓	✓	✓	✓	✓	✓
$SR\#12$	✓	×	×	×	✓	✓
$SR\#13$	✓	✓	×	×	✓	✓
$SR\#14$	✓	✓	✓	✓	✓	×
$SR\#15$	✓	✓	✓	✓	✓	✓
$SR\#16$	✓	✓	×	×	✓	✓

Note: $SR\#1$: correctness; $SR\#2$: offline or online password guessing attack ; $SR\#3$: privileged insider attack; $SR\#4$: user anonymity; $SR\#5$: traceability; $SR\#6$: detection for unauthorized login; $SR\#7$: stolen mobile/smart card attack; $SR\#8$: denial-of-service attack; $SR\#9$: mutual authentication; $SR\#10$: ESL attack; $SR\#11$: replay & man-in-the-middle attacks; $SR\#12$: impersonation attacks; $SR\#13$: Sensing node or drone capture attack; $SR\#14$: revocability; $SR\#15$: formal security verification under any tool; $SR\#16$: password/biometric change..

TABLE 3. Communication cost comparison.

Schemes	# of messages	# of bits
Proposed Scheme	3	1696
Srinivas et al. [17]	3	1536
Tai et al. [26]	4	2560
Turkanović et al. [22]	4	2720
Challa et al. [27]	3	2528
Wazid et al. [42]	3	1696

coordinates is fixed at 160 *bits*, which implies that size of an ECC point is $(160 + 160) = 320$ *bits*. Moreover, it is assumed that all the schemes used $SHA - 1$ algorithm with output size 160 *bits* long.

The Table 3 shows that the communication cost of the proposed scheme is less than the [22], [26], [27]; whereas cost is equal to [42]and has slight more computation cost as compared with [17]. However, only proposed scheme provides all discussed security features. The communication cost is also represented in Fig. 7.

For comparing the costs, we adopted the timing of various operation as per the experiment conducted in [43] on a PC with dual CPU E2200: 2.20GHz using GMP based PBC library. The experiment was performed on 32 bit Ubuntu 12.04.1 LTS having RAM size 2048 MB. The computed time for the hash-function (T_h) is 0.0023 *ms*, for ECC point multiplication (T_m) is 2.226 *ms*, for symmetric enc/dec (T_{sym}) is 0.0046*ms* and time required for the fuzzy-extractor is $T_m \approx T_{fe} \approx 2.226$ *ms* [17]. The total number of operations required for execution of a single cycle of the proposed scheme are
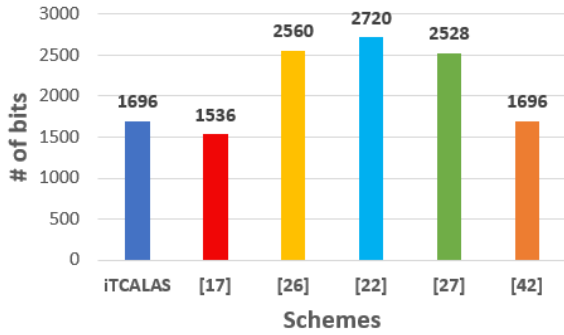
FIGURE 7. Communication cost comparison.

TABLE 4. Computation cost comparison.

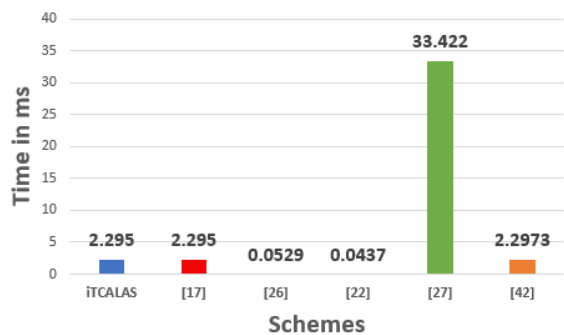| Schemes	Mobile device	Ground station server	Drone	$\approx$ computation
Proposed Scheme	$10T_h + T_{fe}$	$7T_h + 3T_{sym}$	$7T_h$	≈ 2.295
Srinivas et al. [17]	$14T_h + T_{fe}$	$9T_h$	$7T_h$	≈ 2.295
Tai et al. [26]	$7T_h$	$6T_h$	$10T_h$	≈ 0.0529
Turkanović et al. [22]	$7T_h$	$5T_h$	$7T_h$	≈ 0.0437
Challa et al. [27]	$5T_h + T_{fe}$ $+5T_m$	$4T_h + 5T_m$	$3T_h$ $+4T_m$	≈ 33.422
Wazid et al. [42]	$16T_h + T_{fe}$	$8T_h$	$7T_h$	≈ 2.2973

FIGURE 8. Computation cost comparison.

$24T_h + 1T_{fe} + 3T_{sym}$ with running time $\approx 2.295ms$. Computation cost of various schemes are presented in Table 4 as well as in Figure 8. Citing Table 4, proposed scheme incurs more computation time as compared with [22], [26] and same as of [17] and less than [42] and [27]. However, only proposed scheme provides all security features.

VII. CONCLUSION

The surveillance data is important and sensitive in nature and among other methods, the drones can be very useful for obtaining such data from in-accessible places like fire sites, battle field and mountains peeks etc. However, due to the underlying open channel, this data as well as the drones can be used for wicked intentions. In this paper, we examined a recent authentication scheme for protecting drone access by unauthorized users. We have proven that the scheme of Srinivas et al. is insecure against traceability and impersonation based on stolen verifier. It is also shown that their scheme has scalability issues and can work when there

is only one flying zone/cluster present in the environment. For securing the surveillance and drones, we presented an improved scheme using only light weight hash and symmetric encryption/decryption operations. The security of the proposed scheme is proved through formal, informal and automated methods. While providing all the security features and resistance against many known attacks, proposed scheme completes authentication process with same computation time as of Srinivas et al.'s scheme. Therefore, proposed scheme is best suitable for securing the surveillance data communicated through drones.

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