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LAKE-IoD: Lightweight Authenticated Key Exchange Protocol for the Internet of Drone Environment

MUHAMMAD TANVEER[1], AMJAD HUSSAIN ZAHID[2], MUSHEER AHMAD[3], ABDULLAH BAZ[4], (Senior Member, IEEE), AND HOSAM ALHAKAMI[5], (Member, IEEE)

[1]Telecommunications and Networking (TeleCoN) Research Laboratory, GIK Institute of Engineering Sciences and Technology, Topi 23640, Pakistan
[2]Department of Informatics and Systems, University of Management and Technology, Lahore 54700, Pakistan
[3]Department of Computer Engineering, Jamia Millia Islamia, New Delhi 110025, India
[4]Department of Computer Engineering, College of Computer and Information Systems, Umm Al-Qura University, Makkah 21955, Saudi Arabia
[5]Department of Computer Science, College of Computer and Information Systems, Umm Al-Qura University, Makkah 21955, Saudi Arabia

Corresponding author: Musheer Ahmad (musheer.cse@gmail.com)

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ABSTRACT A drone is an unmanned aerial vehicle, which is deployed in a particular Fly Zone (FZ), and used to collect crucial information from its surrounding environment to be transmitted to the server for further processing. Generally, a Mobile User (MU) is required to access the real-time information collected by the drone stationed in a specific FZ securely. Therefore, to ensure secure and reliable communications an Authenticated Key Exchange (AKE) protocol is imperative to the Internet of Drone (IoD) environment. An AKE scheme ensures only authentic MU to access IoD network resources. Upon successful authentication, MU and drone can set up a secret session key for secure communication in the future. This paper presents a novel Lightweight AKE Protocol for IoD Environment (LAKE-IoD), which first ensures the authenticity of MU and also renders session key establishment mechanism between MU and drone with the help of a server. LAKE-IoD is an AKE protocol, which is based on an authenticated encryption scheme AEGIS, hash function, and bit-wise XOR operation. Meticulous formal security verification by employing a software tool known as Scyther and informal security analysis demonstrates that LAKE-IoD is protected against different well-known active and passive security attacks. Additionally, Burrows-Abadi-Needham logic is applied to verify the logical completeness of LAKE-IoD. Furthermore, a comparison of LAKE-IoD with the related schemes shows that LAKE-IoD incurs less communication, computational and storage overhead.

INDEX TERMS Internet of Drone, authenticated key exchange, lightweight cryptography, unmanned aerial vehicles, security and privacy.

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) applications have observed outstanding growth in diverse fields along with the colossal demand of the Internet of Things (IoT). UAV can be employed in several applications, such as security surveillance system, traffic monitoring system in a smart city [1], disaster management, goods distribution, data collection, distributed processing, object detection and tracking, localization and mapping, environmental monitoring, health-care system, and rescue system [2]–[4]. Besides, the advancements presented by UAVs, these also have motivated the way for the unification of UAVs, like smart drones within IoT domain. Drones are existing around for a long time; recently their uses within IoT realm have become a vital research topic [4].

Drones are a new form of the flying IoT objects acting as a sensing device. The synthesis of the smart drones and IoT domain is known as the Internet of Drone (IoD). IoD is a layered network control architecture devised especially to control the airspace by deploying drones technology and by establishing the coordination among the drones [5]. Fig. 1 shows a high-level architecture of the IoD system [6], [7], which is the interconnection of a Ground Station (GS), and smart drone deployed in the airspace. A drone is a fundamental component of IoD networks. The primary function

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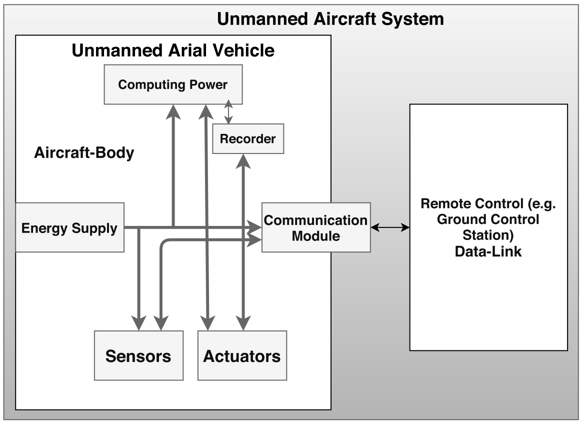


FIGURE 1. IoD system architecture.

of the drone is to collect the information from a specific Fly Zone (FZ) and transmit the collected information to GS. It is usually equipped with a communication module for transmission with GS, sensors used to collect the information, memory to store the data collected by the sensor, and also has computational capabilities and power resources [6], [7].

IoD is a new paradigm in wireless communication, which utilizes IoT technologies to accomplish its various critical operations. The cost-effective operational functionalities such as drone monitoring and control, trajectory planning, localization, authorization, and security and privacy are the prime requirements of IoD networks [8]–[10]. Irrespective of the advancements and plethora of solutions for drone communications, security and privacy in an IoD environment is still a major issue. IoD networks are resource constricted because a drone has limited computational, storage, and power resources. However, to enhance the lifetime of an IoD network, it is inevitable to devise a communication protocol that requires minimum resources [11]. Therefore, an efficient AKE protocol is necessary before utilizing a cryptographic encryption and decryption mechanism to ensure the secure and reliable transmission of information in an IoD network. This paper proposed a novel and lightweight AKE protocol for an IoD environment to ensure secure communication. The proposed scheme utilized a Lightweight Cryptographic (LWC) and Authenticated Encryption (AE) mechanism to ensure the confidentiality and integrity of the exchanged messages during the AKE phase. An AE encryption and decryption scheme can provide confidentiality and integrity simultaneously. LWC mechanism is suitable for the resource constricted environment.

A. RESEARCH CONTRIBUTION

The summary of the main contributions are listed as follows:

- In this paper, we devised a novel and lightweight Authenticated Key Exchange (AKE) protocol named as Lightweight AKE protocol for IoD Environment (LAKE-IoD). The proposed AKE scheme utilizes an AE algorithm AEGIS, a hash function (SHA-256), and exclusive-OR operation. LAKE-IoD renders password update phase, revocation or reissue phase, and dynamic drone deployment phase.
- Informal security analysis shows that LAKE-IoD is secure. Furthermore, LAKE-IoD is analyzed formally by employing Burrows-Abadi-Needham (BAN) logic and by using automatic verification software tool Scyther, which shows that the proposed LAKE-IoD is logically complete and secure against the various security attacks, such as Man-in-the-Middle (MITM) attack and replay attack.
- Finally, LAKE-IoD is compared with the related existing AKE schemes in terms of computational, communication, and storage overheads. The comparisons illustrate that the proposed scheme incurs fewer overheads than the existing schemes.

B. PAPER ORGANIZATION

The rest of the paper is organized as follows. Section II reports different relevant security schemes for the IoD environment. System models are presented in Section III and preliminaries are discussed in Section IV. The details of the devised LAKE-IoD scheme are described in Section V. Security analysis of LAKE-IoD is provided in Section VI. A detailed comparison of LAKE-IoD with the recent related schemes is presented in Section VII. Finally, the paper is concluded in Section VIII.

II. RELATED WORK

In this section, various related user authentication schemes are discussed. Lin *et al.* [11] present a review on the security and privacy issues in the Internet of Drone (IoD) and discuss various applications of IoD in the next generation of communication technology. Wazid *et al.* [12] present a survey on the security requirements in the IoD environment and also analyze various security protocols suitable for the IoD environment. Wazid *et al.* [6] proposed user Authentication and Key Establishment (AKE) scheme for the IoD environment. The proposed scheme is lightweight and insecure against various well-known attacks. Srinivas *et al.* [7] an AKE scheme for IoD, which is insecure against impersonation and privilege insider attacks. Srinivas *et al.*'s scheme also does not scale well as demonstrated in [13]. Wazid *et al.* [6] presented a security solution based on convolution neural networks for the IoD environment.

Farash and Attari [14] presented an Elliptic Curve Cryptography (ECC) based AKE scheme for Session Initiation Protocol (SIP). Thereafter, Lu *et al.* [15] demonstrated that scheme presented by Farash *et al.* is insecure against the off-line-password guessing attack, and they presented an AKE scheme based on ECC to remove the shortcomings of Farash *et al.* Zhang *et al.* [16] presented an authentication strategy for SIP. However, the proposed scheme is vulnerable to various security attacks such as privileged-insider attack and Daniel-of-Service (DoS) attack as pointed out in [17]. Kumari *et al.* [18] proposed an AKE scheme for the Multi-Server Environment (MSE) based on ECC. Feng *et al.* [19]

pointed out the scheme devised by Kumari *et al.* is insecure against the server-impersonation Attack and presented an authentication scheme for the MSE environment. Ali and Pal [20] devised an AKE based on ECC for MSE and thereafter, Wang *et al.* [21] demonstrated that the scheme proposed by Ali *et al.* can not withstand privileged insider attack, user/server impersonation attack, DoS attack, and fails to provide forward-secrecy. Challa *et al.* [22] devised an ECC based AKE scheme, which is unprotected against various security attacks.

Amin *et al.* [23] constructed an AKE scheme for the cloud computing-based IoT environment, which is lightweight and suitable for resource constricted devices. However, the strategy presented by Amin *et al.* can not withstand the impersonation attack and privileged insider attack as demonstrated in [24]. Das *et al.* [24] proposed an AKE scheme for the IoT environment, which utilized lightweight hash function and FE technique for the bio-metric verification and cannot withstand traceability attack. Hussain and Chaudhry [25] pointed out that the scheme proposed by DAS *et al.* is vulnerable to various security attacks such as traceability attack, stolen-verifier attack, stolen/lost smart-device attack, and also does not render forward secrecy. Moreover, Challa *et al.* [26] presented an AKE scheme based on ECC, which is not suitable for resource-limited devices because of high computational overhead. Additionally, Jia *et al.* [27] highlighted that the scheme presented by Challa *et al.* is insecure against the impersonation attack and also does not ensure the untraceability property. Sharma and Kalra [28] proposed an AKE scheme for the cloud-based IoT environment. However, Sharma *et al.*'s scheme is vulnerable to the privileged-insider attack. Tanveer *et al.* [29] proposed an AKE scheme for 6LoWPAN resource-limited devices, which utilizes an authenticated encryption scheme known as ASCON and hash function. However, this scheme cannot resist the tractability attack.

The existing studies and their shortcomings motivate us to work on their weakness. For this aim, we target to construct a novel security scheme called LAKE-IoD. The LAKE-IoD utilizes a Secure Hash Algorithm (SHA-256), an AE scheme known as AEGIS, which is LWC mechanism, and an FE for the bio-metric verification of a user.

III. SYSTEM MODELS

We consider the following two models in designing the proposed LAKE-IoD.

A. NETWORK MODEL

For the remote user authentication, this paper considers the network model as shown in Fig. 2. According to the network model, the airspace is divided into multiple FZs and many drones can be deployed in a specific FZ to monitor a particular environment (airspace). The drone deployed in a particular FZ collects data or information from the surrounding environment and transmits the gathered information to the Management Server (MS), which is stationed at the Ground Station (GS). The MS is used to store the data collected by the drone. It also stores the secret information related to the user, drone, and airspace. An internal user usually sits in the Control Room (CR) to monitor an IoD environment. Promising technologies such as 4G/5G cellular networks are used to provide wireless connectivity in a specific FZ. There is a wired connectivity between the GS and wireless access point. Generally, the External User (EU) requires to collect the real-time information from the drone instead of using buffered (stored) information at the MS. For instance, an ambulance driver requires to know the traffic condition on the roads to reach the destination (for example, a hospital) as soon as possible. To access the real-time information from a particular drone, an EU must register himself/herself with the MS. An EU and a drone require to authenticate with each other through MS. After authentication, both the drone and EU can establish the session-key (secret-key) to secure future communication.

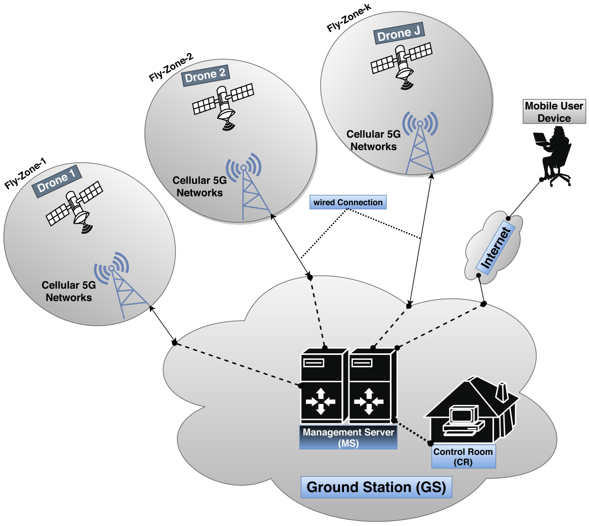


FIGURE 2. Internet of drone network model.

B. THREAT MODEL

We follow the widely accepted Dolev and Yao (DY) [30] threat model for the proposed scheme LAKE-IoD.

1) According to DY model, two entities (drone and EU) in the network can communicate using public (insecure) channel, and endpoint entities are trustworthy. Therefore, an adversary $\mathcal{A}$ can capture or eavesdrop the communicated information or messages and can also forge or modify the exchanged messages.
2) The drone is usually deployed in a hostile or unattended environment. It is possible that $\mathcal{A}$ can capture the drone and can also extract the secret information stored in the drone memory by employing the power analysis attack. However, the MS is considered as a secure entity in the proposed scheme and $\mathcal{A}$ can not compromise the MS.

IV. PRELIMINARIES

A. FUZZY EXTRACTOR (FE)

In this paper, we employ Fuzzy Extractor (FE) [31] for the bio-metric (BU) verification of the user. FE consists of the following two algorithms:

1) $Gen(.)$: It is Bio-metric Key (BK) generation algorithm. The $Gen(.)$ is a probabilistic algorithm. It takes BU as an input and generates $BK \in [0,1]^L$ and a Reproduction Parameter (RP), where L is the length of the BK, that is, $Gen(BU) = \{BK, RP\}$.
2) $Rep(.)$: It is a deterministic algorithm, which takes the noisy BU' and RP as input and recovers the BK. This implies that $Rep(BU', RP) = BK$ provided the condition $HD(BU, BU') \leq ET$ holds, where HD is the Hamming Distance between BU & BU', and ET is the predefined Error Tolerance.

B. AEGIS

AEGIS is a dedicated, lightweight, and high-performance Authenticated Encryption with Associative Data (AEAD) is an LWC mechanism. A brief description of AEGIS is given below:

1) The AEGIS was submitted to CAESAR competition and selected as the finalist candidates [32].
2) The AEGIS renders high security and speed of AEGIS is double as compared to Advance Encryption Standard (AES), i.e, ($2{*}AES$), 8 times of AES-CBC, and slightly faster than AES-CTR. The details of the recommended parameters for the AEGIS are given in [32], [33]. The AEGIS is appropriate for RFID tags and resource constricted IoT devices. It requires less computational resources as compared to AES and AES-GCM.
3) The AEGIS is an encryption algorithm, which generates output $\langle CT, AUTH_{tag} \rangle$, where CT is the ciphertext, $AUTH_{tag}$ is the authentication parameter, by taking the plaintext PT as input. Logical operation of AEGIS can be expressed as $CT = E_K\{\{IV, AD\}, PT\}$ and $AUTH_{tag}$, where K is the key, IV is the Initialization Vectors, and AD is the Associative Data. $AUTH_{tag}$ is used to ensure the authenticity and integrity of AD and CT. In this paper, we employ AEGIS as the encryption/decryption algorithm.

V. LAKE-IoD SCHEME

The proposed scheme LAKE-IoD comprises six phases, such as (i) Drone registration phase, (ii) User registration phase, (iii) User authentication and key exchange, (iv) Password and bio-metric update phase, (v) Revocation phase, (vi) Dynamic drone deployment phase. It is assumed that all the nodes in entities in an IoD environment are time-synchronized. Secure Hash Algorithm (SHA-256) utilized in the proposed scheme, which takes arbitrary input and generates a fixed-sized output. It is also assumed that all the entities in an IoD environment are time- synchronized. Table 1 presents the list of notations utilized in the proposed strategy. A detailed description of all phases of LAKE-IoD is presented as follows.

TABLE 1. List of notations.

Symbol	Description
ID_{MS}, SID_{MS}	Real-identity and temporary-identity of the Management Server (MS), respectively
$ID_{MU_i}, SID_{MU_i}, SP_{MU_i}$	Real-identity, temporary-identity, and authentication parameter for the user, respectively
MU_i, MD_i	Mobile user, mobile device, respectively
$ID_{D_j}, SID_{D_j}, FID_k, SP_{D_j}$	Real-identity, temporary-identity, Fly Zone (FZ) identity, and secret parameter for the drone, respectively
T_1, T_2, T_3	Timestamps utilized during the authentication phase, respectively
$T^1_{ad}, T^2_{ad}, T^3_{ad}$ and T^R	Maximum time delay and message received time, respectively
K_1, K_2, K_3	Shared-secret Key used during the Authentication phase
$E_k(x)$, $D_k(x)$	AEGIS encryption and decryption of message "x" using the secret-key "k", respectively.
$R_{MU_i}, R_{MS}, R_{D_j}$	Temporary random number used during authentication phase
$Gen(.)$, $Rep(.)$	Fuzzy-extractor key generation and reproduction function, respectively
$BK^{reg}_{MU_i}, BK^{LO}_{MU_i}$	The bio-metric key during registration and login phase, respectively
$HW(x)$	Hamming Weight of x
$Rot(y, HW(x))$	Rotate left/right with respect to the $HW(x)$.
$H(.)$, $\oplus$, $\Vert$	Cryptographic hash-function, bit-wise XOR, and concatenation, respectively

A. DRONE REGISTRATION PHASE (DRP)

In this phase, the registration process for a drone $D_j | j = 1, 2..N_j$ is discussed, where N_j is the total number of D_j. It is assumed that the airspace is divided into k number of Fly Zones (FZ). Each FZ is assigned with a unique Fly Zone Identity ($FID_k | k = 1, 2..N_k$). It is necessary to register D_j with the Management Server (MS) before its deployment in a specific FZ. It is assumed that MS has a unique identity ID_{MS} and temporary identity SID_{MS}, which are known only to MS. The detailed process of D_j registration is given below.

1) Step DRP-1: MS assigns a unique identity ID_{D_j} and Fly Zone Identity FID_k to D_j before its deployment in a specif FZ.
2) Step DRP-2: MS computes the temporary identity SID_{D_j} for D_j by computing $Q = H(ID_{MS} \parallel SID_{MS} \parallel R_{D_i})$, where R_{D_i} is a random number of 128 bits, $SID_{D_j} = Q_1 \oplus Q_2$, where Q_1 and Q_2 are the two equal chunks (128-bits) of Q.
3) Step DRP-3: MS computes secret parameter SP_{D_j} for the drone D_j by computing $SP_{D_j} = R_{D_j} \oplus Q_1$.
4) Step DRP-4: Finally, MS stores the parameters $\{ID_{D_j}$, SID_{D_j}, SP_{D_j}, $FID_k\}$ in the memory of D_j. MS also stores these credentials in its memory.

B. MOBILE-USER REGISTRATION PHASE (MURP)

An MU_i requires to register with MS in IoD environment before accessing the services provided by the Zone Service Provider (ZSP) (ZSP is an organization, which monitors and maintains an IoD network). After successful registration, ZSP allow an MU_i to acquire the real-time vital information from a specific drone deployed in a particular FZ. The details of an MU_i registration process are given as follows.

1) Step MURP-1: MU_i picks his/her unique identity ID_{MU_i}, and PW_{MU_i}.
2) Step MURP-2: MD_i selects a random number R_{IN} and computes $RID_{MUi} = H(ID_{MU_i} \parallel R_{IN})$ and sends RID_{MUi} to MS through a secure channel.
3) Step MURP-3: After obtaining RID_{MUi} from MD_i, MS selects timestamp T_{MS} of size 32-bits, picks master-key MSK_{MU_i} for MU_i and computes $S_{ms} = H(T_{MS} \parallel RID_{MUi} \parallel SID_{MS})$, $SID_{MU_i} = S^1_{ms} \oplus S^2_{ms}$, where S^1_{ms} and S^1_{ms} are the two equal 128-bits chunks of S_{ms}. MS calculates the Secret Parameter (SP_{MU_i}) for MU_i by computing $AP = (ID_{MS} \parallel MSK_{MU_i} \parallel S^2_{ms})$, $SP_{MU_i} = AP_1 \oplus AP_2$, where AP_1 and AP_2 are the two equal parts of AP.
4) Step MURP-4: MS sends tuple $TU = \{SID_{MU_i}, SP_{MU_i}, SID_{MS}, SID_{D_j}\}$ to MD_i through a reliable channel.
5) Step MURP-5: MD_i receives TU from MS, MD_i calculates $A_{11} = SID_{MS} \oplus SID_{MU_i} \oplus SP_{MU_i} \oplus SID_{D_j}$, $(BK^{reg}_{MU_i}, RP^{reg}) = Gen(BU_{MU_i})$, $A_2 = SID_{MU_i} \parallel SID_{MS} \oplus H(ID_{MU_i} \parallel BK^{reg}_{MU_i} \parallel PW_{MU_i})$, $A_3 = SID_{D_j} \parallel SP_{MU_i} \oplus H(BK^{reg}_{MU_i} \parallel ID_{MU_i} \parallel PW_{MU_i})$, $AUTH_{reg} = H(ID_{MU_i} \parallel BK^{reg}_{MU_i} \parallel PW_{MU_i} \parallel A_{11})$, and deletes A_{11} from the memory.
6) Step MURP-6: Finally, MD_i stores the parameters $\{A_2, A_3, AUTH_{reg}, Gen(), Rep(.), RP^{reg}, ET\}$ in its memory.

C. USER LOGIN & AUTHENTICATION PHASE (ULP)

This phase explains the AKE process between an MD_i and a D_j with the help of MS. In this phase all the entities utilize the public communication channel for AKE. Upon receiving the login request from MD_i, MS validates the validity of the receives message and also verifies the existence of an MD_i in its database. An MD_i has a list of D_j form which he/she is allowed to acquire the real-time data collected by D_j. The succeeding steps describe the details of ULP.

1) Step ULP-1: An MU_i inputs his/her real identity ID_{MU_i} and PW_{MU_i} on the available device login interface. He/she also imprints his/her bio-metric information BU_{MU_i} on the sensor available on the MD_i.
2) Step ULP-2: An MD_i calculates $BK^{LO}_{MU_i} = Rep(BU^{LO}_{MU_i}, RP^{reg})$ provided the condition $HD(BU^{LO}_{MU_i}, BU^{reg}_{MU_i}) \leq ET$ holds, where HD is the hamming distance between $BU^{LO}_{MU_i}$ and $BU^{reg}_{MU_i}$). Additionally, an MU_i also computes $(SID_{MU_i} \parallel SID_{MS}) = A_2 \oplus H(ID_{MU_i} \parallel BK^{LO}_{MU_i} \parallel PW_{MU_i})$ and $(SID_{D_j} \parallel SP_{MU_i}) = A_3 \oplus H(BK^{LO}_{MU_i} \parallel ID_{MU_i} \parallel PW_{MU_i})$. Furthermore, an MD_i calculates $A^{LO}_1 = SID_{MS} \oplus SID_{MU_i} \oplus SP_{MU_i} \oplus SID_{D_j}$. To verify the login request, an MD_i computes $AUTH_{LO} = H(ID_{MU_i} \parallel BK^{LO}_{MU_i} \parallel PW_{MU_i} \parallel A^{LO}_{11})$ and checks the condition $AUTH_{LO} = AUTH_{reg}$. If the condition holds, MD_i continues the authentication process. Otherwise, MD_i aborts the authentication process promptly.
3) Step ULP-3: After successful verification of the login parameters of MU_i, MD_i picks timestamp T_1 of 32 bit size, and random number R_{MU_i} of 128 bits. MD_i derives $P_1 = R_{MU_i}$ and $P_2 = SID_{D_j}$, where P_1 and P_2 are the plaintext. Moreover, MD_i calculates $A_1 = H(SID_{MU_i} \parallel SID_{MS} \parallel SP_{MU_i})$, $K_1 = A_2 \oplus A_3$, where A_2 and A_3 are the two equal 128-bits chunks of A_1. Furthermore, MD_i computes $G = HW(SID_{MS})$, where HW is the Hamming Weight, $Z = (T_1 \parallel 0^l \parallel T_1 \parallel 1^l)$, where $l = 32, ZZ = Rot(Z_1, G), A_4 = SID_{MU_i} \oplus ZZ \oplus SID_{MS}$, and $AD_1 = A_4$. The AEGIS takes two parameter as input, which are secret key K_1 of size 128-bits and Initialization Vector (IV) of 128-bits. The IV is a public parameter. It is required to transmit IV with the communicated message. In the proposed scheme, IV can be computed as $IV_1 = A_2 \oplus AD_1$, which can be derived at the receiver side in the same way. Therefore, in the proposed scheme IV will not be transmitted with the exchanged messages to decrease the communication overhead. Furthermore, MD_i computes $(C^{mu}_1, C^{mu}_2) = E_{K_1}\{\{IV_1, AD_1\}, P_1, P_2\}$, and $AUTH_{tag1}$ by using AEGIS encryption algorithm, where AD_1 is the associative data. Finally, MD_i constructs the message $M_1 : \langle T_1, A_4, C^{mu}_1, C^{mu}_2, AUTH_{tag1}\rangle$ and forwards M_1 to MS through a public channel.
4) Step ULP-4: Upon receiving M_1, MS checks freshness of M_1 by checking the condition $T^1_{ad} \geq |T^R - T_1|$. If the condition holds, the received M_1 is considered to be a fresh message. Otherwise, MS rejects M_1. MS computes $G_1 = HW(SID_{MS})$, $Z_1 = (T_1 \parallel 0^l \parallel T_1 \parallel 1^l)$, $ZZ_1 = Rot(Z_1, G_1)$, $SID_{MU_i} = A_4 \oplus ZZ_1 \oplus SID_{MS}$, and verifies if SID_{MU_i} exists in its database or not. If SID_{MU_i} is found, MS retrieves SP_{MU_i} related to SID_{MU_i} from the database and continues the AKE process. Otherwise, MS aborts the AKE process promptly. Furthermore, MS computes $A_5 = H(SID_{MU_i} \parallel SID_{MS} \parallel SP_{MU_i})$ and $K_1 = A_6 \oplus A_7$. MS picks A_4 from the received M_1 and calculates $IV_2 = A_6 \oplus A_4$, and $AD_2 = A_4$. Additionally, MS computes $P_1, P_2 = D_{K_1}\{\{IV_2, AD_2\}, C^{mu}_1, C^{mu}_2\}$, and $AUTH_{tag2}$ by using AEGIS decryption algorithm. To verify the authenticity of the received M_1, MS checks the condition $AUTH_{tag1} = AUTH_{tag2}$. If the condition does not hold, MS aborts the AKE process promptly. Otherwise, MS considers M_1 as a valid message and continues the AKE process.
5) Step ULP-5: Moreover, MS picks T_2, R_{MS}, and computes $P_3 = R_{MS} \oplus R_{MU_i}$, $G_2 = HW(SID_{D_j})$, $Z_2 = (T_2 \parallel 0^l \parallel T_2 \parallel 1^l)$, $ZZ_2 = Rot(Z_2, G_2)$, $A_9 = H(ID_{D_j} \parallel FID_k \parallel SP_{D_j})$, $K_2 = A_{10} \oplus A_{11}$, $A_{12} = SID_{MU_i} \oplus ZZ_2 \oplus SID_{D_j}$, $AD_3 = A_{12}$, and $IV_3 = A_{10} \oplus AD_3$. Additionally, MS calculates $C^{ms}_1 = E_{K_2}\{\{IV_3, AD_3\}, P_3\}$, and $AUTH_{tag3}$ by employing the encryption algorithm. Finally, MS constructs the message $M_2 : \langle T_2, A_{12}, C^{ms}_1, AUTH_{tag3}\rangle$ and dispatches M_2 to D_j through a public channel.

Mobile-User/Mobile-Device MU_i/MD_i	Management Server MS	Drone D_j
$\langle A_2, A_3, AUTH_{reg}, Gen(), Rep(.), RP^{reg}, ET\rangle$	$\langle (SID_{MU_i}, SP_{MU_i}), (ID_{D_j}, SID_{D_j}, SP_{D_j}, FID_k,)\rangle$	$\langle (SID_{D_j}, ID_{D_j}, SP_{D_j}, FID_k)\rangle$
Inputs ID_{MU_i}, PW_{MU_i} and imprints $BU^{LO}_{MU_i}$, computes $BK^{LO}_{MU_i} = Rep(BU^{LO}_{MU_i}, RP^{reg})$, $(SID_{MU_i} \Vert SID_{MS}) = A_2 \oplus H(ID_{MU_i} \Vert BK^{LO}_{MU_i} \Vert PW_{MU_i})$, $(SID_{D_j} \Vert SP_{MU_i}) = A_3 \oplus H(BK^{LO}_{MU_i} \Vert ID_{MU_i} \Vert PW_{MU_i})$, $A^{LO}_1 = SID_{MS} \oplus SID_{MU_i} \oplus SP_{MU_i} \oplus SID_{D_j}$, $AUTH_{LO} = H(ID_{MU_i} \Vert BK^{LO}_{MU_i} \Vert PW_{MU_i} \Vert A^{LO}_1)$, Checks if $AUTH_{LO} = AUTH_{reg}$?, if so, picks timestamp T_1 and random number R_{MU_i}, derives $P_1 = R_{MU_i}$, $P_2 = SID_{D_j}$, computes $A_1 = H(SID_{MU_i} \Vert SID_{MS} \Vert SP_{MU_i})$, $K_1 = A_2 \oplus A_3$, $G = HW(SID_{MS})$, $Z = (T_1 \Vert 0^l \Vert T_1 \Vert 1^l)$, $ZZ = Rot(Z_1, G)$, $A_4 = SID_{MU_i} \oplus ZZ \oplus SID_{MS}$, $AD_1 = A_4$, $IV_1 = A_2 \oplus AD_1$ $(C^{mu}_1, C^{mu}_2) = E_{K_1}\{\{IV_1, AD_1\}, P_1, P_2\}$, and $AUTH_{tag1}$. $\xrightarrow[\text{via an open channel to MS}]{M_1:\{T_1,\ A_4,\ C^{mu}_1,\ C^{mu}_2,\ AUTH_{tag1}\}}$		
	Checks if $T^1_{ad} \geq \lvert T^R - T_1?\rvert$, If so, picks T_1 from M_1, and computes $G_1 = HW(SID_{MS})$, $Z_1 = (T_1 \Vert 0^l \Vert T_1 \Vert 1^l)$, $ZZ_1 = Rot(Z_1, G_1)$, $SID_{MU_i} = A_4 \oplus ZZ_1 \oplus SID_{MS}$, checks if SID_{MU_i} exists in the database, if yes, retrieves SP_{MU_i} related to SID_{MU_i}, computes $A_5 = H(SID_{MU_i} \Vert SID_{MS} \Vert SP_{MU_i})$, $K_1 = A_6 \oplus A_7$, and picks A_4 from M_1, computes $AD_2 = A_4$, $IV_2 = A_6 \oplus A_4$, $P_1, P_2 = D_{K_1}\{\{IV_2, AD_2\},\ C^{mu}_1,\ C^{mu}_2\}$, and $AUTH_{tag2}$, checks if $AUTH_{tag1} = AUTH_{tag2}$?, if so, picks T_2, R_{MS}, and computes $P_3 = R_{MS} \oplus R_{MU_i}$, $G_2 = HW(SID_{D_j})$, $Z_2 = (T_2 \Vert 0^l \Vert T_2 \Vert 1^l)$, $ZZ_2 = Rot(Z_2, G_2)$, $A_9 = H(ID_{D_j} \Vert FID_k \Vert SP_{D_j})$, $K_2 = A_{10} \oplus A_{11}$, $A_{12} = SID_{MU_i} \oplus ZZ_2 \oplus SID_{D_j}$, calculates $AD_3 = A_{12}$, $IV_3 = A_{10} \oplus AD_3$, $C^{ms}_1 = E_{K_2}\{\{IV_3, AD_3\}, P_3\}$, and $AUTH_{tag3}$ $\xrightarrow[\text{via an open channel to } D_j]{M_2:\{T_2,\ A_{12},\ C^{ms}_1,\ AUTH_{tag3}\}}$	
		Checks if $T^2_{ad} \geq \lvert T^R - T_2?\rvert$, if so, computes $G_3 = HW(SID_{D_j})$, $Z_3 = (T_2 \Vert 0^l \Vert T_2 \Vert 1^l)$, $ZZ_3 = Rot(Z_3, G_3)$, $A_{13} = H(ID_{D_j} \Vert FID_k \Vert SP_{D_j})$, $K_2 = A_{14} \oplus A_{15}$, $SID_{MU_i} = A_{12} \oplus Z_3 \oplus SID_{D_j}$, picks A_{12} from M_2, computes $AD_4 = A_{12}$, $IV_4 = A_{14} \oplus AD_4$, $P_3 = D_{K_2}\{\{IV_4, AD_4\}, C^{ms}_1\}$, and $AUTH_{tag4}$, checks if $AUTH_{tag4} = AUTH_{tag3}$?, if so, retrieves $P_3 = R_{MU_i} \oplus R_{MS}$ from C^{ms}_1, picks T_3, R_{D_i}, and computes $P_4 = R_{D_i} \oplus FID_k \oplus P_3$, $A_{16} = H(SID_{D_j} \Vert SID_{MU_i} \Vert T_3)$, $K_3 = A_{17} \oplus A_{18}$, computes $SK_X = H(SID_{D_j} \Vert P_4 \Vert SID_{MU_i} \Vert T_3)$, $A_{19} = SK^1_X \oplus SK^2_X \oplus SID_{MU_i}$, $AD_5 = A_{19}$, $IV_5 = A_{17} \oplus AD_4$, $C^d_1 = E_{K_3}\{\{IV_5, AD_5\}, P_4\}$, and $AUTH_{tag5}$, $\xleftarrow[\text{via an open channel to } MD_i]{M_3:\{T_3,\ A_{19},\ C^d_1,\ AUTH_{tag5}\}}$
Checks if $T^3_{ad} \geq \lvert T^R - T_3\rvert$, if so, computes $A_{20} = H(SID_{D_j} \Vert SID_{MU_i} \Vert T_3)$, $K_3 = A_{21} \oplus A_{22}$, picks A_{19} from M_3 and computes $AD_6 = A_{19}$, $IV_6 = A_{21} \oplus AD_6$, $P_4 = D_{K_3}\{\{IV_6, AD_6\}, C^d_1\}$, and $AUTH_{tag6}$, checks if $AUTH_{tag6} = AUTH_{tag5}$?, if so, retrieves $P_4 = R_{D_i} \oplus FID_k \oplus P_3$, computes $SK_Y = H(SID_{D_j} \Vert P_4 \Vert SID_{MU_i} \Vert T_3)$, $A_{23} = SK^1_Y \oplus SK^2_Y \oplus SID_{MU_i}$, checks if $A_{19} = A_{23}$?, if so, $SK_X (= SK_Y)$.		
$SK_X (= SK_Y) = H(SID_{D_j} \Vert R_{D_i} \oplus FID_k \oplus P_3 \Vert SID_{MU_i} \Vert T_3)$		

FIGURE 3. LAKE-IoD login and authentication phase.

6) Step ULP-6: After receiving M_2 from MS, D_j verifies the condition $T^2_{ad} \geq |T^R - T_2|$. If the condition does not hold, M_2 is considered to be outdated message. Otherwise, D_j calculates $G_3 = HW(SID_{D_j})$, $Z_3 = (T_2 \| 0^l \| T_2 \| 1^l)$, $ZZ_3 = Rot(Z_3, G_3)$, $A_{13} = H(ID_{D_j} \| FID_k \| SP_{D_j})$, $K_2 = A_{14} \oplus A_{15}$, and $SID_{MU_i} = A_{12} \oplus ZZ_3 \oplus SID_{D_j}$. D_j picks the A_{12} from the received message M_2 and computes $AD_4 = A_{12}$, and $IV_4 = A_{14} \oplus AD_4$. Additionally, D_j calculates $P_3 = D_{K_2}\{\{IV_4, AD_4\}, C^{ms}_1\}$, and $AUTH_{tag4}$ by using AEGIS decryption algorithm. To establish the authenticity of the received message M_2, MS validates the condition $AUTH_{tag4} = AUTH_{tag3}$. If the condition does not hold, D_j rejects the message and aborts the AKE process. Otherwise, D_j retrieves $P_3 = R_{MU_i} \oplus R_{MS}$ from C^{ms}_1, which is received with M_2.
7) Step ULP-7: D_j picks T_3, R_{D_i}, and computes $P_4 = R_{D_i} \oplus FID_k \oplus P_3$, $A_{16} = H(SID_{D_j} \| SID_{MU_i} \| T_3)$, and $K_3 = A_{17} \oplus A_{18}$. To secure the communication between D_j and MD_i, D_j computes the session-key by computing $SK_X = H(SID_{D_j} \| P_4 \| SID_{MU_i} \| T_3)$. Moreover, D_j calculates $A_{19} = SK^1_X \oplus SK^2_X \oplus SID_{MU_i}$, $AD_5 = A_{19}$, and $IV_5 = A_{17} \oplus AD_5$. Additionally, D_j calculates $C^d_1 = E_{K_3}\{\{IV_5, AD_5\}, P_4\}$, and $AUTH_{tag5}$ by using AEGIS. Finally, D_j constructs the message $M_3 : \langle T_3,\ A_{19},\ C^d_1,\ AUTH_{tag5}\rangle$ and sends M_3 to MD_i.
8) Step ULP-8: After receiving the message M_3 from D_j, MD_i checks the freshness of M_3 by checking the condition $T^3_{ad} \geq |T^R - T_3|$. If the condition holds, MD_i computes $A_{20} = H(SID_{D_j} \| SID_{MU_i} \| T_3)$ and $K_3 = A_{21} \oplus A_{22}$. MD_i picks A_{19} from the received message M_3 and calculates $AD_6 = A_{19}$ and $IV_6 = A_{21} \oplus AD_6$. Additionally, MU_i computes $P_4 = D_{K_3}\{\{IV_6, AD_6\}, C^d_1\}$, and $AUTH_{tag6}$ by using AEGIS decryption process. MD_i verifies if the condition $AUTH_{tag6} = AUTH_{tag5}$ holds. If so, MD_i retrieves $P_4 = R_{D_i} \oplus FID_k \oplus P_3$ from C^d_1. To secure the communication between MD_i and D_j, MD_i computes the session-key by computing $SK_Y = H(SID_{D_j} \| P_4 \| SID_{MU_i} \| T_3)$. Finally, MD_i computes $A_{23} = SK^1_Y \oplus SK^2_Y \oplus SID_{MU_i}$ and checks the

condition $A_{19} = A_{23}$. If the condition holds, it indicates that SK_X computed at D_j and SK_Y computed at MD_i are same.

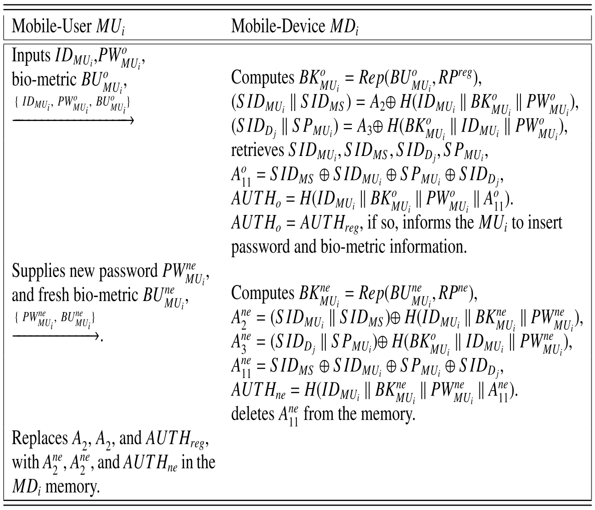
The summary of AKE process is shown in the Fig. 3.

D. PASSWORD/BIO-METRIC UPDATE PHASE (PUP)

A legitimate registered MU_i with an MD_i is required to execute the following steps to update the password PW_{MU_i} and BU_{MU_i} information of MU_i. BU_{MU_i} of MU_i remains unchanged and old bio-metric information is considered as new or fresh. However, to strengthen the security of the system, it is imperative to update MU_i's password frequently. In this paper, we insinuate updating both PW_{MU_i} and BU_{MU_i} of MU_i.

1) Step PUP-1: MU_i enters his/her ID_{MU_i}, old password $PW^o_{MU_i}$, imprints old $BU^o_{MU_i}$, and calculates the following operations, such as computes $BK^o_{MU_i} = Rep(BU^o_{MU_i}, RP^{reg})$ to reproduce the bio-metric key, $(SID_{MU_i} \parallel SID_{MS}) = A_2 \oplus H(ID_{MU_i} \parallel BK^o_{MU_i} \parallel PW^o_{MU_i})$, $(SID_{D_j} \parallel SP_{MU_i}) = A_3 \oplus H(BK^o_{MU_i} \parallel ID_{MU_i} \parallel PW^o_{MU_i})$, and retrieves SID_{MU_i}, SID_{MS}, SID_{D_j}, and SP_{MU_i}. Furthermore, MD_i computes $A^o_{11} = SID_{MS} \oplus SID_{MU_i} \oplus SP_{MU_i} \oplus SID_{D_j}$, and $AUTH_o = H(ID_{MU_i} \parallel BK^o_{MU_i} \parallel PW^o_{MU_i} \parallel A^o_{11})$. MU_i checks the condition $AUTH_o = AUTH_{reg}$. If the condition holds, the MU_i continues the PUP. Otherwise, MU_i terminates the PUP promptly.
2) Step PUP-2: MU_i enters his/her ID_{MU_i}, new password $PW^{ne}_{MU_i}$, imprints new/fresh bio-metric information $BU^{ne}_{MU_i}$ (both the old and new bio-metric information are same), and calculates the following operations, such as computes $BK^{ne}_{MU_i} = Rep(BU^{ne}_{MU_i}, RP^{ne})$ to reproduce the bio-metric key, $A^{ne}_2 = (SID_{MU_i} \parallel SID_{MS}) \oplus H(ID_{MU_i} \parallel BK^{ne}_{MU_i} \parallel PW^{ne}_{MU_i})$, $A^{ne}_3 = (SID_{D_j} \parallel SP_{MU_i}) \oplus H(BK^o_{MU_i} \parallel ID_{MU_i} \parallel PW^{ne}_{MU_i})$, $A^{ne}_{11} = SID_{MS} \oplus SID_{MU_i} \oplus SP_{MU_i} \oplus SID_{D_j}$, and $AUTH_{ne} = H(ID_{MU_i} \parallel BK^{ne}_{MU_i} \parallel PW^{ne}_{MU_i} \parallel A^{ne}_{11})$. MD_i deletes A^{ne}_{11} from its memory.
3) Step PUP-3: Finally, MD_i stores the parameters $\{A^{ne}_2$, A^{ne}_3, $AUTH_{ne}$, $Gen()$, $Rep(.)$, RP^{ne}, ET^{ne} $\}$ in its memory.

Fig. 4 illustrates the summary of PUP.



Mobile-User MU_i

Mobile-Device MD_i

Inputs ID_{MU_i},$PW^o_{MU_i}$,
bio-metric $BU^o_{MU_i}$,
$\xrightarrow{\{ ID_{MU_i},\ PW^o_{MU_i},\ BU^o_{MU_i}\}}$

Computes $BK^o_{MU_i} = Rep(BU^o_{MU_i}, RP^{reg})$,
$(SID_{MU_i} \parallel SID_{MS}) = A_2 \oplus H(ID_{MU_i} \parallel BK^o_{MU_i} \parallel PW^o_{MU_i})$,
$(SID_{D_j} \parallel SP_{MU_i}) = A_3 \oplus H(BK^o_{MU_i} \parallel ID_{MU_i} \parallel PW^o_{MU_i})$,
retrieves $SID_{MU_i}, SID_{MS}, SID_{D_j}, SP_{MU_i}$,
$A^o_{11} = SID_{MS} \oplus SID_{MU_i} \oplus SP_{MU_i} \oplus SID_{D_j}$,
$AUTH_o = H(ID_{MU_i} \parallel BK^o_{MU_i} \parallel PW^o_{MU_i} \parallel A^o_{11})$.
$AUTH_o = AUTH_{reg}$, if so, informs the MU_i to insert password and bio-metric information.

Supplies new password $PW^{ne}_{MU_i}$,
and fresh bio-metric $BU^{ne}_{MU_i}$,
$\xrightarrow{\{ PW^{ne}_{MU_i},\ BU^{ne}_{MU_i}\}}$.

Computes $BK^{ne}_{MU_i} = Rep(BU^{ne}_{MU_i}, RP^{ne})$,
$A^{ne}_2 = (SID_{MU_i} \parallel SID_{MS}) \oplus H(ID_{MU_i} \parallel BK^{ne}_{MU_i} \parallel PW^{ne}_{MU_i})$,
$A^{ne}_3 = (SID_{D_j} \parallel SP_{MU_i}) \oplus H(BK^o_{MU_i} \parallel ID_{MU_i} \parallel PW^{ne}_{MU_i})$,
$A^{ne}_{11} = SID_{MS} \oplus SID_{MU_i} \oplus SP_{MU_i} \oplus SID_{D_j}$,
$AUTH_{ne} = H(ID_{MU_i} \parallel BK^{ne}_{MU_i} \parallel PW^{ne}_{MU_i} \parallel A^{ne}_{11})$.
deletes A^{ne}_{11} from the memory.

Replaces A_2, A_2, and $AUTH_{reg}$, with A^{ne}_2, A^{ne}_2, and $AUTH_{ne}$ in the MD_i memory.

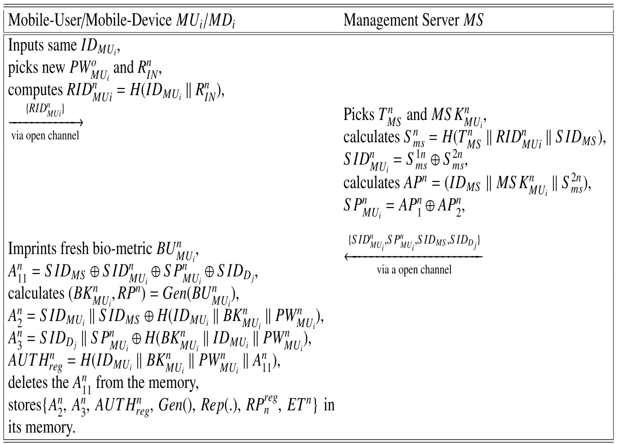
FIGURE 4. Password/bio-metric update phase.

E. REVOCATION OR RE-ISSUE PHASE (RRP)

An authorized MU_i can get a new mobile device MD^{new}_i after losing the old MD^{old}_i. For this, MU_i requires to accomplish the following steps.

1) Step RRP-1: MU_i only needs to remember or maintain ID_{MU_i} and picks a new password $PW^n_{MU_i}$.
2) Step RRP-2: MD_i picks a new random number R^n_{IN}), computes $RID^n_{MUi} = H(ID_{MU_i} \parallel R^n_{IN})$, and sends RID^n_{MUi} to MS through a secure channel.
3) Step RRP-3: Upon receiving RID^n_{MUi} from MD_i, MS picks fresh/new timestamp T^n_{MS}, new master-key $MSK^n_{MU_i}$ for MU_i, calculates $S^n_{ms} = H(T^n_{MS} \parallel RID^n_{MUi} \parallel SID_{MS})$, and $SID^n_{MU_i} = S^{1n}_{ms} \oplus S^{2n}_{ms}$. MS calculates new Secret Parameter ($SP^n_{MU_i}$) for MU_i by computing $AP^n = (ID_{MS} \parallel MSK^n_{MU_i} \parallel S^{2n}_{ms})$ and $SP^n_{MU_i} = AP^n_1 \oplus AP^n_2$. MS transmits the tuple $\{SID^n_{MU_i}, SP^n_{MU_i}, SID_{MS}, SID_{D_j}\}$ to MU_i through a secure channel.
4) Step RRP-4: Upon receiving the response from MS, MD_i calculates the following operations $A^n_{11} = SID_{MS} \oplus SID^n_{MU_i} \oplus SP^n_{MU_i} \oplus SID_{D_j}$ and computes the new bio-metric key $(BK^n_{MU_i}, RP^n) = Gen(BU^n_{MU_i})$ by taking the fresh bio-information of the user (both the old and new bio-metric information are same) as input. Furthermore, MD_i also calculates $A^n_2 = SID_{MU_i} \parallel SID_{MS} \oplus H(ID_{MU_i} \parallel BK^n_{MU_i} \parallel PW^n_{MU_i})$, $A^n_3 = SID_{D_j} \parallel SP^n_{MU_i} \oplus H(BK^n_{MU_i} \parallel ID_{MU_i} \parallel PW^n_{MU_i})$, $AUTH^n_{reg} = H(ID_{MU_i} \parallel BK^n_{MU_i} \parallel PW^n_{MU_i} \parallel A^n_{11})$, and deletes A^n_{11} from its memory.
5) Step RRP-5: Finally, MD_i stores the parameters $\{A^n_2$, $A^n_3, AUTH^n_{reg}, Gen(), Rep(.), RP^{reg}_n, ET^n\}$ in its memory.

Fig. 5 illustrates the summary of RRP.



Mobile-User/Mobile-Device MU_i/MD_i

Management Server MS

Inputs same ID_{MU_i},
picks new $PW^o_{MU_i}$ and R^n_{IN},
computes $RID^n_{MUi} = H(ID_{MU_i} \parallel R^n_{IN})$,
$\xrightarrow{\{RID^n_{MUi}\}}$
via open channel

Picks T^n_{MS} and $MSK^n_{MU_i}$,
calculates $S^n_{ms} = H(T^n_{MS} \parallel RID^n_{MUi} \parallel SID_{MS})$,
$SID^n_{MU_i} = S^{1n}_{ms} \oplus S^{2n}_{ms}$,
calculates $AP^n = (ID_{MS} \parallel MSK^n_{MU_i} \parallel S^{2n}_{ms})$,
$SP^n_{MU_i} = AP^n_1 \oplus AP^n_2$,

$\xleftarrow{\{SID^n_{MU_i}, SP^n_{MU_i}, SID_{MS}, SID_{D_j}\}}$
via a open channel

Imprints fresh bio-metric $BU^n_{MU_i}$,
$A^n_{11} = SID_{MS} \oplus SID^n_{MU_i} \oplus SP^n_{MU_i} \oplus SID_{D_j}$,
calculates $(BK^n_{MU_i}, RP^n) = Gen(BU^n_{MU_i})$,
$A^n_2 = SID_{MU_i} \parallel SID_{MS} \oplus H(ID_{MU_i} \parallel BK^n_{MU_i} \parallel PW^n_{MU_i})$,
$A^n_3 = SID_{D_j} \parallel SP^n_{MU_i} \oplus H(BK^n_{MU_i} \parallel ID_{MU_i} \parallel PW^n_{MU_i})$,
$AUTH^n_{reg} = H(ID_{MU_i} \parallel BK^n_{MU_i} \parallel PW^n_{MU_i} \parallel A^n_{11})$,
deletes the A^n_{11} from the memory,
stores$\{A^n_2$, A^n_3, $AUTH^n_{reg}$, $Gen()$, $Rep(.)$, RP^{reg}_n, $ET^n\}$ in its memory.

FIGURE 5. Revocation or re-issue phase.

F. DYNAMIC DRONE DEPLOYMENT (DDD) PHASE

Following steps are required to execute for the deployment of new drone device, say D_j^{new} in some existing Fly Zone (FZ) with unique identity FID_k.

1) Step DDD-1: MS assigns a unique identity $ID_{D_i}^{new}$ and Fly Zone Identity FID_k^{new} to drone D_j^{new}.
2) Step DDD-2: MS computes the temporary identity SID_{D_j} of drone by calculating $Q^{new} = H(ID_{MS} \parallel SID_{MS} \parallel R_{D_i}^{new})$, where $R_{D_i}^{new}$ is a random number of 128 bits, $SID_{D_i}^{new} = Q_1^{new} \oplus Q_2^{new}$.
3) Step DDD-3: MS computes secret parameter $SP_{D_j}^{new}$ for D_j^{new} by computing $SP_{D_j}^{new} = R_{D_j}^{new} \oplus Q_1^{new}$.
4) Step DDD-4: Finally, MS stores the parameters $\{ID_{D_i}^{new}$, $SID_{D_i}^{new}$, $SP_{D_j}^{new}$, $FID_k^{new}\}$ in the memory of D_j^{new}. MS also stores these credentials in its memory.

VI. SECURITY ANALYSIS

Both informal and formal security analyses have been conducted on LAKE-IoD to ascertain its immunity against various harmful attacks, such as device capture attack, Man-in-the-Middle (MITM) attack, and replay attack. BAN logic is applied to examine the logical completeness of LAKE-IoD. Scyther, a software tool, is utilized to examine the security characteristics of LAKE-IoD in an automatic way.

A. INFORMAL SECURITY ANALYSIS

Following informal security analysis explicates that LAKE-IoD is immune to various attacks, and also guarantees user's un-traceability/anonymity.

1) OFFLINE PASSWORD-GUESSING ATTACK

Presume that an adversary $\mathcal{A}$ somehow gets or steals MD_i of MU_i. $\mathcal{A}$ by applying the power-analysis attack [34] can procure the information stored in the memory of MD_i, such as $\{A_2, A_3, AUTH_{reg}, Gen(), Rep(.), RP^{reg}, ET\}$. The extracted information does not provide any secret information to $\mathcal{A}$ related to MU_i, such as ID_{MU_i}, PW_{MU_i}, and BU_{MU_i}. Therefore, without knowing valid parameters, such as ID_{MU_i} and BU_{MU_i}, it is hard for $\mathcal{A}$ to guess the correct PW_{MU_i} of MU_i. Hence, LAKE-IoD is resistant to the password-guessing attack.

2) PASSWORD AND BIO-METRIC UPDATE ATTACK

Suppose that an adversary $\mathcal{A}$ somehow has obtained the lost or stolen MU_i's MD_i and extricates the stored information, such as $\{A_2, A_3, AUTH_{reg}, Gen(), Rep(.), RP^{reg}, ET\}$ by employing the power analysis attack [34]. Now, $\mathcal{A}$ tries to update the password PW_{MU_i} and bio-metric information BU_{MU_i} of MU_i. For this purpose, $\mathcal{A}$ picks bogus password $PW_{MU_i}^{\mathcal{A}}$, bio-metric information $BU_{MU_i}^{\mathcal{A}}$, identity $ID_{MU_i}^{\mathcal{A}}$, and calculates $BK_{MU_i}^{\mathcal{A}} = Rep(BU_{MU_i}^{\mathcal{A}}, RP^{reg})$, $(SID_{MU_i}^{\mathcal{A}} \parallel SID_{CS}^{\mathcal{A}}) = A_2 \oplus H(ID_{MU_i}^{\mathcal{A}} \parallel BK_{MU_i}^{\mathcal{A}} \parallel PW_{MU_i}^{\mathcal{A}})$, $(SID_{D_j}^{\mathcal{A}} \parallel SP_{MU_i}^{\mathcal{A}}) = A_3 \oplus H(BK_{MU_i}^{\mathcal{A}} \parallel ID_{MU_i}^{\mathcal{A}} \parallel PW_{MU_i}^{\mathcal{A}})$, $A_{11}^{\mathcal{A}} = SID_{MS}^{\mathcal{A}} \oplus SID_{MU_i}^{\mathcal{A}} \oplus SP_{MU_i}^{\mathcal{A}} \oplus SID_{D_j}^{\mathcal{A}}$, and $AUTH_{\mathcal{A}} = H(ID_{MU_i}^{\mathcal{A}} \parallel BK_{MU_i}^{\mathcal{A}} \parallel PW_{MU_i}^{\mathcal{A}} \parallel A_{11}^{\mathcal{A}})$, and checks the condition $AUTH_{\mathcal{A}} = AUTH_{reg}$. To execute these computation, $\mathcal{A}$ requires to know valid secret parameters, such as ID_{MU_i}, BU_{MU_i}, and PW_{MU_i} of MU_i, which are secret and known only to MU_i. Without having the knowledge of these parameters, it is hard for $\mathcal{A}$ to execute this attack. Therefore, LAKE-IoD is secure against the password/bio-metric update attack.

3) IDENTITY-GUESSING ATTACK

During MU_i registration phase, MU_i sends RID_{MU_i} to MS, where $RID_{MU_i} = H(ID_{MU_i} \parallel R_{IN})$, through public communication channel. It is observed that the registration message does not provide any information about the identity ID_{MU_i} of MU_i. Now suppose that, insider attacker/adversary $\mathcal{A}$ of MS has obtained lost/stolen device of MU_i and extricates the parameters $\{A_2, A_3, AUTH_{reg}, Gen(), Rep(.), RP^{reg}, ET\}$ stored on device. After getting these parameters, $\mathcal{A}$ can not procure any significant information about the user identity ID_{MU_i}. Therefore, to guess the identity of MU_i, $\mathcal{A}$ needs to know both ID_{MU_i} and R_{IN} to compute $HID_{MU_i} = H(ID_{MU_i} \parallel R_{IN})$. Without knowing ID_{MU_i} and R_{IN}, it is hard for $\mathcal{A}$ guess the correct identity of MU_i. Above discussion shows that LAKE-IoD is secure against the identity-guessing attack.

4) USER ANONYMITY/UN-TRACEABILITY

According to the threat model described in Section III-B, an adversary $\mathcal{A}$ can intercept the communicated messages M_1: $\{ T_1, A_4, C_1^{mu}, C_2^{mu}, AUTH_{tag1} \}$, M_2:$\{ T_2, A_{12}, C_1^{ms}, AUTH_{tag3} \}$, and M_3: $\{T_3, A_{19}, C_1^{d}, AUTH_{tag5} \}$, where $A_4 = SID_{MU_i} \oplus ZZ \oplus SID_{MS}$, and $A_{12} = SID_{MU_i} \oplus ZZ_2 \oplus SID_{D_j}$, which are communicated during the AKE phase. However, without knowing the valid secret parameters and based on the discussion for the identity-guessing attack as in Section VI-A3, it is hard for $\mathcal{A}$ to derive the real identity of MU_i. Thus, LAKE-IoD ensures the anonymity of MU_i. All the exchanged messages are dynamic in nature, which incorporates the latest timestamps, fresh random numbers, and random Initialization Vectors (IV). Therefore, $\mathcal{A}$ can not correlate two messages of different AKE sessions. So, LAKE-IoD also ensures the user's un-traceability.

5) DRONE CAPTURE ATTACK

From the threat model as discussed in Section III-B, it is possible for an adversary $\mathcal{A}$ to capture the drone device D_j because they are deployed in the hostile environment. By utilizing the power analysis attack [34], $\mathcal{A}$ can retrieve the secret information stored in memory of D_j, such as ID_{D_j}, SID_{D_j}, SP_{D_j}, and FID_k and can compromise the session key security of the captured D_j. However, by compromising the security of captured D_j, $\mathcal{A}$ can not breach the security of other non compromised D_j because of the uniqueness of the secret parameters ID_{D_j}, SID_{D_j}, SP_{D_j}, and FID_k. Therefore, LAKE-IoD is resilient against the drone captured attack.

6) IMPERSONATION ATTACK

The succeeding impersonation attacks associated to LAKE-IoD are considered.

- MU_i Impersonation Attack: According to the threat model described in Section III-B, an adversary $\mathcal{A}$ can capture M_1: { T_1, A_4, C_1^{mu}, C_2^{mu},$AUTH_{tag1}$} transmitted by MU_i during the login and AKE phase. Further, $\mathcal{A}$ can act as a legitimate MU_i by producing some bogus message M_1' to persuade MS that M_1' is from a valid MU_i. However, $\mathcal{A}$ can generate the timestamp T_1' but without the knowledge of valid parameters, such as SID_{MU_i}, SID_{MS}, SP_{MU_i}, and K_1, it is hard for $\mathcal{A}$ to generate a valid M_1 because the authenticity of M_1 is checked against the condition $AUTH_{tag1} = AUTH_{tag2}$. Without satisfying this condition, $\mathcal{A}$ cannot impersonate as a legitimate user in IoD environment. Therefore, LAKE-IoD is resistant against MU_i impersonation attack.
- MS Impersonation Attack: An adversary $\mathcal{A}$ can capture M_2:{T_2, A_{12}, C_1^{ms}, $AUTH_{tag3}$} and also generate a fake message M_2' to make D_j believe that M_2' is from a legitimate MS. However, M_2 received by D_j during the login and AKE phase will be checked against the condition $AUTH_{tag3} = AUTH_{tag4}$. If the condition holds, M_2 will be accepted. Otherwise, D_j rejects M_2. Therefore, it is hard for $\mathcal{A}$ to generate a valid message M_2, without the knowledge of the secret parameters, such as SID_{D_j}, ID_{D_j}, FID_k, and SP_{D_j}. Hence, LAKE-IoD is resistant against MS impersonation attack.
- D_j Impersonation Attack: In this case, an adversary $\mathcal{A}$ intercepts the message M_3: {T_3,A_{19}, C_1^d, $AUTH_{tag5}$} transmitted by the D_j and generates a fake message M_3' on behalf of D_j to convince MU_i that M_3' is from a legitimate D_j. However, without the knowledge of secrete parameters SID_{MU_i}, and SID_{D_j}, it is hard for$\mathcal{A}$ to generate a fake message on behalf of D_j. Therefore, the proposed scheme is secure against D_j impersonation attack.

7) MAN-IN-THE-MIDDLE ATTACK

During the login & authentication phase, $\mathcal{A}$ tries to intercept the exchanged messages, such as M_1: { T_1, A_4, C_1^{mu}, C_2^{mu}, $AUTH_{tag1}$ }, M_2:{ T_2, A_{12}, C_1^{ms}, $AUTH_{tag3}$ }, M_3: {T_3, A_{19}, C_1^d, $AUTH_{tag5}$ }, and attempts to modify the contents of M_1, M_2, and M_3. By framing this attack, the objective of $\mathcal{A}$ is to make the entities in IoD environment, such as MU_i, MS, and D_j, which are involved in the AKE process believe that the messages are from a legitimate entity. However, $\mathcal{A}$ can not frame this attack without computing valid secret credentials, such as K_1, K_2, and K_3 because these credentials are derived by using secret parameters SID_{MU_i}, SID_{MS}, SP_{MU_i}, SID_{D_j}, and SP_{D_j}, which are unknown to $\mathcal{A}$. Therefore, without knowing these secret parameters, it is hard for $\mathcal{A}$ to frame this attack. Hence, LAKE-IoD is secure against the Man-in-the-Middle attack.

8) DANIEL-OF-SERVICE (DoS) ATTACK

In the proposed scheme LAKE-IoD, MU_i enters his/her secret credentials, such as password PW_{MU_i}, bio-metric information BU_{MU_i}, and identity ID_{MU_i} at the available interface of MD_i. These parameters are verified locally by checking the condition $AUTH_{LO} = AUTH_{reg}$ before sending an authentication request to MS. If the condition holds, MD_i will then send authentication request to MS. If the condition does not hold, MD_i aborts AKE process promptly and prevent MU_i from sending too many authentication requests to MS. Above discussion shows that LAKE-IoD is resistant to the DoS attack.

9) REPLAY ATTACK

In this attack, an adversary $\mathcal{A}$ attempts to capture the communicated messages, such as M_1: { T_1,A_4, C_1^{mu}, C_2^{mu}, $AUTH_{tag1}$ }, M_2:{ T_2, A_{12}, C_1^{ms}, $AUTH_{tag3}$ }, and M_3: {T_3, A_{19}, C_1^d, $AUTH_{tag5}$ } during the AKE process in the proposed scheme to launch the replay attack by replying the forged instances of the messages to the receiver. However, all the exchanged messages incorporate the timestamps and fresh random numbers. At first, the receiver of the message checks the freshness of each message by cheeking the condition $T_{ad}^1 \geq |T^R - T_1|$ for M_1, $T_{ad}^2 \geq |T^R - T_2|$ for M_2, and $T_{ad}^3 \geq |T^R - T_3|$ for M_3. If all the received messages are with in allowed delay time limit, the received messages are considered as latest/fresh messages. Otherwise, the receiver discards the delayed messages. Additionally, the receiver will validate the authenticity and integrity of each received message by checking the condition $AUTH_{tag1} = AUTH_{tag2}$ for M_1, $AUTH_{tag3} = AUTH_{tag4}$ for M_2, and $AUTH_{tag5} = AUTH_{tag6}$ for M_3. All the exchanged message during the AKE phase are considered to be authentic, if these satisfy these conditions. Without knowing the valid secret parameters, it is hard for $\mathcal{A}$ to reproduce a valid message and cannot frame this attack. Therefore, LAKE-IoD is immune to the replay attack.

10) EPHEMERAL SECRET LEAKAGE (ESL) ATTACK

It is possible that an adversary $\mathcal{A}$ may compromise the long-term and short-term secret parameters of the communicating entities in IoD environment. By utilizing these compromised secret parameters, $\mathcal{A}$ may reveal the secret session key between the two communicating entities. This type of attack is referred to as Ephemeral Secret Leakage (ESL) attack.

- Case-1: Suppose that the short-term (ephemeral) secret parameters, such as R_{MU_i}, R_{MS}, and R_{D_i} are somehow revealed to the adversary $\mathcal{A}$. Now, the objective of $\mathcal{A}$ is to generate the secret session key by computing $SK_X(= SK_Y) = H(SID_{D_j} \parallel P_4 \parallel SID_{MU_i} \parallel T_3)$. However, without knowing other long-term secret credentials SID_{D_j}, SID_{MU_i}, and FID_k, it is hard for $\mathcal{A}$ to generate the valid secret session key $SK_X(= SK_Y)$.
- Case-2: In this case, if the log-term secret credential SID_{D_j}, SID_{MU_i}, and FID_k are somehow reveled to $\mathcal{A}$, still $\mathcal{A}$ is required to know the short-term secret parameters, such as R_{MU_i}, R_{MS}, and R_{D_i} to derive the valid session key $SK_X(= SK_Y)$.

It is clear from the above discussion that $\mathcal{A}$ needs to know both the long-term and short-term secret parameters to breach the security of the session key $SK_X (= SK_Y)$. Therefore, the proposed LAKE-IoD is secure against ESL attack.

11) MUTUAL AUTHENTICATION

LAKE-IoD renders the mutual authentication among the involved entities in the IoD environment. The details of the mutual authentication process are given below.

- $MU_i \rightarrow MS$: MS after receiving the message M_1: $\{T_1, A_4, C_1^{mu}, C_2^{mu}, AUTH_{tag1}\}$ authenticates MU_i by checkingSID_{MU_i} in its database and ensures the authenticity of M_1 by verifying the condition $AUTH_{tag1} = AUTH_{tag2}$.
- $MS \rightarrow D_j$: Upon receiving the message M_2:$\{T_2, A_{12}, C_1^{ms}, AUTH_{tag3}\}$ from MS, D_j computes $SID_{MU_i} = A_{12} \oplus SID_{D_j}$. Further, D_j verifies the authenticity of M_2 by checking the condition $AUTH_{tag3} = AUTH_{tag4}$ and extracts $P_3 = R_{MS} \oplus R_{MU_i}$.
- $D_j \rightarrow MU_1$: M_3: MU_i receives the message $\{T_3, A_{19}, C_1^d, AUTH_{tag5}\}$ from D_j and checks the condition to authenticate D_j by verifying the condition $AUTH_{tag6} = AUTH_{tag5}$. After the authentication of D_j, MU_i retrieves the plaintext $P_4 = R_{D_j} \oplus FID_k \oplus P_3$ form the ciphertext C_1^d.

Above discussion reveals that the proposed LAKE-IoD achieves the mutual authentication between MU_i and D_j with the help of MS. After achieving the mutual authentication, both entities MU_i and D_j establish a secret session-key $SK_X (= SK_Y) = H(SID_{D_j} \parallel P_4 \parallel SID_{MU_i} \parallel T_3)$.

B. FORMAL SECURITY ANALYSIS

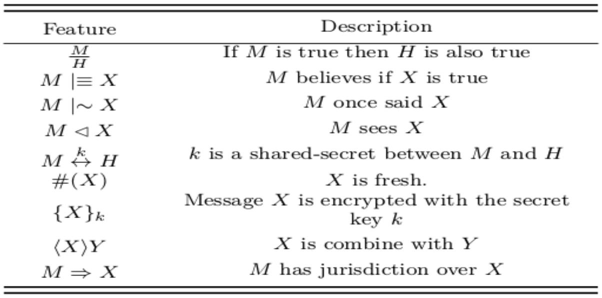
This section provides the formal analysis of the proposed scheme by employing the Burrows *et al.* [35] logic and software verification tool Scyther [36].

1) MUTUAL AUTHENTICATION VERIFICATION BY USING BAN LOGIC

Burrows-Abadi-Needham (BAN) logic [35] is an epistemic logic devised for the analysis of communication security protocols. The BAN logic is a set of rules for describing and validating the completeness of an authentication protocol. Particularly, BAN logic assists its users to determine whether the exchanged information is reliable. The semantics of the BAN logic comprises of the expression presented in Table 2 and different inference derivation rules are specified in Table 3.

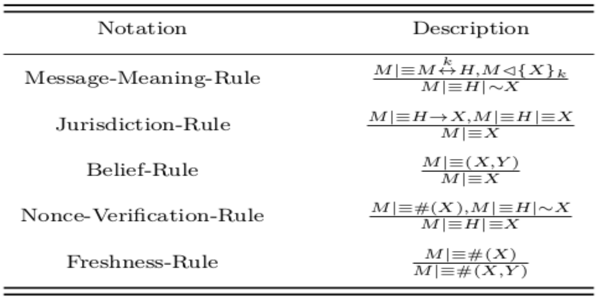
1) Assumptions: The subsequent assumptions are considered at the inception of the proposed scheme LAKE-IoD, to validate its mutual authentication.
   - A-1: $MD_j \mid\equiv \#T_1, \#T_3, \#R_{MU_i}$
   - A-2: $MD_i \mid\equiv (MD_i \overset{K_3}{\longleftrightarrow} D_j)$
   - A-3: $MD_i \mid\equiv D_j \Longrightarrow (D_j \overset{SK}{\leftrightarrow} MD_i)$
   - A-4: $MD_i \mid\equiv \Longrightarrow D_j \mid\sim P_4$
   - A-4: $MD_i \mid\equiv (MD_i \overset{K_1}{\longleftrightarrow} MS)$
   - A-5: $MS \mid\equiv \#T_1, \#T_2, \#R_{MU_i}, \#R_{MS}$
   - A-6: $MS \mid\equiv (MS \overset{K_1}{\longleftrightarrow} MD_i)$

TABLE 2. BAN logic notations.



Feature	Description
$\frac{M}{H}$	If M is true then H is also true
$M \mid\equiv X$	M believes if X is true
$M \mid\sim X$	M once said X
$M \lhd X$	M sees X
$M \overset{k}{\leftrightarrow} H$	k is a shared-secret between M and H
$\#(X)$	X is fresh.
$\{X\}_k$	Message X is encrypted with the secret key k
$\langle X \rangle Y$	X is combine with Y
$M \Rightarrow X$	M has jurisdiction over X

TABLE 3. BAN logic inference rules.



Notation	Description
Message-Meaning-Rule	$\frac{M \mid\equiv M \overset{k}{\leftrightarrow} H, M \lhd \{X\}_k}{M \mid\equiv H \mid\sim X}$
Jurisdiction-Rule	$\frac{M \mid\equiv H \rightarrow X, M \mid\equiv H \mid\equiv X}{M \mid\equiv X}$
Belief-Rule	$\frac{M \mid\equiv (X,Y)}{M \mid\equiv X}$
Nonce-Verification-Rule	$\frac{M \mid\equiv \#(X), M \mid\equiv H \mid\sim X}{M \mid\equiv H \mid\equiv X}$
Freshness-Rule	$\frac{M \mid\equiv \#(X)}{M \mid\equiv \#(X,Y)}$

   - A-7: $MS \mid\equiv (MS \overset{K_2}{\longleftrightarrow} D_j)$
   - A-8: $D_j \mid\equiv MS \Longrightarrow MS \mid\sim P_3$
   - A-9: $D_j \mid\equiv \#T_2, \#T_3$
   - A-10: $D_j \mid\equiv \#R_{MS}, \#R_{D_j}$
   - A-11: $D_j \mid\equiv (D_j \overset{K_2}{\longleftrightarrow} MS)$
   - A-12: $D_j \mid\equiv (D_j \overset{K_3}{\longleftrightarrow} MD_i)$

2) Idealized Form:
   - IDF-1: $\{T_1, A_4, R_{MU_i}, SID_{D_j}\}_{(MD_i \overset{K_1}{\longleftrightarrow} MS)}$
   - IDF-2: $\{T_2, R_{MS}, \langle P_3 \rangle\}_{(MS \overset{K_2}{\longleftrightarrow} D_j)}$
   - IDF-3: $\{T_3, P_4, (D_j \overset{SK}{\longleftrightarrow} MD_i)\}_{(D_j \overset{K_3}{\longleftrightarrow} MD_i)}$

3) Goals:
   - G-1: $D_j \mid\equiv (D_j \overset{SK}{\longleftrightarrow} MD_i)$
   - G-2: $MD_i \mid\equiv (MD_i \overset{SK}{\longleftrightarrow} D_j)$

2) FORMAL VERIFICATION

We validate the mutual authentication property of LAKE-IoD formally by utilizing THE basic BAN Logic rules defined in Table 2, BAN Inference rules defined in Table 3, and by using the assumptions. Details of the steps are given below.

- FV-1: From IDF-1, by applying the A-6, A-7, and Message-Meaning Rule (MMR), we get
- FV-2: By using A-6 and Freshness Rule (FR), we obtain

$$\frac{MS \mid\equiv \#T_1}{MS \mid\equiv \#(T_1, A_4, R_{MU_i}, SID_{D_j})}.$$

- FV-3: From FV-1, FV-2, and by using the Nonce-Verification Rule (NVR), we obtain
- FV-4: Form IDF-2, by using A-9, A-10, A-11, A-12, and Message-Meaning Rule (MMR), we obtain

$$\frac{D_j \mid\equiv (D_j \overset{K_2}{\longleftrightarrow} MS), D_j \lhd \{T_2, A_{12}, \langle P_3\rangle\}_{(D_j \overset{K_2}{\longleftrightarrow} MS)}}{D_j \mid\equiv MS \mid\sim \{T_2, A_{12}, \langle P_3\rangle\}_{(MD_j \overset{K_2}{\longleftrightarrow} MS)}}.$$

- FV-5: By employing A-10, A-11, and by using FR, we get

$$\frac{D_j \mid\equiv \#T_2}{D_j \mid\equiv \#(T_2, A_{12}, \langle P_3\rangle)}.$$

- FV-6: From FV-4, FV-5, and by using NVR, we achieve

$$\frac{D_j \mid\equiv \#(T_2, A_{12}, \langle P_3\rangle), D_j \lhd (T_2, A_{12}, \langle P_3\rangle)}{D_j \mid\equiv MS \mid\equiv (T_2, A_{12}, \langle P_3\rangle)}$$

- FV-7: From FV-4, FV-5, FV-6, by applying A-19, and by using NVR, we get $D_j \mid\equiv R_{MU_i} \oplus R_{MS}$.
- FV-8: Using FV-7, and by using A-9, A-10, A-11, and A-12, G-1 is achieved

$$D_j \mid\equiv (D_j \overset{SK}{\longleftrightarrow} MD_j).$$

- FV-9: From IDF-3, by using A-1, A-2, A-3, and A-4, and by applying MMR, we get
- FV-10: Using A-1 and by using FR, we obtain

$$\frac{MD_i \mid\equiv \#T_3}{MD_i \mid\equiv \#(T_3, P_4, (D_j \overset{SK}{\longleftrightarrow} MD_i))}.$$

- FV-11: From FV-9 and FV-10, and by applying NVR, we get
- FV-12: From FV-9, FV-10, FV-11, and by applying A-15, and NVR, we get $MD_i \mid\equiv P_4$.
- FV-13: Using FV-12, by using A-2, and A-4, G-2 is achieved

$$MD_i \mid\equiv (MD_i \overset{SK}{\longleftrightarrow} D_j).$$

From FV-8 and FV-13, it is clear that M and D_j authenticate with each other through MS.

3) SECURITY ANALYSIS USING SCYTHER TOOL

We employ Scyther tool [36] to analyze security properties and potential weaknesses of the proposed LAKE-IoD formally. The details of the Scyther tool are given below.

- Scyther tool is used for automatic validation of the security schemes. It is better and effective tool for falsification, verification, and analysis of proposed security protocols as compared to other verification tools, such as ProVerif and AVISPA.
- Scyther is based on the perfect cryptographic assumptions. It means that an adversary can not decrypt the encrypted information without knowing the secret key.
- Scyther utilizes the Security-Protocol Description-Language (SPDL) for modeling the user defined security scheme. In SPDL specification, each communicating entity is described by *Role* that can perform various functions such as *Send*, *Recv*, *event*, and security *claim*.
- Scyther tool follows the Dolev-Yao (DY) model and 9 other adversarial models such as eCK model and CK model, etc.
- Scyther renders a set of tests and claims to validate the security properties such as secrecy, authentication, synchronization, aliveness, weak agreement, and agreement.

There are three basic roles involved during the login and authentication phase of the LAKE-IoD, which are the Mobile-User MU_i, the Management Server MS, and drone D_j. The proposed scheme is implemented in SPDL. Scyther takes the SPDL file as input and performs various analyses on the LAKE-IoD scheme. Fig. 6 shows the results generated by Scyther after the analysis of the LAKE-IoD, which demonstrates that the proposed security scheme is secure under the claims as specified.

VII. PERFORMANCE EVALUATION

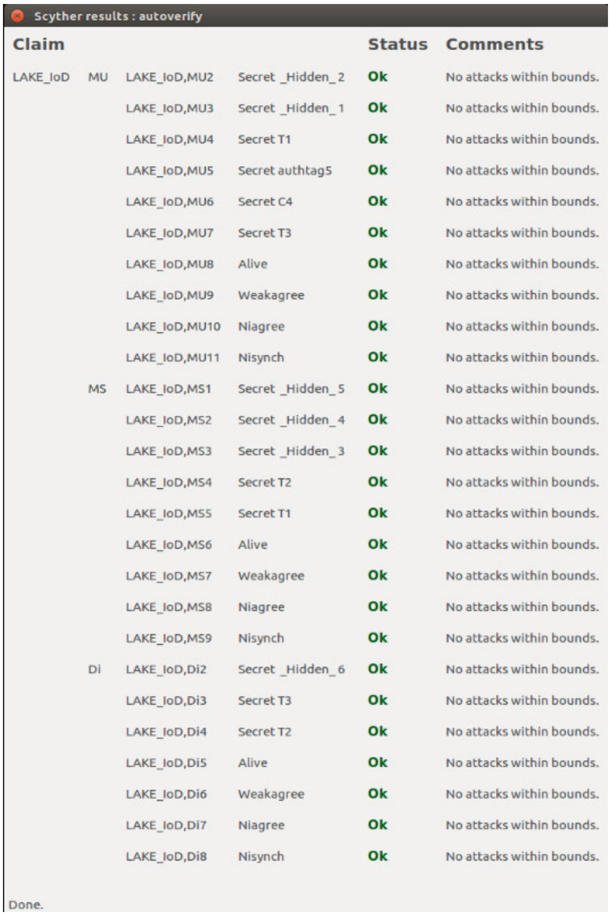
In this section a detailed comparison between the proposed scheme LAKE-IoD and other relevant AKE schemes, such as Wazid *et al.* [6], Das *et al.* [24], Challa *et al.* [26], Srinivas *et al.* [7], and Challa *et al.* [22] is presented. LAKE-IoD is compared in term of security features, storage overhead, communication overhead, and computational cost during the AKE phase.

A. SECURITY FEATURE COMPARISON (SFC)

This section presents the comparison of LAKE-IoD security features and other related AKE schemes. It is obvious from

$$\frac{MS \mid\equiv (MS \overset{K_1}{\longleftrightarrow} MD_i), MS \lhd \{T_1, A_4, R_{MU_i}, SID_{D_j}\}_{(MD_i \overset{K_1}{\longleftrightarrow} MS)}}{MS \mid\equiv MD_i \mid\sim \{T_1, A_4, R_{MU_i}, SID_{D_j}\}_{(MD_i \overset{K_1}{\longleftrightarrow} MS)}}.$$

$$\frac{MS \mid\equiv \#(T_1, A_4, R_{MU_i}, SID_{D_j}), MS \lhd (T_1, A_4, R_{MU_i}, SID_{D_j})}{MS \mid\equiv MD_i \mid\equiv (T_1, A_4, R_{MU_i}, SID_{D_j})}.$$



```
Scyther results : autoverify

Claim                                               Status  Comments
LAKE_IoD  MU  LAKE_IoD,MU2   Secret _Hidden_2      Ok      No attacks within bounds.
              LAKE_IoD,MU3   Secret _Hidden_1      Ok      No attacks within bounds.
              LAKE_IoD,MU4   Secret T1             Ok      No attacks within bounds.
              LAKE_IoD,MU5   Secret authtag5       Ok      No attacks within bounds.
              LAKE_IoD,MU6   Secret C4             Ok      No attacks within bounds.
              LAKE_IoD,MU7   Secret T3             Ok      No attacks within bounds.
              LAKE_IoD,MU8   Alive                 Ok      No attacks within bounds.
              LAKE_IoD,MU9   Weakagree             Ok      No attacks within bounds.
              LAKE_IoD,MU10  Niagree               Ok      No attacks within bounds.
              LAKE_IoD,MU11  Nisynch               Ok      No attacks within bounds.
          MS  LAKE_IoD,MS1   Secret _Hidden_5      Ok      No attacks within bounds.
              LAKE_IoD,MS2   Secret _Hidden_4      Ok      No attacks within bounds.
              LAKE_IoD,MS3   Secret _Hidden_3      Ok      No attacks within bounds.
              LAKE_IoD,MS4   Secret T2             Ok      No attacks within bounds.
              LAKE_IoD,MS5   Secret T1             Ok      No attacks within bounds.
              LAKE_IoD,MS6   Alive                 Ok      No attacks within bounds.
              LAKE_IoD,MS7   Weakagree             Ok      No attacks within bounds.
              LAKE_IoD,MS8   Niagree               Ok      No attacks within bounds.
              LAKE_IoD,MS9   Nisynch               Ok      No attacks within bounds.
          Di  LAKE_IoD,Di2   Secret _Hidden_6      Ok      No attacks within bounds.
              LAKE_IoD,Di3   Secret T3             Ok      No attacks within bounds.
              LAKE_IoD,Di4   Secret T2             Ok      No attacks within bounds.
              LAKE_IoD,Di5   Alive                 Ok      No attacks within bounds.
              LAKE_IoD,Di6   Weakagree             Ok      No attacks within bounds.
              LAKE_IoD,Di7   Niagree               Ok      No attacks within bounds.
              LAKE_IoD,Di8   Nisynch               Ok      No attacks within bounds.

Done.
```

FIGURE 6. Scyther analysis results of LAKE-IoD.

Table 4 that the scheme of Wazid *et al.* [6] does not render *SFC*1, *SFC*3, and *SFC*6, Das *et al.* [24] is insecure against *SFC*1, *SFC*3, *SFC*4, and *SFC*16, Challa *et al.* [26] is vulnerable to *SFC*1, *SFC*2, and *SFC*3, *SFC*4, and *SFC*6, Srinivas *et al.* [7] is not protected against *SFC*1, *SFC*3, and *SFC*6, and Challa *et al.* [22] is unprotected against *SFC*5, *SFC*6, *SFC*7, *SFC*8, and *SFC*9. Security is one of the most important parameters of concern of an AKE scheme. The proposed LAKE-IoD provides more security features as compared to other related AKE schemes. Table 4 illustrates the security feature comparison between LAKE-IoD and other related schemes.

TABLE 4. Security features comparison.

S-Feature	Wazid [6]	Das [24]	Challa [26]	Srinivas [7]	Challa [22]	LAKE-IoD
*SFC*1	×	×	×	×	✓	✓
*SFC*2	✓	✓	×	✓	✓	✓
*SFC*3	×	×	×	×	✓	✓
*SFC*4	✓	×	×	✓	✓	✓
*SFC*5	✓	✓	✓	✓	×	✓
*SFC*6	×	✓	×	×	×	✓
*SFC*7	✓	✓	✓	✓	×	✓
*SFC*8	✓	✓	✓	✓	×	✓
*SFC*9	✓	✓	✓	✓	×	✓
*SFC*10	✓	✓	✓	✓	✓	✓
*SFC*11	✓	✓	✓	✓	✓	✓
*SFC*12	✓	✓	✓	✓	✓	✓
*SFC*13	✓	✓	✓	✓	✓	✓
*SFC*14	✓	✓	✓	✓	✓	✓
*SFC*15	✓	✓	✓	✓	✓	✓
*SFC*16	✓	×	✓	✓	✓	✓

Note: *SFC*1: Stolen-device attack; *SFC*2: Password guessing attack; *SFC*3: Privileged-insider attack; *SFC*4: User anonymity/traceability; *SFC*5: Mutual authentication *SFC*6: Impersonation attack; *SFC*7: DoS attack; *SFC*8: Replay-attack; *SFC*9: Man-in-the-Middle/Forgery attack; *SFC*10: ESL attack; *SFC*11: Sensor/drone capture attack; *SFC*12: Password update phase; *SFC*13: Bio-metric update; *SFC*14: Revocable phase; *SFC*15: Un-authorized login detection; *SFC*15: Session key security;
✓: Shows feature is supported;
×: Shows not supported feature;

B. STORAGE COST COMPARISON

This section presents the storage cost comparison between LAKE-IoD and other related AKE schemes, such as the scheme of Wazid *et al.* [6], Das *et al.* [24], Challa *et al.* [26], Srinivas *et al.* [7], and Challa *et al.* [22]. LAKE-IoD requires to store $\{A_2, A_3, AUTH_{reg}, Gen(.), Rep(.), RP^{reg}, ET\}$, $\{SID_{D_j}, ID_{D_j}, SP_{D_j}, FID_k\}$, and $\{SID_{MU_i}, SP_{MU_i}), (ID_{D_j}, SID_{D_j}, SP_{D_j}, FID_k\}$ of sizes $\{256 + 256 + 128 + 160 + 8\} = 808$ bits, $\{128 + 128 + 128 + 128\} = 512$ bits, and $\{128 + 128 + 128 + 128 + 128 + 128\} = 768$ bits on MU_i, D_j, and MS respectively. The total storage required for LAKE-IoD is $\{808 + 512 + 768\} = 2088$ bits. The comparison exhibits that LAKE-IoD requires less storage cost as compared to Wazid *et al.* [6], Das *et al.* [24], Challa *et al.* [26], Srinivas *et al.* [7], and slightly high storage cost as compared to Challa *et al.* [22]. However, LAKE-IoD renders more security than Challa *et al.* [22], which is the most important parameter of concern for security scheme. Table 5 illustrates the storage

$$\frac{MD_i \mid\equiv (MD_i \overset{K_3}{\longleftrightarrow} D_j), MD_i \lhd \{T_3, P_3, (D_j \overset{SK}{\longleftrightarrow} MD_i)\}_{(MD_i \overset{K_3}{\longleftrightarrow} D_j)}}{MD_i \mid\equiv D_j \mid\sim \{T_3, P_4, (D_j \overset{SK}{\longleftrightarrow} MD_i)\}_{(MD_i \overset{K_3}{\longleftrightarrow} D_j)}}.$$

$$\frac{MD_i \mid\equiv \#(T_3, P_4, (D_j \overset{SK}{\longleftrightarrow} MD_i)), MD_i \lhd (T_3, P_4, (D_j \overset{SK}{\longleftrightarrow} MD_i))}{MD_i \mid\equiv D_j \mid\equiv \#(T_3, P_4, (D_j \overset{SK}{\longleftrightarrow} MD_i))}$$

cost comparison of the proposed LAKE-IoD and other related AKE schemes.

TABLE 5. Storage overhead.

Scheme	User Side	Server Side	Drone Side	Total
Wazid [6]	1288 bits	1120+$(m+1)log_2(p)$ bits	480+$(m+1)log_2(p)$ bits	$2888+2*(m+1)log_2(p)$ bits
Das [24]	768 bits	992+$(m+1)log_2(p)$ bits	640+$(m+1)log_2(p)$ bits	$2400+2*(m+1)log_2(p)$ bits
Challa [26]	488 bits	1928 bits	1600 bits	4016 bits
Srinivas [7]	1120 bits	1120 bits	640 bits	2888 bits
Challa [22]	648 bits	808 bits	320 bits	1776 bits
LAKE-IoD	808 bits	768 bits	512 bits	2088 bits

Note: m is the degree of symmetric bi-variate polynomial and p is the length of symmetric key

C. COMMUNICATION OVERHEAD COMPARISON

In this section, LAKE-IoD is compared with the existing schemes regarding the communication overhead of different involved entities during the AKE phase. The sizes of various credentials, we considered, such as timestamps, identities, random numbers, and EC points are 32 bits, 128 bits, 128 bits, and 160 bits, respectively. Moreover, the output hash function is 256 bits. Furthermore, the key size for the AEGIS is 128 bits and the size of parameter $AUTH_{tagx} = 128$, where $x = 1, 2, 3$. Table 6 illustrates the comparison of communication overhead during the AKE phase between LAKE-IoD and related schemes. LAKE-IoD exchanges three messages during the AKE process, such as M_1:{ T_1, A_4, C_1^{mu}, C_2^{mu}, $AUTH_{tag1}$}, M_2:{ $T_2, A_{12}, C_1^{ms}, AUTH_{tag3}$}, and M_3: {T_3, A_{19}, $C_1^d, AUTH_{tag5}$} with length $M_{au1} = 32 + 128 + 128 + 128 + 128 = 544$ bits, $M_{au2} = 32 + 128 + 128 + 128 = 416$ bits, and $M_{au2} = 32 + 128 + 128 + 128 = 416$ bits, respectively. Total communication overhead during the authentication process of the LAKE-IoD is $\sum_{a=1}^{3} |M_a| = (544 + 416 + 416) = 1376$ bits. Contrarily, the existing authentication scheme proposed by Wazid *et al.* [6], Das *et al.* [24], Challa *et al.* [26], Srinivas *et al.* [7], and Challa *et al.* [22] require 1696 bits, 1536 bits, 2528 bits, 1536 bits, and 1428 bits, respectively. Table 6 and Fig.7 manifest that LAKE-IoD requires less communication overhead as compared to the recent related schemes.

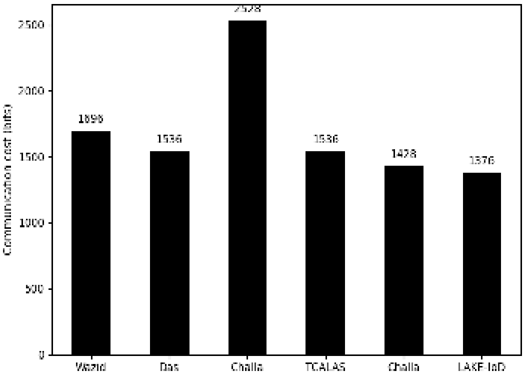


FIGURE 7. Communication overhead.

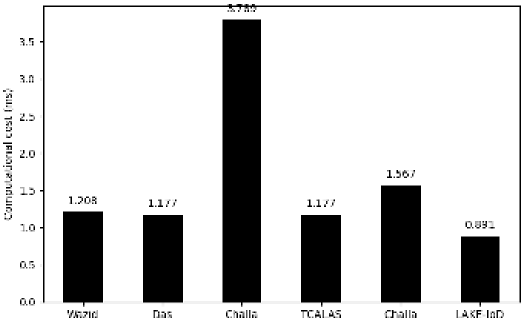


FIGURE 8. Computational overhead.

D. COMPUTATIONAL OVERHEAD COMPARISON

This paper considers the experimental results presented in the Table 7 to compute the computational overhead of the LAKE-IoD and other proposed schemes. The execution time of various operations employed in LAKE-IoD is computed using the system Intel(R) Pentium(R) CPU @ 2.5GHz, with Ubuntu (64 bits) operating system, and RAM 2 GB. Total computational overhead of the LAKE-IoD and the schemes of Wazid *et al.* [6], Das *et al.* [24], Challa *et al.* [26], Srinivas *et al.* [7], and Challa *et al.* [22] require $13T_{SH} + 6T_{AG} + 1T_{BU} \approx 0.8943$ ms, $31T_{SH} + 1T_{BU} \approx 1.2114$ ms, $30T_{SH} + T_{BU} \approx 1.1803$ ms, $12T_{SH} + 14T_{ec} + T_{BU} \approx 3.8354$ ms, $30T_{SH} + 1T_{BU} \approx 1.1803$ ms, and $19T_{SH} + 3T_{ec} + T_{BU} \approx 1.5800$ ms, respectively. Table 8 and Fig. 8 shows the computational cost comparison of LAKE-IoD and the related AKE schemes. Moreover, the proposed LAKE-IoD requires computational cost at the drone side $3T_{SH} + 2T_{AG} \approx 0.2052$ ms, which is comparable with the existing recent related schemes, such as Wazid [6], Das [24], Challa [26], Srinivas [7], and Challa [22], require $7T_{SH} \approx 0.2177$ ms, $7T_{SH} \approx 0.2177$ ms, $3T_{SH} + 4T_{ec} \approx 1.0825$ ms, $7T_{SH} \approx 0.2177$ ms, and $5T_{SH} \approx 0.1555$ ms computational cost at the drone/sensor side, respectively. LAKE-IoD requires slightly high computation cost at drone side as compared to

TABLE 6. Communication overhead.

Scheme	Messages exchanged among the entities during AKE	Total (bits)
Wazid [6]	$MU_i/U_i \xrightarrow{672} MS/GW \xrightarrow{512} D_j/SN_j \xrightarrow{512} MU_i/U_i$	**1696**
Das [24]	$MU_i/U_i \xrightarrow{672} GW/CS \xrightarrow{512} D_j/SN_j \xrightarrow{352} MU_i/U_i$	**1536**
Challa [26]	$MU_i/U_i \xrightarrow{992} GW/CS \xrightarrow{1024} D_j/SN_j \xrightarrow{512} MU_i/U_i$	**2528**
Srinivas [7]	$MU_i/U_i \xrightarrow{672} MS/CS \xrightarrow{512} D_j/SN_j \xrightarrow{352} MU_i/U_i$	**1536**
Challa [22]	$MU_i/U_i \xrightarrow{832} GW/CS \xrightarrow{244} D_j/SN_j \xrightarrow{352} MU_i/U_i$	**1428**
LAKE-IoD	$MU_i/U_i \xrightarrow{544} MS/GW \xrightarrow{416} D_j/SN_j \xrightarrow{416} MU_i/U_i$	**1376**

Note: MU_i/U_i is the mobile user, MS is a management server, GW is the gateway, CS is the control server, D_j is the drone, and SN_j is the sensor node.

TABLE 7. Execution time for various operations.

Notation	Cryptographic Operation	Approximate Time (ms)
T_{SH}	Hash function (SHA-256)	0.0311
T_{AG}	AEGIS	0.056
T_{EC}	ECC point addition	0.2473
$T_{BU} \approx T_{EC}$	Fuzzy extractors	0.2473

TABLE 8. Computational overhead.

Scheme	User Side	Server Side	Drone Side	Total Time
Wazid [6]	$16T_{SH} + T_{BU}$	$8T_{SH}$	$7T_{SH}$	$31T_{SH} + T_{BU} \approx 1.2114$ ms
Das [24]	$14T_{SH} + T_{BU}$	$9T_{SH}$	$7T_{SH}$	$30T_{SH} + T_{BU} \approx 1.1803$ ms
Challa [26]	$5T_{SH} + 5T_{ec} + T_{BU}$	$4T_{SH} + 5T_{ec}$	$3T_{SH} + 4T_{ec}$	$12T_{SH} + 14T_{ec} + T_{BU} \approx 3.8354$ ms
Srinivas [7]	$14T_{SH} + T_{BU}$	$9T_{SH}$	$7T_{SH}$	$30T_{SH} + T_{BU} \approx 1.1803$ ms
Challa [22]	$10T_{SH} + 2T_{ec} + T_{BU}$	$4T_{SH} + T_{ec}$	$5T_{SH}$	$19T_{SH} + 3T_{ec} + T_{BU} \approx 1.5800$ ms
LAKE-IoD	$6T_{SH} + 2T_{AG} + T_{BU}$	$2T_{SH} + 2T_{AG}$	$3T_{SH} + 2T_{AG}$	$11T_{SH} + 6T_{AG} + T_{BU} \approx 0.8943$ ms

Challa [22] and less computational cost as compared to other related AKE schemes. However, the proposed LAKE-IoD is secure and renders more security functionality as compared to Challa [22], which is a critical feature of an AKE scheme.

VIII. CONCLUSION

IoD is a providential technology that will predominate in the anticipated future, and there is an inevitable requirement to guarantee secure communication in IoD environment. The drones collect critical data and outsource it to the cloud and the users can collect buffered data from the cloud or (real-time data) directly from the drone. User authentication is inevitable and one of the principal security requirements to ensure secure communication between a specific drone and authorized user. In this paper, we devised a novel Lightweight Authenticated Key Exchange Protocol for the Internet of Drone Environment (LAKE-IoD) which is a three-factor security scheme employing user's password, mobile device, and bio-metric information. LAKE-IoD is examined meticulously for its security characteristics by employing formal security analysis using BAN logic and Scyther tool and also using informal security analysis. A comprehensive comparison of LAKE-IoD and other relevant security strategies illustrates that LAKE-IoD renders better security functionalities and incurs less computational and communication overhead for IoD resource constricted environment.

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REFERENCES

[1] G. S. Ilgi and Y. K. Ever, "Critical analysis of security and privacy challenges for the Internet of drones: A survey," in *Drones in Smart-Cities*. Amsterdam, The Netherlands: Elsevier, 2020, pp. 207–214.

[2] H. Lei, D. Wang, K.-H. Park, I. S. Ansari, J. Jiang, G. Pan, and M.-S. Alouini, "Safeguarding UAV IoT communication systems against randomly located eavesdroppers," *IEEE Internet Things J.*, vol. 7, no. 2, pp. 1230–1244, Feb. 2020.

[3] Q. Zhang, M. Jiang, Z. Feng, W. Li, W. Zhang, and M. Pan, "IoT enabled UAV: Network architecture and routing algorithm," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 3727–3742, Apr. 2019.

[4] S. Ullah, K.-I. Kim, K. H. Kim, M. Imran, P. Khan, E. Tovar, and F. Ali, "UAV-enabled healthcare architecture: Issues and challenges," *Future Gener. Comput. Syst.*, vol. 97, pp. 425–432, Aug. 2019.

[5] M. Gharibi, R. Boutaba, and S. L. Waslander, "Internet of drones," *IEEE Access*, vol. 4, pp. 1148–1162, 2016.

[6] M. Wazid, A. K. Das, N. Kumar, A. V. Vasilakos, and J. J. P. C. Rodrigues, "Design and analysis of secure lightweight remote user authentication and key agreement scheme in Internet of drones deployment," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 3572–3584, Apr. 2019.

[7] J. Srinivas, A. K. Das, N. Kumar, and J. J. P. C. Rodrigues, "TCALAS: Temporal credential-based anonymous lightweight authentication scheme for Internet of drones environment," *IEEE Trans. Veh. Technol.*, vol. 68, no. 7, pp. 6903–6916, Jul. 2019.

[8] S. H. Alsamhi, O. Ma, M. S. Ansari, and F. A. Almalki, "Survey on collaborative smart drones and Internet of Things for improving smartness of smart cities," *IEEE Access*, vol. 7, pp. 128125–128152, 2019.

[9] Y.-J. Chen and L.-C. Wang, "Privacy protection for Internet of drones: A network coding approach," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 1719–1730, Apr. 2019.

[10] Y. Zhi, Z. Fu, X. Sun, and J. Yu, "Security and privacy issues of UAV: A survey," *Mobile Netw. Appl.*, vol. 25, no. 1, pp. 95–101, Feb. 2020.

[11] 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.

[12] M. Wazid, A. K. Das, and J.-H. Lee, "Authentication protocols for the Internet of drones: Taxonomy, analysis and future directions," *J. Ambient Intell. Humanized Comput.*, pp. 1–10, Aug. 2018, doi: 10.1007/s12652-018-1006-x.

[13] 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.

[14] M. S. Farash and M. A. Attari, "An anonymous and untraceable password-based authentication scheme for session initiation protocol using smart cards," *Int. J. Commun. Syst.*, vol. 29, no. 13, pp. 1956–1967, Sep. 2016.

[15] Y. Lu, L. Li, H. Peng, and Y. Yang, "An anonymous two-factor authenticated key agreement scheme for session initiation protocol using elliptic curve cryptography," *Multimedia Tools Appl.*, vol. 76, no. 2, pp. 1801–1815, Jan. 2017.

[16] 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.

[17] 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.

[18] S. Kumari, X. Li, F. Wu, A. K. Das, K.-K.-R. Choo, and J. Shen, "Design of a provably secure biometrics-based multi-cloud-server authentication scheme," *Future Gener. Comput. Syst.*, vol. 68, pp. 320–330, Mar. 2017.

[19] Q. Feng, D. He, S. Zeadally, and H. Wang, "Anonymous biometrics-based authentication scheme with key distribution for mobile multi-server environment," *Future Gener. Comput. Syst.*, vol. 84, pp. 239–251, Jul. 2018.

[20] R. Ali and A. K. Pal, "An efficient three factor-based authentication scheme in multiserver environment using ECC," *Int. J. Commun. Syst.*, vol. 31, no. 4, p. e3484, Mar. 2018.

[21] F. Wang, G. Xu, C. Wang, and J. Peng, "A provably secure biometrics-based authentication scheme for multiserver environment," *Secur. Commun. Netw.*, vol. 2019, pp. 1–15, Jun. 2019.

[22] 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.

[23] R. Amin, N. Kumar, G. P. Biswas, R. Iqbal, and V. Chang, "A light weight authentication protocol for IoT-enabled devices in distributed cloud computing environment," *Future Gener. Comput. Syst.*, vol. 78, pp. 1005–1019, Jan. 2018.

[24] A. K. Das, M. Wazid, N. Kumar, A. V. Vasilakos, and J. J. P. C. Rodrigues, "Biometrics-based privacy-preserving user authentication scheme for cloud-based industrial Internet of Things deployment," *IEEE Internet Things J.*, vol. 5, no. 6, pp. 4900–4913, Dec. 2018.

[25] 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.

[26] S. Challa, M. Wazid, A. K. Das, N. Kumar, A. G. Reddy, E.-J. Yoon, and K.-Y. Yoo, "Secure signature-based authenticated key establishment scheme for future IoT applications," *IEEE Access*, vol. 5, pp. 3028–3043, 2017.

[27] X. Jia, D. He, L. Li, and K.-K. R. Choo, "Signature-based three-factor authenticated key exchange for Internet of Things applications," *Multimedia Tools Appl.*, vol. 77, no. 14, pp. 18355–18382, 2018.

[28] G. Sharma and S. Kalra, "A lightweight user authentication scheme for cloud-IoT based healthcare services," *Iranian J. Sci. Technol., Trans. Electr. Eng.*, vol. 43, no. S1, pp. 619–636, Jul. 2019.

[29] M. Tanveer, G. Abbas, Z. H. Abbas, M. Waqas, F. Muhammad, and S. Kim, "S6AE: Securing 6LoWPAN using authenticated encryption scheme," *Sensors*, vol. 20, no. 9, p. 2707, May 2020.

[30] 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.

[31] S. Roy, S. Chatterjee, A. K. Das, S. Chattopadhyay, S. Kumari, and M. Jo, "Chaotic map-based anonymous user authentication scheme with user biometrics and fuzzy extractor for crowdsourcing Internet of Things," *IEEE Internet Things J.*, vol. 5, no. 4, pp. 2884–2895, Aug. 2018.

[32] H. Wu and B. Preneel, "AEGIS: A fast authenticated encryption algorithm," in *Selected Areas in Cryptography—SAC 2013*, T. Lange, K. Lauter, and P. Lison k, Eds. Berlin, Germany: Springer, 2014, pp. 185–201.

[33] S. Sharaf and H. Mostafa, "A study of authentication encryption algorithms (POET, Deoxys, AEZ, MORUS, ACORN, AEGIS, AES-GCM) for automotive security," in *Proc. 30th Int. Conf. Microelectron. (ICM)*, Dec. 2018, pp. 303–306.

[34] 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.

[35] M. Burrows, M. Abadi, and R. M. Needham, "A logic of authentication," *Proc. Roy. Soc. A, Math., Phys. Eng. Sci.*, vol. 426, no. 1871, pp. 233–271, 1989.

[36] (Mar. 2020). *The Scyther Tool*. [Online]. Available: https://people.cispa.io/cas.cremers/scyther/

MUHAMMAD TANVEER received the B.S. degree in electronics from GCU Lahore, Pakistan, and the M.S. degree in computer science from the Institute of Management of Sciences (IMS), Lahore, in 2017. He is currently pursuing the Ph.D. degree with the Faculty of Computer Sciences and Engineering. He is also a member of the Telecommunications and Networking (TeleCoN) Research Laboratory, GIK Institute of Engineering Sciences and Technology. His current research interests include remote user authentication, cyber security, security and privacy, cryptography, the Internet of Things, 6LoWPAN, and the Internet of Drone.

AMJAD HUSSAIN ZAHID received the Ph.D. degree in computer science (information security) from the University of Engineering and Technology, Lahore, Pakistan. He is currently working as an Assistant Professor with the University of Management and Technology (UMT), Lahore. He is also the Program Advisor for BS(IT) program and member of many academic bodies. He has been an Active Member of Higher Education Commission (HEC) National Curriculum Revision Committee (NCRC), Pakistan. He has been an Active Member of Faculty Board of Studies with the Punjab University College of Information Technology (PUCIT) and the Virtual University of Pakistan. He possesses quality monitoring and maintaining capabilities along with the strong interpersonal, leadership, and team management skills. He has more than 23 years of qualitative experience in teaching. He is vigorous in academic research. His research interests include information security, programming languages, algorithm design, enterprise architecture, technology management, IT infrastructure, block chain, and so on. He is serving as an Efficient and an effective Reviewer in several reputed international research journals of high impact factor in the domain of information security.

MUSHEER AHMAD received the B.Tech. and M.Tech. degrees from the Department of Computer Engineering, Aligarh Muslim University, India, in 2004 and 2008, respectively, and the Ph.D. degree in chaos-based cryptography from the Department of Computer Engineering, Jamia Millia Islamia, New Delhi, India. From 2007 to 2010, he has worked with the Department of Computer Engineering, Aligarh Muslim University. Since 2011, he has been working as an Assistant Professor with the Department of Computer Engineering, Jamia Millia Islamia. He has published over 80 research papers in international reputed refereed journals and conference proceedings of the IEEE/Springer/Elsevier. He has more than 1000 citations of his research works with an H-index of 18. His research interests include multimedia security, chaos-based cryptography, cryptanalysis, machine learning for security, image processing, and optimization techniques. He has served as a reviewer and a technical program committee member of many international conferences. He has also served as referee of some renowned journals, such as *Signal Processing*, *Information Sciences*, the *Journal of Information Security and Applications*, IEEE ACCESS, the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, the IEEE TRANSACTIONS ON NEURAL NETWORKS AND LEARNING SYSTEMS, *Wireless Personal Communications*, *Neural Computing and Applications*, the *International Journal of Bifurcation and Chaos*, *Optik*, *Optics and Laser Technology*, *Neurocomputing*, *IET Information Security*, *Security and Communication Networks*, *Complexity*, *Computers in Biology and Medicine*, *Chaos Solitons & Fractals*, *Physica A: Statistical Mechanics and its Applications*, *Signal Processing: Image Communication*, the *Journal of the Chinese Institute of Engineers*, *Computational and Applied Mathematics*, and *ETRI Journal*.

ABDULLAH BAZ (Senior Member, IEEE) received the B.Sc. degree in electrical and computer engineering from Umm Al-Qura University (UQU), in 2002, the M.Sc. degree in electrical and computer engineering from KAU, in 2007, and the M.Sc. degree in communication and signal processing and the Ph.D. degree in computer system design from Newcastle University, in 2009 and 2014, respectively. From 2014 to 2020, he was a Vice-Dean and the Dean of the Deanship of Scientific Research with UQU. He is currently an Assistant Professor with the Computer Engineering Department, a Vice-Dean of DFMEA, the General Director of the Decision Support Center, and the Consultant of the University Vice Chancellor with UQU. His research interests include data science, ML, AI, VLSI design, EDA/CAD tools, intelligent transportation, computer system and architecture, smart systems, and smart health. Since 2015, he has been served as a Review Committee Member of the IEEE International Symposium on Circuits and Systems (ISCAS) and a member of the Technical Committee of the IEEE VLSI Systems and Applications. He served as a Reviewer in a number of journals, including the IEEE INTERNET OF THINGS, *IET Computer Vision*, *Artificial Intelligence Review*, and *IET Circuits, Devices and Systems*.

HOSAM ALHAKAMI (Member, IEEE) received the B.Sc. degree in computer science from King Abdulaziz University, Saudi Arabia, in 2004, the M.Sc. degree in internet software systems from Birmingham University, Birmingham, U.K., in 2009, and the Ph.D. degree in software engineering from De Montfort University, in 2015. From 2004 to 2007, he worked with Software Development Industry, where he implemented several systems and solutions for a national academic institution. From 2015 to 2020, he was the Vice-Dean of the Deanship of Admission and Registration for Academic affairs with Umm Al-Qura University (UQU). He is currently an Associate Professor with the Computer Science Department, UQU. He focuses on enhancing real-world matching systems using machine learning and data analytics in a context of supporting decision-making. His research interests include algorithms, semantic web, and optimization techniques.