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# Lightweight Secure Message Delivery for E2E S2S Communication in the IoT-Cloud System

MUSTAFA A. AL SIBAHEE<sup>1,2</sup>, SONGFENG LU<sup>3,1</sup>, ZAID AMEEN ABDULJABBAR<sup>4,3,5</sup>, ERASMUS(XIN LIU)<sup>5</sup>, HEMN BARZAN ABDALLA<sup>6</sup>, MOHAMMED ABDULRIDHA HUSSAIN<sup>4,5</sup>, ZAID ALAA HUSSIAN<sup>7,5</sup> AND MUDHAFAR JALIL JASSIM GHRABAT<sup>3</sup>

<sup>1</sup>Shenzhen Institute of Huazhong University of Science and Technology, Shenzhen, China

<sup>2</sup>Iraq University College, Basrah, Iraq

<sup>3</sup>Hubei Engineering Research Center on Big Data Security, School of Cyber Science and Engineering, Huazhong University of Science and Technology, Wuhan, China

<sup>4</sup>Computer Science Department, College of Education for Pure Science, University of Basrah, Basrah, Iraq

<sup>5</sup>Neusoft Institute Guangdong, Guangdong, China

<sup>6</sup>School of Computer Science, Wenzhou-Kean University, Wenzhou, China

<sup>7</sup>Information Technology Department, Management Technical College, Southern Technical University, Basrah, Iraq

Corresponding author: Songfeng Lu (e-mail: lusongfeng@hust.edu.cn).

**ABSTRACT** The continuous increase in the use of smart devices and the need for E2E smart2smart (S2S) services in IoT systems play effective and contemporary roles in the field of communication, and a large amount of resources is required. Thus, IoTs and cloud computing must be integrated. One of the results of this integration is the increase in the number of attacks and vulnerabilities in the E2E S2S message delivery service of such an IoT-cloud system. However, none of the traditional security solutions can be sufficiently regarded as a secure and lightweight mechanism for ensuring that the security requirements for E2E S2S message transmission in the IoT-cloud system are fulfilled. This work aims to provide an efficient and secure, lightweight E2E S2S message delivery function, which includes the E2E S2S secure key and biometric parameter exchange function, a bio-shared parameter and bio-key generation function, secure lightweight E2E S2S communication negotiation and secure E2E S2S lightweight message delivery. The secure, lightweight cryptographic communication procedure is negotiated between a pair of smart devices during each E2E session to minimize the power consumption required of limited-energy devices. Such a negotiation process prevents known attacks by providing responsive mutual authentication. Lightweight message delivery by the two smart devices can satisfy the basic security requirements of E2E communication and ensure that the computational cost required for a real-time system is as low as possible.

**INDEX TERMS** *Message delivery function, IoT-cloud system, smart devices, E2E S2S, mutual authentication.*

## I. INTRODUCTION

CLOUD computing has revolutionized information technology and attracted extensive attention from the research community and leading companies [1]. Cloud computing can be considered a new generation of computing infrastructure; this technology enables users to use vast resources in terms of storage and processing provides quick access to available services on request [2]. The Internet of Things (IoT) can affect changes in daily activities and behaviours [3], [4], [5], [6]. An IoT system may suffer from problems related to available resources in terms of

transmission, storage, and processing. Consequently, cloud computing and IoTs need to be interconnected physically or virtually for smart device users to maximize cloud computing services [7]. Cloud computing and IoT users face certain information security challenges and requirements with regard to communication [7].

Numerous smart devices are currently used, and these devices need to communicate with one another. E2E S2S communication is an important issue in the IoT-cloud system. In 2014, the number of smart mobile devices used by people exceeded 1.2 billion [8]. In particular, fourth- and fifth-

generation smart devices can connect to the Internet quickly, thus allowing people to send and receive E2E messages easily via smart mobile devices. Therefore, E2E S2S communication plays an active role in IoTs and is expected to be crucial to the IoT-cloud system. However, the computing capabilities of smart devices cannot keep up with the increase in the computing power of Personal Computers (PCs). Security solutions are in high demand due to the increasing dependence of the IoT-cloud environment on E2E smart device communication and the increase in attacks. Data authentication and integrity are important security essentials for users of services and applications, and they must be considered when planning the security of applications and services for smart devices [9], [10]. No applicable solutions are available for such services on smart devices in the IoT-cloud environment. Smart devices with limited computing capabilities remain vulnerable to attacks that occur in E2E communication and whose aims are to change the content of a message (e.g. replay and Denial-of-Service (DoS) attacks) [9], [10]. One of the most important requirements for safeguarding communication is the capability of two smart devices to communicate securely and effectively despite the challenges posed by current known attacks [9], [10]. The available solutions for enabling secure communication between two smart devices are still not completely secure against certain attacks, such as key guessing and replay [9], [10], [11]; these solutions are designed to address secure communication between PCs [9].

### A. PROBLEM STATEMENT

Two of the most important real-life security challenges are the authentication and integrity of message delivery between a pair of smart devices that use IoT systems for cloud computing. Thus, the integrity and authentication of data transmitted between smart devices and the confidentiality of such data are essential. Security is a critical function of smart devices that use IoTs for cloud computing services [7], [9]. However, IoT systems were created with a large number of known attacks that hinder communication between smart devices and decrease the confidence of users; these known attacks include replay, forgery, parallel session, Man-In-The-Middle (MITM), reflection, offline guessing, online guessing, brute force, dictionary, statistical and visual attacks. Existing solutions are inapplicable to smart devices that use IoT-cloud systems due to the weaknesses of the proposed methods in terms of security requirements or the limits on computational costs that prevent smart devices in such IoT-cloud systems from selecting appropriate security methods [5]. In our work, we identify a suitable means of ensuring secure communication for energy-limited smart devices in an IoT-cloud system.

### B. MECHANISM AND OBJECTIVE OVERVIEW

Our work focuses on overcoming the aforementioned problems by providing a method for the secure exchange of secret keys and users' biometric parameters for E2E S2S and cloud server negotiations. The secret keys are used

to protect the biometric parameters and bio-key exchange function. Our work also provides a lightweight negotiation method for providing secure communication for each E2E session for a pair of smart devices. Without such negotiations, most solutions cannot prevent illegal or unauthorized users from using secure E2E S2S communications in the IoT-cloud system. Our work offers a secure and low-complexity E2E S2S message delivery function by adopting a powerful assurance factor as a one-time bio-key with MAC-SHA-1 via random mapping [12], [13], [14], [15] and by embedding the summation of MAC-SHA-1 (*MACLESS* for short) in a low-complexity cover image through double-stegging [16] based on DWT steganography [17], [18] to maintain message authentication and integrity. Double-stegging increases the resistance of the system to common forms of attacks, and *MACLESS* further reduces the size of the embedded MAC; *MACLESS* is more efficient in processing the steganography operation than the MAC for energy-limited devices.

### C. CONTRIBUTIONS

This work provides the following contributions. First, the proposed scheme has a new E2E S2S low-complexity message delivery function to protect messages without losing integrity and authentication during the transmission of messages between a pair of smart devices for secure E2E communication in an IoT-cloud system. Second, our scheme establishes a secure, lightweight negotiation method for E2E S2S communications that offers responsive mutual authentication and secure E2E S2S lightweight message delivery. Hence, efficiency, reduced computational costs, and reduced energy consumption and memory size are achieved. Third, the message delivery function is computationally efficient and can be connected to the available infrastructure. It is also easy to deploy and manage. Fourth, the message delivery function integrates cryptographic MAC-SHA-1 and the secret bio-key of the smart device sender via random mapping, and then it embeds *MACLESS* as a summation of MAC-SHA-1 in a stego-image to authenticate the origin of the sender's message transmission. This scheme does not attract the attention of eavesdroppers because it conceal *MACLESS* in cover images via double-stegging based on DWT steganography; this feature also prevents replay and DoS attacks. Fifth, the proposed scheme does not require an expensive device to acquire biometric data, such as those from irises or fingerprints. Smart device users can use a simple scanner or mobile camera to obtain the handwritten signature. Finally, communication and signal processing attacks are prevented by the cryptanalysis mechanism.

The rest of this paper is structured as follows. Section II presents previously developed solutions related to the current problem. Section III provides an overview of the proposed scheme, and Section IV introduces the overall architecture of the secure message delivery function in detail. Section V presents a security analysis with respect to common attacks. Section VI describes the results, comparisons, and analyses in terms of performance and security. Section

VII provides the conclusions.

## II. RELATED WORKS

Many schemes that combine factors with cryptographic hash functions or digital signatures to ensure message authentication and integrity between two parties over the Internet have been developed. However, only a few researchers have developed secure lightweight methods that are compatible with limited-resource devices in an IoT system. This literature review focuses on related studies that developed secure message delivery methods in a lightweight manner.

### A. LIGHTWEIGHT SOLUTIONS BASED ON DIGITAL SIGNATURES

Elliptic Curve Cryptography (ECC) is a reliable encryption method that is widely used in various fields of encryption and includes a digital signature algorithm called ECDSA [19]. ECDSA has many drawbacks, such as slow implementation and design flaws. In 2017, Yasir et al. [20] proposed a low-complexity authentication mechanism by combining ElGamal and ECC to generate a pair of secret keys for encryption and decryption operations in S2S communications over IoT. In 2018, Muhammad et al. [21] presented a solution for secure data transmission between a pair of smart devices over IoT by providing an ECDSA with a limited cost and complexity. Given that the proposed method deals with complex numbers, it requires numerous processing sources, leading to increased energy consumption. In the same year, Mohseni et al. [22] proposed a lightweight scheme for data sharing between a pair of devices using 5G technology. In this scheme, a digital signature is used to meet the basic security requirements of data sharing. Particularly, MAC-SHA2 and ECC are utilized. However, this solution cannot provide identity anonymity. Hence, attackers can easily determine the user's identity. In the same year, Alizai et al. [23] proposed a secure authentication scheme based on the two-factor concept and digital signatures for E2E devices in IoT. The first factor is the device capability, which is based on puzzles. The second factor is the timestamp, which can prevent attacks. ECC is used to ensure the confidentiality of the digital signatures and secure key exchange. However, the researchers did not provide a mutual authentication mechanism to prevent illegal devices from stealing sensitive authentication parameters. In 2019, Adeel et al. [24] used ECC-ElGamal encryption to develop a lightweight authentication scheme by utilizing ECC with Public Key Infrastructure (PKI) to generate a secret key and exchange it between D2D devices over IoT. Similarly, this solution does not consider mutual authentication, which plays a role in preventing spoofing and other attacks.

### B. LIGHTWEIGHT SOLUTIONS BASED ON KEYED MAC

The factors associated with a MAC allow for a secure exchange and transfer of data between parties and the verification of authentication, integrity, and confidentiality. In 2008, Rabadi and Mahmud [25] suggested using the message anonymity concept. They attempted to maintain the authentication,

anonymity, and integrity of message delivery from vehicle to vehicle using a timestamp as a factor for anonymous message provision. However, to retain the identity, this scheme uses a hardware registration device, and this leads to extra costs; additionally, each vehicle requires a shared symmetric key. Moreover, the protocol was not clarified in the security analysis. In 2011, Liu et al. [26] adopted the same concept to generate one-time message anonymity. They utilized a scheme consisting of a hash function, shared key, validity period and timestamp to achieve secure message transmission between two parties on the Internet. However, the authors did not discuss the attacks that the scheme could withstand. Naqvi and Akram [27] presented another concept in the same year. They aimed to increase the security and reliability of HMAC-MD5. To compute such a robust MAC, they utilized a key generated by MD6 to maintain randomization and make prediction by attackers difficult. This scheme can prevent birthday and exhaustive key search attacks, as discussed in the security analysis of the paper. In 2012, Chaisri et al. [28] proposed the concept of utilizing MD5 and DES to protect the document integrity of a fax. DES is used to encrypt and maintain the MD5 value. In this concept, the sender must embed the secret key of DES into the document to be faxed, and this is considered a major weakness. An attacker could extract the secret key and reuse it to decrypt the MAC. In addition, the attacker could use the hacked secret key to recreate a fake replica, and this could make the receiver believe that the legitimate sender sent it. In 2014, Shen and Liu [29] proposed a technique for handling digital images and documents. The researchers safeguarded the authentication code by utilizing a Markov chain to enhance content-based watermarking. A disadvantage of this scheme is that the least significant bits based on sequence mapping are applied to embed the authentication code on a cover image, resulting in limited embedding efficiency and many security problems. Another drawback is that the authentication code could be extracted by attackers. When the valid user logs out, an attacker could reuse the stolen key to log in as the legitimate user.

In 2016, Chen et al. [30] presented a mechanism for protecting M2M message transmission in IoT on the basis of a trapdoor HMAC and a random number. However, this method has a problem, that is, the overhead of exchanging cryptographic keys leads to a high computational cost. In addition, the authors did not address the use of the advantages of cloud computing for message delivery amongst a set of smart devices in the IoT system. In 2019, Byoungjin Seok et al. [31] proposed device-to-device communication in a secure manner on the basis of Authentication Encryption with Associated Data (AEAD) and ECC for IoT devices. AEAD was applied to provide data confidentiality and integrity on the basis of an HMAC. The limitation of this scheme is that authentications between pairs of devices are provided without consideration of their mutual authentication. Moreover, it has an overhead in terms of key generation during device-to-device communication. Mohammad Ayoub et al.

[32] developed an authentication and data confidentiality scheme in 2020. In this scheme, secure authentication is based on a user ID and password, with biometric parameters of patients and SHA-512 added for further security. Improved Elliptic Curve Cryptography (IECC) is also applied to securely send the collected information by sensors. However, mutual authentication was not considered in this study, and known attacks, such as replay and MITN, could occur due to this limitation.

**DISCUSSION:** The limitations of existing works [25], [26], [27], [28], [29], [30], [31], [32] can be viewed from different aspects. First, most of these solutions suffer from a computational overhead that is not supported by smart device resources with respect to performing ECC in the data delivery function. In contrast, our scheme uses ECC in the registration phase and a secure, lightweight negotiation method for E2E S2S communications to protect the shared key and biometric user parameters. In our work, ECC is not used for secure message delivery in the IoT-cloud phase of each session of E2E S2S communication in the IoT-cloud system. This phase is the most used one in terms of smart device communication and message delivery processes in real-world applications. Additionally, existing solutions have limited storage capabilities because smart devices have limited resources. Furthermore, in our work, we consider the massive data characteristics of cloud servers for the storage process, and this can allow smart devices to access extended storage at no cost. Second, these existing works did not sufficiently address the vulnerabilities of E2E S2S communication in an IoT-cloud system. In contrast, in our work, we carefully design the E2E S2S message delivery function on the basis of lightweight secure bio-keys that are generated and shared with a lightweight, well-designed mutual authentication to verify the origin of the sender. Hence, the threats of MITN attacks that impersonate the owner of the plaintext or cipher message being sent are prevented without needing to change or view the message. In addition, our work reduces the probability of other well-known attacks, as proven by the conducted security analysis.

### III. SCHEME OVERVIEW

Despite the achievements of previous related studies, these studies failed to establish an applicable method for secure, lightweight message delivery between the sender and receiver in which E2E S2S communications can be used for IoT-cloud systems. We provide a low-complexity and secure solution for E2E S2S messaging in IoT-cloud system. Registration and key negotiation and secure message delivery in IoT-cloud phases make up the proposed solution. During the former step, which is performed only once, smart device users (the sender and receiver) register their identities and secure E2E S2S biometric user parameters for E2E S2S messaging in the IoT-cloud system. These parameters are a bio-shared vector  $Rv$  and shared key  $Shk$  generated based on the union of their handwritten signatures. Furthermore, a smart device user invokes the latter phase each time that he/she wants to

launch a secure, lightweight E2E S2S communication negotiation and then enables the lightweight and secure message delivery function for sending an authenticated message to another user. Secure, lightweight message delivery is E2E- and S2S-based. It meets application requirements in terms of security, performance and scalability and enables the integration of IoT systems and cloud infrastructure. The architecture of the secure lightweight message delivery system for E2E S2S messaging in an IoT-cloud system is shown in Fig. 3.

### IV. E2E S2S MESSAGE DELIVERY DETAILS

The following sections show in detail how E2E S2S message delivery can be easily tracked during both phases. We discuss the construction of our scheme, which further describes a property of an authenticated message for security and the prevention of tampering with a message exchange between a pair of smart device users in the IoT-cloud system.

#### A. REGISTRATION AND KEY NEGOTIATION PHASE OVERVIEW

The main components of the registration phase (i.e. cloud server or  $CS$ , smart device sender or  $SDS$  and smart device receiver or  $SDR$ ) also use ECC [33] as the asymmetric key encryption/decryption function  $Enc(.) / Dec(.)$  to secure the passing of sensitive parameters among them. The reason for using ECC instead of other methods, especially RSA, is that it has high performance in limited-power devices, low time consumption and limited memory size [33]. In addition, ECC can only be executed once in the registration phase by these components when transmitting sensitive parameters ( $ID_{SDS}, HS_{SDS}, ID_{SDR}, HS_{SDR}, Rv$  and  $Shk$ ) over an insecure channel to the  $CS$  and the initial part of the second phase called secure lightweight E2E S2S communication negotiation. Therefore, for secure communication, ECC is not needed in the whole process of secure E2E S2S lightweight message delivery but only in the registration phase and negotiation between pairs of smart devices.

#### 1) DESIGN FOR SMART DEVICE REGISTRATION IN AN IOT-CLOUD SYSTEM

The variable  $n$  pertains to the number of smart devices in the IoT-cloud system. When a smart device user wants to send an authenticated message to a set of smart devices consisting of other user members, the smart device should create the registration phase. Such registration generates accounting parameters ( $ID_{SDS}, HS_{SDS}$  and  $Sk_{SDS}$  for the sender and  $ID_{SDR}, HS_{SDR}$  and  $Sk_{SDR}$  for the receiver). Furthermore, the  $CS$  initiates the shared biometric vector  $Rv$  and shared key  $Shk$  and keeps them secure in the cloud server. Then, it sends an encrypted version of  $Shk$  to a pair of users to maintain secure E2E S2S communication, especially secure message delivery, in the IoT-cloud system. Fig. 1 illustrates the negotiation request of the registration phase.

The pair of smart devices sends a request to the  $CS$  for initiating a registration session, especially a key exchange session, and generates a set of critical parameters to be ex-



changed in both private and public manners while maintaining a secure E2E S2S transmission in the IoT-cloud system. The architecture of the registration process for users' smart devices for lightweight and secure E2E S2S communication in IoT-cloud services is shown in Fig. 1 and described in the following steps.

- Secure key and biometric parameter exchange function

The *CSP*, *SDS* and *SDR* run ECC to generate public keys ( $PU_{CS}$ ,  $PU_{SDS}$  and  $PU_{SDR}$ ) and private keys ( $PR_{CS}$ ,  $PR_{SDS}$  and  $PR_{SDR}$ ). The public keys can be exchanged amongst the *CS*, *SDS* and *SDR* through an unsecure channel. Public keys become ineffective when they are acquired by attackers. In particular, these keys are utilized to acquire secure handwritten signatures and achieve identity transmission from the *SDS* and *SDR* to the *CS*. Thus, the *SDS* and *SDR* encrypt their handwritten signatures and identities by applying the ECC encryption algorithms  $Enc_{PU_{CS}}(HS_{SDS}||ID_{SDS})$  and  $Enc_{PU_{CS}}(HS_{SDR}||ID_{SDR})$ , respectively. They use  $PU_{CS}$  and send them to the *CS*.

Upon receiving the encrypted sensitive parameters of the sender and receiver, the *CS* decrypts the received handwritten signatures and identities by using the private key  $PR_{CS}$  and applying the ECC decryption algorithms  $Dec_{PR_{CS}}(Enc_{PU_{CS}}(HS_{SDS}||ID_{SDS})) = (HS_{SDS}||ID_{SDS})$  and  $Dec_{PR_{CS}}(Enc_{PU_{CS}}(HS_{SDR}||ID_{SDR})) = (HS_{SDR}||ID_{SDR})$ . Then, it saves these parameters securely and generates a bio-shared handwritten signature by combining the parameters ( $SHS = HS_{SDS} \cup HS_{SDR}$ ) to compute the vector of features  $Rv = Fx(SHS)$  and the shared key  $Shk = Fx(SHS)$ . The *CS* also generates a temporary biometric salt key for each session  $T (Sk_{SD_i}) \in (Rv) \rightarrow I_i, E$ , where  $I_i$  and  $E$  are the starting and end points, respectively, from the vector of the extracted features ( $Rv$ ), and  $SD_i$  refers to the *SDS* and *SDR*. In each message delivery session,  $I_i$  and  $E$  are randomly selected.  $I_i$  and  $E$  should be in the range of the feature vector length, which is 3060 bytes ( $I_i$  and  $E \in Z_{3060}$ ;  $I_i \neq E$ ). Afterwards, the *CS* sends the encrypted version of  $Shk$  and  $Sk_{SD_i}$  to the *SDS* and *SDR*.

**REMARK:** The *CS* does not send  $Rv$  to prevent either of the two parties from obtaining the signature of the other party because this bio-shared vector  $Rv$  is the result of performing operations on the combined handwritten signatures of the two parties. Instead, the *CS* sends the biometric key  $Shk$  as a random part of  $Rv$ , and this keeps the biometric parameters unknown to both parties. Moreover, the secret key  $PR_{CS}$  is kept secure only by the *CS*.

- Bio-shared parameter and bio-key generation

$FX$  refers to a function that employs a histogram of the LBP filter to perform feature extraction from normalized bio-shared handwritten signature data ( $SHS$ ) and build a wide dimension range of 3060 bytes [15]. In detail,  $SHS$  is divided into 12 blocks that overlap by 60% [15]. Thereafter, the histograms of all the blocks are calculated and concatenated

as follows:

$$H_{LBP} = \{h_{LBP}^i \mid i = 1, 2, \dots, 12\} \quad (1)$$

of adimension  $12 \cdot 255 = 3060$ .

Hence, the vector features of a handwritten signature can be written as follows:

$$Rv = (X_1, X_2, X_3, X_4, \dots, X_{3060}) \quad (2)$$

Afterwards,  $Rv$  is saved securely only by the *CS* as  $Enc_{PU_{CS}}(Rv)$ , and  $Shk$  is encrypted by the *CS* using the public keys  $PU_{SDS}$  and  $PU_{SDR}$  with ECC as  $Enc_{PU_{SDS}}(Shk)$  and  $Enc_{PU_{SDR}}(Shk)$ . Then, the *CS* sends these cipher versions to the *SDS* and *SDR*. The received cipher  $Shk$  is decrypted by the *SDS* and *SDR* by using their private keys ( $PR_{SDS}$ ,  $PR_{SDR}$ ) and by applying ECC as  $Dec_{PR_{SDS}}(Enc_{PU_{SDS}}(Shk))$  and  $Dec_{PR_{SDR}}(Enc_{PU_{SDR}}(Shk))$ , respectively. The secure message delivery phase of the IoT-cloud system is invoked after the registration phase has been completed. Generally, in such a phase, the *SDS/SDR* can use bio-key  $Shk$  together with secret key  $Sk_{SDS}/SDR$ , the temporary session key  $Sk_{CS}^T$  and a random number  $R^T$  to generate a one-time variable or an anonymous authentication code. Then, a summation of the message authentication code ( $MAC_{LESS}$ ) is provided.  $MAC_{LESS}$  and  $R^T$  are subsequently embedded into a cover image via double-stegging based on DWT steganography. The cover image with the embedded  $MAC_{LESS}$  and  $R^T$  along with the message are then ready for transmission. The message integrity of the sender *SDS* can be verified by comparing the embedded integrity value called  $MAC_{LESS}(Msg^T)$  and the newly recomputed value  $MAC_{LESS}(Msg^R)$  on the receiver side *SDR*, and this completes the secure message delivery phase. This phase is illustrated in the following subsection and in Fig. 3.

- Registration session for a smart device in the IoT-cloud system

In the registration session, a smart device ( $SD_i$  for short; referring to the *SDS* or *SDR*) should send a request message for the registration process  $Enc_{PU_{CS}}(HS_{SD_i})||Enc_{PU_{CS}}(ID_{SD_i})$  to the *CS*.  $Enc(.)$  is an ECC asymmetric cryptographic encryption process. Upon receiving such a request from the  $SD_i$ , the *CS* executes the decryption operation  $Dec_{PR_{CS}}(Enc_{PU_{CS}}(HS_{SD_i})||Enc_{PU_{CS}}(ID_{SD_i})) = HS_{SD_i}||ID_{SD_i}$  to verify and store the plain text of the requested message parameters consisting of the identity of the smart device and the biometric parameter (handwritten signature) as a unique feature for each user. To clarify, the *CS* verifies whether the identities  $ID_{SD_i}$  and  $HS_{SD_i}$  are present in the IoT-cloud system. If both parameters are found,  $ID_{SD_i}$  and  $HS_{SD_i}$  are securely saved by the *CS*, and the verified or agreed-upon answer is sent to the other party  $SD_i$ .

Aside from a successful verification result, the *CS* also generates  $Rv$  and  $Shk$ , encrypts them as  $Enc_{PU_{SD_i}}(Rv_{SD_i})$  and  $Enc_{PU_{SD_i}}(Shk_{SD_i})$  and outputs the relevant bio-secret key  $Enc_{PU_{SD_i}}(Sk_{SD_i})$ . Afterwards, the *CS* sends the encrypted versions  $Enc_{PU_{SD_i}}(Shk_{SD_i})$

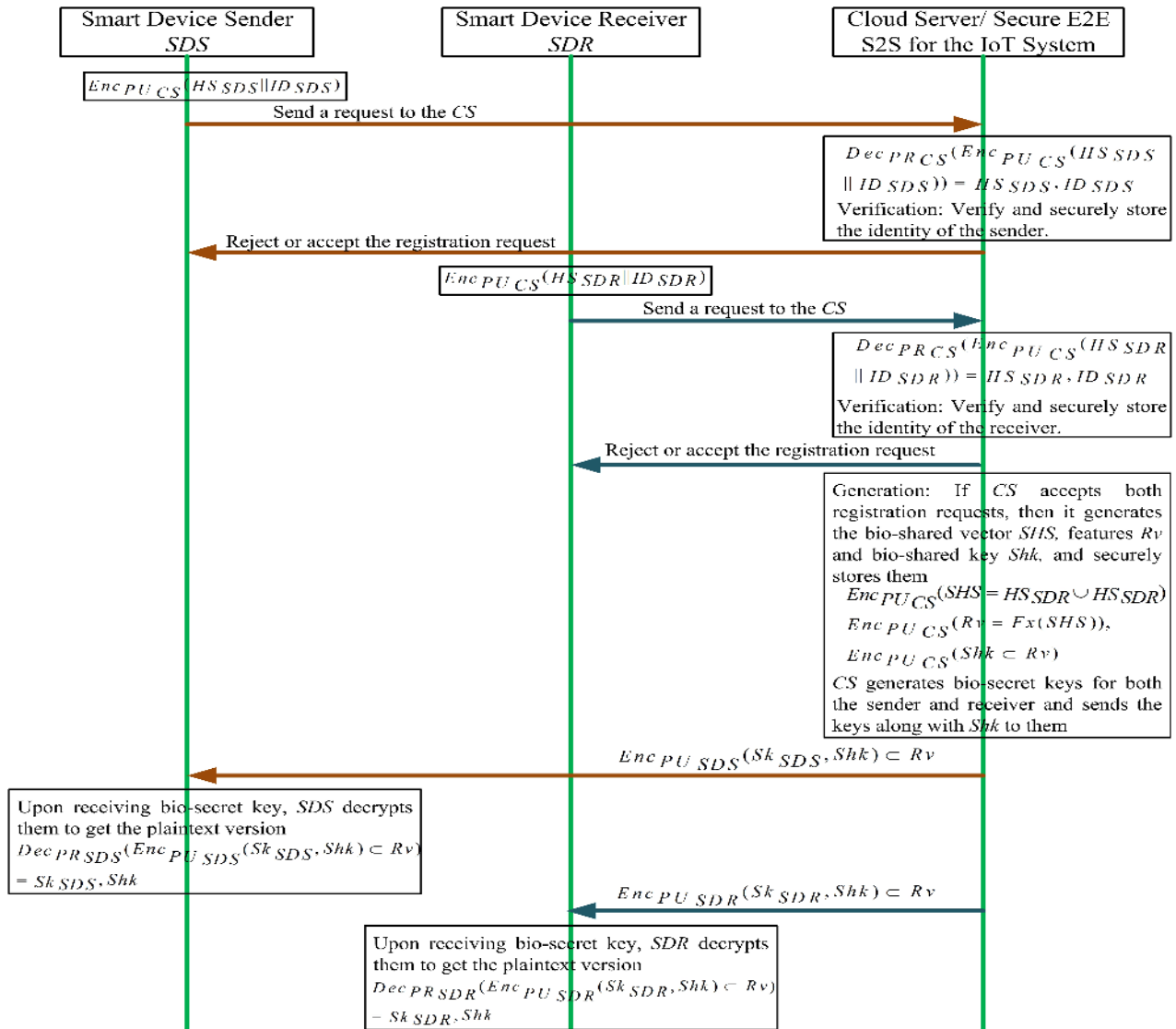


FIGURE 1. Registration and key negotiation phase.

and  $Enc_{PU_{SDi}}(Sk_{SDi})$  to both smart devices. The smart devices decrypt these parameters to obtain plain text version  $Shk_{SDi} = Dec_{PR_{SDi}}(Enc_{PU_{SDi}}(Shk_{SDi}))$  and  $Sk_{SDi} = Dec_{PR_{SDi}}(Enc_{PU_{SDi}}(Sk_{SDi}))$ .

For example, the smart devices  $SDS$  and  $SDR$  send a request to the  $CS$  consisting of their encrypted  $ID$ s together with handwritten signatures  $HS$  to initiate a registration session (Fig. 1). The  $CS$  saves their identities  $ID_{SDS}$  and  $ID_{SDR}$ , handwritten signatures  $HS_{SDS}$  and  $HS_{SDR}$  and private cryptographic keys, then generates the bio-shared vector  $Rv$  and bio-shared secret keys  $Shk$  and  $Sk_{SDi}$ . It keeps  $Rv$  to itself and securely sends the others to the  $SDS$  and  $SDR$ .

### B. SECURE MESSAGE DELIVERY IN THE IOT-CLOUD PHASE

The following subsections illustrate the secure, lightweight E2E S2S communication negotiation and message delivery function for the IoT-cloud system. In the secure E2E S2S

communication negotiation shown in Fig. 2, the  $CS$  and a pair of smart devices negotiate a request message via the  $CS$  and generate a temporary secret key  $Sk_{CS}^T$  for each session ( $T$ ) to allow for E2E S2S secure communication. The second part is designed for lightweight message delivery between a smart device sender  $SDS$  and smart device receiver  $SDR$  in an IoT-cloud system.

#### 1) SECURE LIGHTWEIGHT E2E S2S COMMUNICATION NEGOTIATION

If a pair or set of smart devices wants to initiate and coordinate secure E2E communication in the IoT-cloud system to be used for launching a secure lightweight message delivery function later on, the S2S devices should generate and organize a set request to the  $CS$  for E2E communication in the IoT system. A secure set is established by performing the following steps.

- The CS generates  $lp$  as a large prime random number  $r^T$ , computes  $d^{r^T}$  as ( $d^{r^T} \in Z_{lp}^*$ ) and provides a one-time temporary session salt key ( $Sk_{CS}^T = d^{r^T} \bmod lp$ ) for each session request message  $T$ . Then, it sends the encrypted versions  $Enc_{PU_{SDS}}(Sk_{CS}^T)$  and  $Enc_{PU_{SDR}}(Sk_{CS}^T)$  to the smart devices of the sender and receiver, respectively.
- Upon receiving the encrypted temporary session key, the SDS decrypts it by performing  $Dec_{PR_{SDS}}(Enc_{PU_{SDS}}(Sk_{CS}^T))$ . Then, the SDS uses its public key and the encryption function ECC of the CS to form an encrypted negotiation request  $Enc_{PU_{CS}}((Sk_{CS}^T \oplus Sk_{SDS}) || ID_{CS} || ID_{SDS} || ID_{SDR} || Shk)$ . The SDS sends the encrypted request to the CS.

**REMARK:** The shared bio-keys  $Shk$  and  $Sk_{SDS}$  can help prove the origin of the request because the bio-features are generated by the combined handwritten signatures of the sender and receiver equations (1), (2), and such features are unique and cannot be generated by attacks. In addition, these features were previously protected with ECC encryption before they were sent to the SDS. All data sent from smart devices are stored in encrypted form in the IoT-cloud system due to the large storage and processing capabilities of cloud computing.

- Upon receiving the encrypted version of the request message from the SDS for initiating secure E2E S2S communication in the IoT-cloud, the CS decrypts such a request by using the ECC decryption function  $Dec_{PR_{CS}}(Enc_{PU_{CS}}((Sk_{CS}^T \oplus Sk_{SDS}) || ID_{CS} || ID_{SDS} || ID_{SDR} || Shk)) = (Sk_{CS}^T \oplus Sk_{SDS}) || ID_{CS} || ID_{SDS} || ID_{SDR} || Shk$ . Afterwards, the CS compares the received identities of the cloud server, SDS and SDR and matches them with the registered identities in the database of the registration phase. In addition, the CS checks the secret key of its session  $((Sk_{CS}^T \oplus Sk_{SDS}) \oplus Sk_{SDS}) = Sk_{CS}^T$  and verifies the origin of the request via  $((Sk_{SDS} \oplus Sk_{CS}^T) \oplus Sk_{CS}^T) = Sk_{SDS}$ . If both matching and verification are successful, the CS forwards a request to the destination SDR  $Enc_{PU_{SDR}}((Sk_{CS}^T \oplus Sk_{SDS}) || ID_{CS} || ID_{SDS} || ID_{SDR} || Shk)$ . Otherwise, the CS sends a rejection response to the SDS.
- Similar to the same approach adopted by the CS, once the receiver SDR receives the session launch request, it decrypts the encrypted request,  $Dec_{PR_{SDR}}(Enc_{PU_{SDR}}((Sk_{CS}^T \oplus Sk_{SDS}) || ID_{CS} || ID_{SDS} || ID_{SDR} || Shk)) = (Sk_{CS}^T \oplus Sk_{SDS}) || ID_{CS} || ID_{SDS} || ID_{SDR} || Shk$ . Then, the SDR verifies if the original request was delivered from the SDS by using  $((Sk_{CS}^T \oplus Sk_{SDS}) \oplus Sk_{SDS}) = Sk_{SDS}$  and if it has passed through the CS by using  $((Sk_{CS}^T \oplus Sk_{SDS}) \oplus Sk_{SDS}) = Sk_{CS}^T$ . If  $Sk_{SDS}$  matches  $Sk_{SDR}$  as generated in the registration phase and  $Sk_{CS}^T$  is verified, then the check is complete, and  $Sk_{SDS}$  and  $Sk_{SDR}$  are considered symmetric keys. The SDR can decide whether to ac-

cept or reject the request delivered from the CS. If it is rejected, a rejection response is sent to the server CS, which in turn forwards the response to the SDS. In contrast, the SDR sends the encrypted response back to the CS as  $Enc_{PU_{CS}}((Sk_{CS}^T \oplus Sk_{SDR}) || ID_{CS} || ID_{SDS} || ID_{SDR} || Shk)$  by using the ECC encryption function.

- When the encrypted response is delivered from the SDR to the CS, the latter decrypts it by using  $Dec_{PR_{CS}}(Enc_{PU_{CS}}((Sk_{CS}^T \oplus Sk_{SDR}) || ID_{CS} || ID_{SDS} || ID_{SDR} || Shk)) = (Sk_{CS}^T \oplus Sk_{SDR}) || ID_{CS} || ID_{SDS} || ID_{SDR} || Shk$ . Similarly, the CS checks the origin of this response by comparing  $((Sk_{CS}^T \oplus Sk_{SDR}) \oplus Sk_{CS}^T) = Sk_{SDR}$  with the one stored in the database of the registration phase. For further security, the CS verifies its secret key via  $((Sk_{CS}^T \oplus Sk_{SDR}) \oplus Sk_{SDR}) = Sk_{CS}^T$ . If the keys match, then the origin is proven. Afterwards, the CS encrypts the parameters together with the temporary secret key of the session launched by the SDS and SDR by using the ECC encryption function  $Enc_{PU_{SDS}}((Sk_{CS}^T \oplus Sk_{SDR}) || ID_{CS} || ID_{SDS} || ID_{SDR} || Shk)$ . Finally, the CS sends the encrypted response to this request as a result of the sender's response.
- Upon receiving the response message from the CS, in response to the sender's request, the SDS decrypts the message by using the ECC decryption function  $Dec_{PR_{SDS}}(Enc_{PU_{SDS}}((Sk_{CS}^T \oplus Sk_{SDR}) || ID_{CS} || ID_{SDS} || ID_{SDR} || Shk)) = (Sk_{CS}^T \oplus Sk_{SDR}) || ID_{CS} || ID_{SDS} || ID_{SDR} || Shk$ . The SDS also verifies the origin of the response by matching  $((Sk_{CS}^T \oplus Sk_{SDR}) \oplus Sk_{CS}^T) = Sk_{SDR}$  with the generated  $Sk_{SDS}$  kept in the former phase; it also verifies  $Sk_{CS}^T$  by  $((Sk_{CS}^T \oplus Sk_{SDR}) \oplus Sk_{SDR}) = Sk_{CS}^T$ . If both are equal, then secure E2E S2S communication is achieved. A pair of smart devices can launch the secure message delivery session as illustrated below.

**DISCUSSION:** The success of the negotiation plays an effective role in ensuring responsive mutual authentication between the SDS user and the IoT-cloud server, between the last and current SDR user, between the last user and the IoT-cloud server and most importantly between the SDS and SDR user by comparing  $Sk_{SDS}$ ,  $Sk_{SDR}$  and  $Sk_{CS}^T$  to verify the origin of the request. This request results in secure E2E S2S communication over the IoT-cloud system. It also brings secure communication in terms of the credibility and legitimacy of the parties involved. Moreover, both parties obtain the secret key  $Sk_{CS}^T$  generated and sent by the server. Consequently, such a negotiation may greatly reduce attackers' attempts to impersonate the legitimacy of the sender and recipient and even attempts to counterfeit a server.

## 2) SECURE E2E S2S LIGHTWEIGHT MESSAGE DELIVERY

Many applications in our daily life, such as news and others, do not need message encryption to maintain confidentiality,

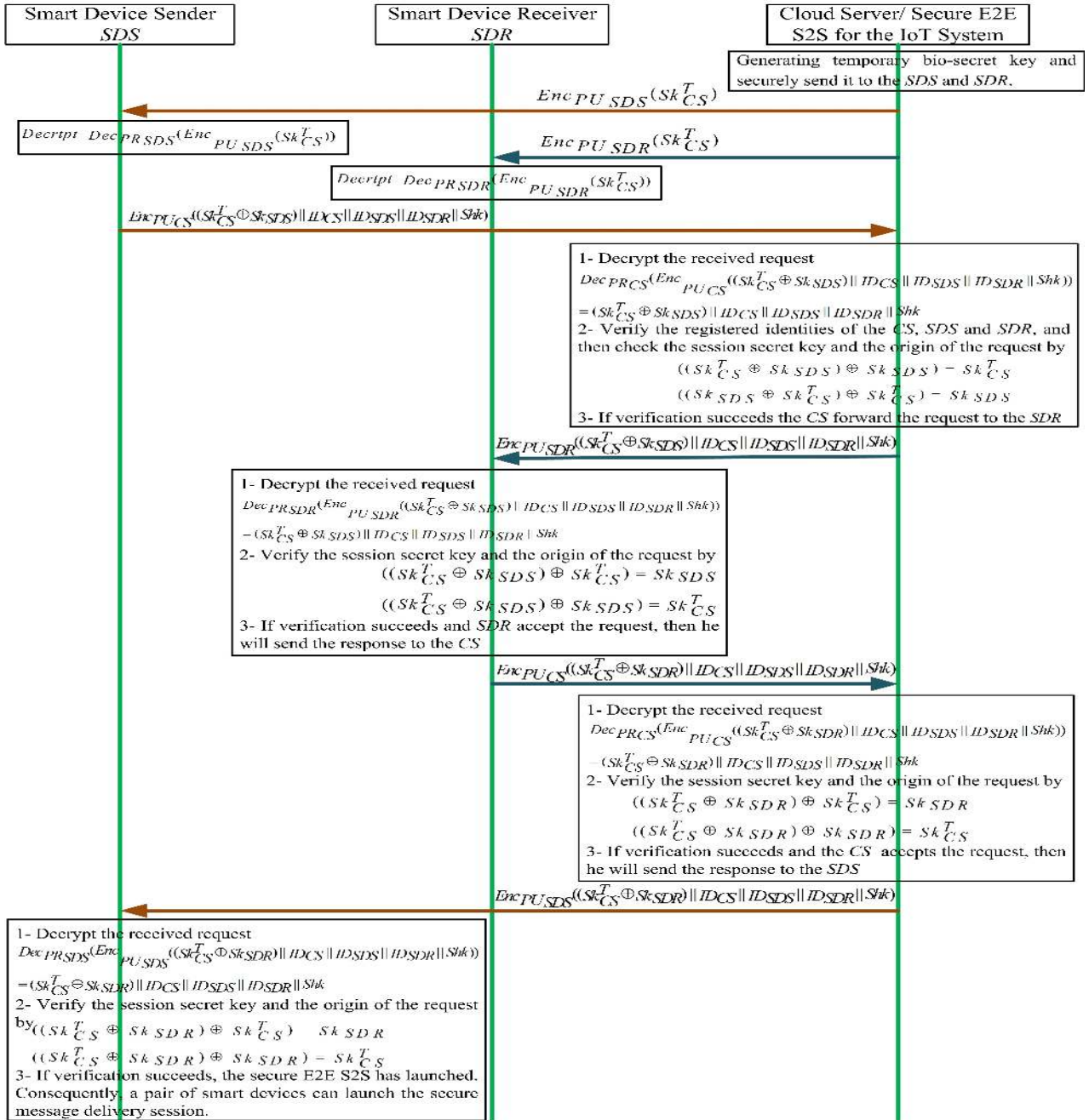


FIGURE 2. Secure lightweight E2E S2S communication negotiation.

but they need it to ensure authentication and integrity (Fig. 3). Given that smart devices have limited resources, especially in terms of processing costs, such messages do not need to be encrypted. Thus, the maintenance of energy consumption is the primary goal. Fig. 3 shows the mechanism of secure lightweight message transmission between a pair of smart devices in the IoT-cloud system.

### 3) SMART DEVICE SENDER (SDS) SIDE

To send an authenticated message ( $Msg$ ), the SDS generates a random number  $R^T$  for each session  $T$  to be used in

the generated MACLESS or limited-size, one-time, biometric message authentication code, i.e.  $MACLESS(Msg) = \sum_{i=1}^L h(Msg || Sk_{CS}^T || Sk_{SDS} || Shk || R^T) = 4$  bytes. The SDS has to send  $R^T$  to the SDR in a secure manner together with MACLESS. We propose to use double-stegging steganography for hiding MACLESS and  $R^T$  in the limited size of a cover image to maintain the communication cost in the IoT-cloud system. The following discussion shows why we use steganography.

The SDS embeds  $MACLESS(Msg)$  and  $R^T$  into a



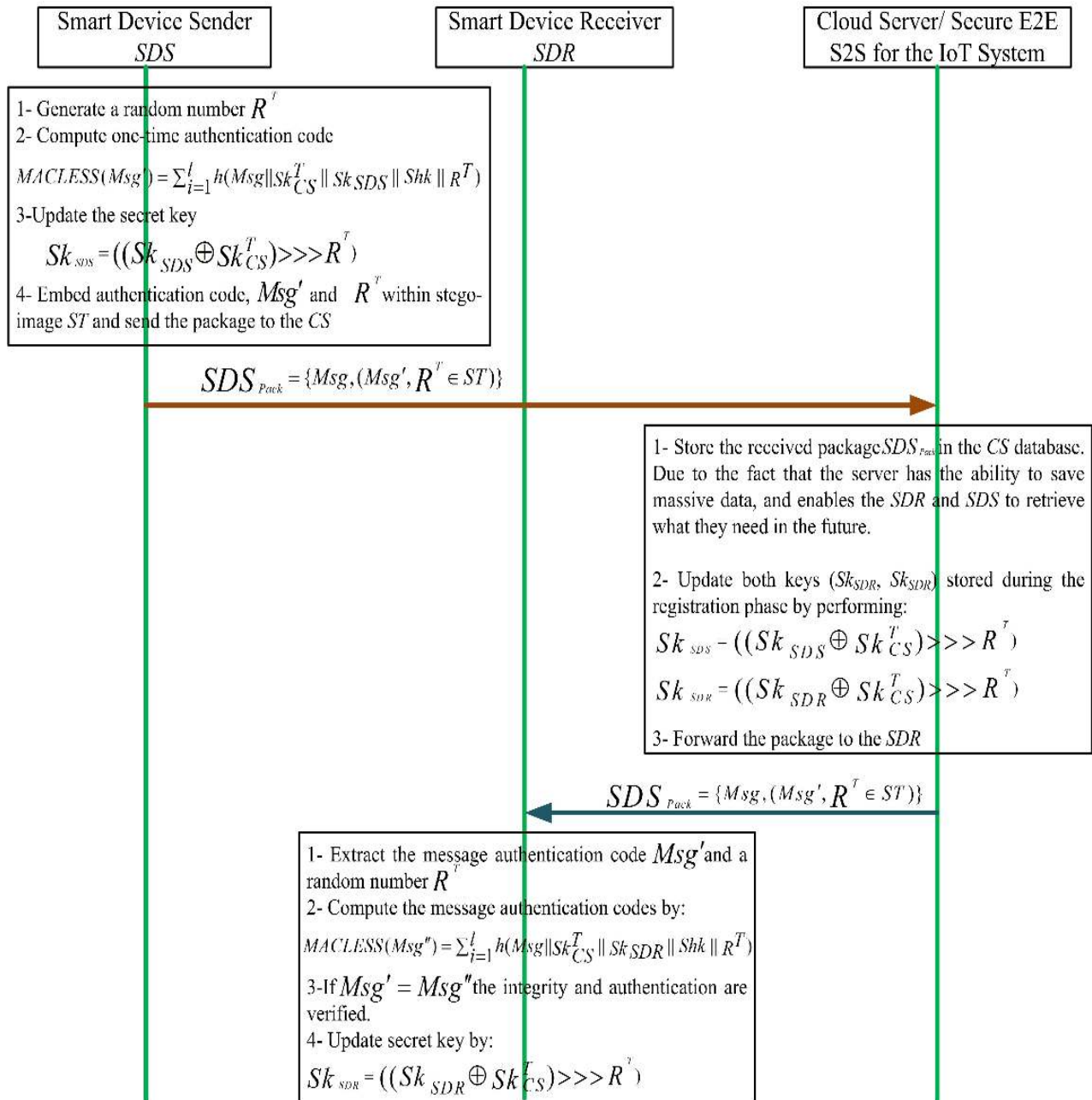


FIGURE 3. Secure E2E S2S lightweight message delivery.

cover image via the double-stegging steganography mechanism. This technique is performed to add extra security for concealing  $Msg'$ . In particular, DWT is performed on the cover image as follows: co-cover = (LL, LH, HL, and HH). Afterwards, the embedding of  $Msg'$  proceeds as follows.

Step 1: The coefficients for the first embedding can be selected from (LL, HL, LH, and HH) [13], [18]. In detail, the coefficients can be represented by  $[C_{ij}; i = 1, \dots, K; j = 1, \dots, N]$ , and  $Msg' = [Msg'_{ij}; i = 1, \dots, K; j = 1, \dots, N; Msg'_{ij} = \{0,1\}]$  is resized to the same dimension as that of  $C$ . For each embedding bit of  $MACLESS$  in the coefficients  $[C_{ij}]$ , the first

concealing process consists of comparing  $Msg'_{ij}$  with  $C_{ij}$  to obtain modified  $C'_{ij}$  as follows:

If  $Msg'_{ij} = 0 \wedge C_{ij} \bmod 1 \neq 0$ , then  $C'_{ij} = C_{ij}$   
If  $Msg'_{ij} = 0 \wedge C_{ij} \bmod 1 = 0$ , then  $C'_{ij} = \text{sgn}(C_{ij}) \cdot (|C_{ij}| - 1/2)$   
If  $Msg'_{ij} = 1 \wedge C_{ij} \bmod 1 \neq 0$ , then  $C'_{ij} = \text{sgn}(C_{ij}) \cdot (|C_{ij}| - 1/2)$   
If  $Msg'_{ij} = 1 \wedge C_{ij} \bmod 1 = 1$ , then  $C'_{ij} = C_{ij}$   
where  $C'_{ij}$  denotes the modified coefficients.

Step 2: The second embedding process consists of comparing the modified coefficients  $C'_{ij}$  with other selected coefficients from (LL, HL, LH, and HH) to obtain a modified  $C'_{ij}$  denoted as  $C''_{ij}$ . Single-level inverse DWT (IDWT) is

TABLE 1. Message anonymity explanation.

Message	MAC-SHA-1
Hello	'f95005ea64b1dd74aac6d6b27c31fad9590481a2'
Hello	'd60222b5f1defcb40f3d0012d87bc975389c2651'
Hello	'ad9bd2fef9c33b7997b752d1bc1d0bcafc8ef46c'
Hello	'2a7044a82f48473eb1ff17fabe693374d601eff1'

TABLE 2. Explanation of the variable-length bio-key  $Sk_{SD_i}$ .

No. of Verification run	$I_i$	E	Length	Value of variable-length bio-key $(Sk_{SD_i}) \in (Rv) \rightarrow I_i, E$
1	5	35	31	5104972361858340921340056774328
2	940	956	17	31278291161131045
3	701	730	30	164785329091273107618291769200
4	878	900	23	89172311410650019727431
5	604	617	14	81523106131297

then performed on  $C''_{ij}$  to obtain a stego-image.

The two steps can be performed to embed 4 bytes, as this is the length of *MACLESS*, and the same process can be used to embed the random number  $R^T$ .

For increased security, the *SDS* updates its secret key  $Sk_{SDS}$  to obtain a one-time key periodically by using a simple operations  $(Sk_{SDS} = (Sk_{SDS} \oplus Sk_{CS}^T) \gg \gg R^T)$  for the next secure message delivery. Similarly, the *CS* and *SDR* must update  $(Sk_{SDS}$  and  $Sk_{SDR})$  upon receiving  $R^T$ . Then, the *SDS* sends a package consisting of  $Msg$  and the stego-image,  $SDS_{Pack} = \{Msg, (Msg', R^T \in \text{Stego-image})\}$ , to the *CS*.

**DISCUSSION:** Encryption is the ideal solution for securing a random number  $R^T$ , but this brings us back to the limited processing power of smart devices. Steganography can hide critical data in an unquestionable way. Thus, we suggest using the double-stegging steganography method to embed the random number  $R^T$  and a limited-size authentication code (*MACLESS*) in a low-dimensional and minimally-complex cover image simultaneously. Particularly, hiding limited-size data in a minimally-complex and low-dimensional image requires little computational time and maintains the communication cost, and this approach is compatible with limited-resource devices [34], [35]. This method prevents the attacker from discovering the presence of  $R^T$  and *MACLESS*, which the attacker may reuse. It also provides security and hides the transmission of  $R^T$  and *MACLESS*. We believe that sending data, such as *MACLESS* and  $R^T$ , in a hidden manner distracts attackers; this procedure may even be better than encrypting and sending the data publicly. Moreover, hiding  $R^T$  safely and effectively prevents attackers from extracting and obtaining it.

It also enables the message delivery mechanism to update the keys by using a simple, low-complexity operation. If the attacker guesses  $R^T$ , it is useless because it is used only once for each message delivery in E2E S2S communication in the IoT-cloud system. Moreover, the attacker does not possess the secret keys  $Sk_{SDS}$  and  $Sk_{SDR}$ .

#### 4) IoT-CLOUD SIDE

After receiving the package  $SDS_{Pack} = \{Msg, Msg', R^T \in ST (\text{Stego-image})\}$  from the *SDR*, the *CS* stores it in the database securely. Given that the server can save massive amounts of data, the *CS* is used in our proposal for storage, thus allowing smart devices to reduce their storage operations and retrieve what they need from the stored data on the IoT-cloud server in the future. Similarly, the *CS* extracts  $R^T$  from the cover image and updates both keys to form one-time keys  $(Sk_{SDR}, Sk_{SDS})$ , which are stored during the registration phase by performing a simple operations  $(Sk_{SDS} = (Sk_{SDS} \oplus Sk_{CS}^T) \gg \gg R^T)$  and  $(Sk_{SDR} = (Sk_{SDR} \oplus Sk_{CS}^T) \gg \gg R^T)$ . Then, the *CS* forwards  $SDS_{ack} = \{Msg, Msg', R^T \in ST (\text{Stego-image})\}$  to the *SDR*.

#### 5) SMART DEVICE RECEIVER (*SDR*) SIDE

Upon receiving the *SDS* package from the *CS*, the *SDR* verifies the message integrity and authentication by extracting the message document authentication code (*MACLESS* ( $Msg'$ )) and random number  $R^T$ . It is the opposite of the embedding process and is performed through the following steps.

Step 1: The first level of decoding is performed to recover the first modified coefficients  $C'_{ij}$  from the second modified coefficients  $C''_{ij}$ .

Step 2: The second level of decoding is performed to recover the original  $Msg'_{ij}$  from the first modified coefficients  $C'_{ij}$  as follows:

$$Msg'_{ij} = 0 \text{ if } C'_{ij} \bmod 1 = 0$$

$$Msg'_{ij} = 1 \text{ if } C'_{ij} \bmod 1 \neq 0$$

The two steps can be performed to extract 4 bytes, which is the length of *MACLEE*, and the same process can be used to extract the random number  $R^T$ .

**REMARK:** This technique's important advantage is that the source image does not need to be present in the *SDR* for the successful extraction of *MACLESS* ( $Msg'$ ) and  $R^T$ . Therefore, nobody (unauthorised people or third parties) can detect or even observe the secret communication between pairs of smart devices except for the sender and receiver themselves; that is, no one will even suspect the existence of hidden information *MACLESS* ( $Msg'$ ) and  $R^T$ . The *SDR* computes *MACLESS* ( $Msg''$ )  $= \sum_{i=1}^L h(Msg \parallel Sk_{CS}^T \parallel Sk_{SDR} \parallel Shk \parallel R^T) = 4$  bytes. If  $Msg''$  matches the extracted  $Msg'$ , then the *SDR* ensures the integrity and authentication of the message that the *SDS* has sent. Otherwise, the secure message delivery phase is terminated. Moreover, the *SDR* has to update its secret key  $Sk_{SDR}$  by performing  $(Sk_{SDR} = (Sk_{SDR} \oplus Sk_{CS}^T) \gg \gg R^T)$  so that the key can be used in the next message delivery function.

**REMARK:** During each iteration of E2E S2S message delivery,  $Sk_{SDS}$  and  $Sk_{SDR}$  are updated in the *SDS* and *SDR*, respectively. These keys are protected by  $R^T$  for a specific session  $T_i$ , and the secure E2E S2S lightweight message delivery function can easily prevent online and offline guessing attacks.

**TABLE 3.** Required time to try all possible combinations.

Key Size (bits)	Number of alternative keys	Required time
3060	$2^{3060} = 1.418 * 10^{921}$	4.494 * 10907 years

**TABLE 4.** MSE and PSNR of the proposed scheme (MACLESS).

Message	MAC	MACLESS	Measures	Stego-image Lena(128*128) pixels
Hello	'54d32f 22593cb 0000a6f0 9d19e99 b36fc20 c383c'	2695	MSE	0.0015 dB
Hello	'54d32f 22593cb 0000a6f0 9d19e99 b36fc20 c383c'	2695	PSNR	+76.4279 dB

## V. SECURITY ANALYSIS

We argue that the proposed scheme can withstand several threats, such as replay, forgery, parallel session, MITM, insider, reflection, online guessing, offline guessing, statistical and visual attacks, to E2E S2S communications in an IoT-cloud system. Our proposed scheme has several merits; it consists of a temporary session key  $Sk_{CS}^T$  and one-time bio-keys  $Sk_{SDS}$  and  $Sk_{SDR}$ . For each session request, a one-time anonymous message authentication code, biometric key management and double-stepping based on DWT steganography are used to hide MACLESS without attracting the attention of eavesdroppers. Moreover, our work meets the requirements of secure M2M communication [36], [37].

### A. SECURITY MERITS

**Theorem 1.** The proposed scheme can support biometric key management and a one-time biometric key.

*Proof.* In the proposed scheme, the CS uses a secret salt key  $[(Sk_{SDS}) \in (Rv) \rightarrow I_i, E; (Rv = Fx(SHS)); (SHS = HS_{SDS} \cup HS_{SDR})]$  to compute  $MACLESS(Msg') = \sum_{i=1}^L h(Msg \| Sk_{CS}^T \| Sk_{SDS} \| Shk \| R^T) = 4$  bytes when the SDS sends a message (Msg) to SDR or vice versa in the IoT-cloud system. In detail, the mechanism for computing  $Sk_{SDS}$  is based on the extracted features (Rv) of the combined bio-shared image of the handwritten signatures of the SDS and SDR ( $SHS = HS_{SDS} \cup HS_{SDR}$ ) and the one-time random indexes generated by the CS ( $I_i, E$ ) during the registration phase.  $I_i$  and  $E$  are the starting and end points, respectively, from the vector of the extracted features (Rv). We notice that  $I_i$  and  $E$  are generated once for each SDS and SDR session. Moreover, the SDS and SDR perform  $(Sk_{SDS} = (Sk_{SDS} \oplus Sk_{CS}^T) \gg \gg R^T)$  and  $(Sk_{SDR} = (Sk_{SDR} \oplus Sk_{CS}^T) \gg \gg R^T)$  to update their secret keys to be used in the next round of message delivery. Therefore, this scheme provides bio-key management and a one-time biometric key.

**Theorem 2.** The proposed scheme can support a biometric

MAC.

*Proof.* The biometric operator identifies a person based on particular physiological features, such as his/her handwritten signature. A handwritten signature is one of the most commonly used security measures in biometrics [15]. However, no previous scheme has focused on combining the biometric technique with MACs for E2E S2S communication in an IoT-cloud system. In contrast, in the proposed scheme, during the registration phase, the SDS and SDR send their handwritten signatures ( $HS_{SDS}$  and  $HS_{SDR}$ ) to the CS through a secure transmission using ECC. Afterwards, the CS saves ( $HS_{SDS}, HS_{SDR}$ ), generates bio-shared handwritten signatures ( $SHS = HS_{SDS} \cup HS_{SDR}$ ) and extracts a vector of features ( $Rv = Fx(SHS)$ ). Rv is then used to generate  $Shk, Sk_{SDS}$  and  $Sk_{SDR}$ , in the registration phase. During the secure E2E S2S lightweight message delivery phase, the SDS or SDR should generate a biometric MAC MACLESS ( $Msg') = \sum_{i=1}^L h(Msg \| Sk_{CS}^T \| Sk_{SDi} \| Shk \| R^T) = 4$  bytes based on the biometric salt-key ( $Sk_{SDi} \in (Rv) \rightarrow I_i, E$  when the SDS and SDR wish to send a message to each other. Hence,  $Sk_{SDi}$  refers to the secret key of the SDS or SDR. Such a scheme can clearly provide a biometric MAC.

**Theorem 3.** The proposed scheme can robustly provide anonymity for the user message and authentication code.

*Proof.* Assume that the SDS/SDR tries to resend a similar user's message. The attacker often attempts to steal or eavesdrop on the sender's login request ( $Msg, Msg', R^T, ST$ ). As long as the sender generates MACLESS ( $Msg') = \sum_{i=1}^L h(Msg \| Sk_{CS}^T \| Sk_{SDi} \| Shk \| R^T)$  once for each E2E S2S sender request, the attacker cannot use the same authentication code MACLESS for E2E S2S communication in the IoT-cloud system. A random number  $R^T$  is generated once for each message delivery, and a one-time bio-key  $Sk_{SDi}$  is selected and integrated with MAC-SHA-1 for each session request to generate an anonymous one-time message authentication code. In addition,  $Sk_{SDS}$  and  $Sk_{SDR}$  are updated each session on the basis of  $(Sk_{SDS} = (Sk_{SDS} \oplus Sk_{CS}^T) \gg \gg R^T)$  and  $(Sk_{SDR} = (Sk_{SDR} \oplus Sk_{CS}^T) \gg \gg R^T)$ . Hence, computing the MACLESS for the SDS becomes difficult for an eavesdropper. The proposed scheme can support the anonymity of user messages (Table 1).

**Theorem 4.** The proposed scheme supports a temporary, variable-length bio-salt key for each session.

*Proof.* In this work, the bio-key  $Sk_{SDi}$  does not have a fixed length that depends on  $(Sk_{SDi}) \in (Rv) \rightarrow I_i, E$ , where  $I_i$  and  $E$  change each session (Table 2). Similarly,  $Sk_{CS}^T$  is generated as a strong one-time key by applying  $(Sk_{CS}^T = d^{r^T} \text{mod } lp)$  and delivering it to the SDS and SDR for each E2E S2S session launch. Moreover, for each session, the secret keys are periodically updated using the random number  $R^T$ . Consequently, the variable-length bio-salt key and continuous periodic update are difficult for the attacker to guess because they are not equal under different runs and constantly change when the SDS and SDR wish to exchange messages. Therefore, our proposed scheme provides flexible-length bio-keys,  $Sk_{SDS}$  and  $Sk_{SDR}$ , for each session launch.

## B. COMMUNICATION ATTACKS

**Theorem 1.** The proposed scheme can resist replay attacks.

*Proof.* An attacker performs this type of attack by eavesdropping on the rightfully transmitted *SDS/SDR* login request. When the smart device user logs out of the IoT-cloud system, the attacker attempts to impersonate the valid user by reusing this message. In our scheme, the user's login request each time must be identical to the *CS* parameters in the registration and key negotiation and secure message delivery phases in the IoT-cloud system ( $Sk_{CS}^T, Sk_{SDS}, Shk, R^T, MACLESS(Msgl) = \sum_{i=1}^L h(Msgl \| Sk_{CS}^T \| Sk_{SDi} \| Shk \| R^T)$ ).

Moreover,  $Msgl$  is generated once by using the user's one-time bio-key  $Sk_{SDi}$  for each session  $T$ , and the distinct random number  $R^T$  is generated once by the smart device sender and embedded into the stego-image ( $ST$ ) to be extracted later by the *CS* and the smart device receiver. Subsequently,  $Msgl$  and  $R^T$  are protected well and no longer valid.

Even if the attacker could derive the random number  $R^T$ , the attacker would not know the authentication code  $Msgl$  because the attacker does not have the secret bio-keys  $Sk_{SDi}$  and  $Sk_{CS}^T$  generated based on the biometric parameters of both smart device users. In detail, in our secure E2E S2S communication method in an IoT-cloud system, attackers cannot generate valid *MACLESS* because we use the distinct-to-distinct secret bio-keys  $Sk_{SDi}$  and  $Sk_{CS}^T$  for each session  $T$  and securely keep these keys in the *SDS*, *SDR* and *CS* by using ECC. Our scheme also enjoys a mutual authentication mechanism in the secure E2E S2S communication negotiation process. Such mutual authentication can hinder the impersonating smart device that aims to derive sensitive parameters by using an illegal  $ID_i$ . Therefore, an attacker cannot pass any replayed message for the verification of the *CS* and *SDR*. Consequently, the attacker fails to perform this type of attack.

**Theorem 2.** The proposed scheme can prevent parallel-session and forgery attacks.

*Proof.* If an attacker attempts impersonation, he/she can obtain access to a valid session message  $SDS_{Pack} = \{Msgl, MACLESS(Msgl) = \sum_{i=1}^L h(Msgl \| Sk_{CS}^T \| Sk_{SDi} \| Shk \| R^T)\}$  and  $R^T \in ST$  (Stego-image) by using  $R^T, Sk_{SDi}, Sk_{CS}^T$  and  $Shk$  as the secret sensitive parameters of the secure message delivery function for E2E S2S communication in the IoT-cloud system. In the proposed scheme, these parameters, derived from users' biometric features  $Rv, Shk, SHS, HS_{SDS}$  and  $HS_{SDR}$  are securely transmitted and kept amongst the *CS*, *SDS* and *SDR* by using ECC during the registration phase. Therefore, an attacker does not have any knowledge of  $Rv, Shk, SHS, HS_{SDS}$  and  $HS_{SDR}$  to compute ( $Msgl$ ) and fails to forge a valid session message; thus, he/she cannot perform forgery and parallel-session attacks. The proposed scheme can prevent forgery attacks.

**Theorem 3.** The proposed scheme can resist MITM attacks.

*Proof.* To perform this attack, the attacker tries to intercept the message between the *SDS* and *SDR*. The attacker

takes advantage of the user logging out from the IoT-cloud system and reuses their message. In our work, pairs of smart devices wish to use the message delivery function to transmit a message (between the *SDS* and *SDR*). They must initiate the registration and secure lightweight E2E S2S communication negotiation phases. For instance, these phases can be used to generate a temporary, strong one-time key  $Sk_{CS}^T$  by applying ( $Sk_{CS}^T = d^{r^T} \bmod lp$ ) and the user's one-time bio-keys  $Sk_{SDS}$  and  $Sk_{SDR}$  for each specific session  $T$  to form once-sensitive data  $SDS_{Pack} = \{Msgl, MACLESS(Msgl) = \sum_{i=1}^L h(Msgl \| Sk_{CS}^T \| Sk_{SDi} \| Shk \| R^T)$  and  $R^T \in ST$  (Stego-image)} to be sent to the *SDR* for maintaining the integrity and authentication of the message delivery function. When the *SDS/SDR* logs out of the IoT-cloud system, the once-sensitive data become useless. An attacker eavesdropping on the transmission between the *SDS* and *SDR* finds that computing  $Msgl$  might be useless, difficult or even impossible because the keys  $Sk_{CS}^T, Sk_{SDS}$  and  $Sk_{SDR}$  are only generated and used once each with a mechanism to update the user's keys  $Sk_{SDS}$  and  $Sk_{SDR}$  for each message delivery by a random number  $R^T$  during each session of E2E S2S communication in the IoT-cloud system.

Moreover, our solution prevents MITM attacks by providing mutual authentication, as proven in the subsection "Secure Lightweight E2E S2S Communication Negotiation". For instance, the *SDS* can verify the origin of *SDR* by driving  $Sk_{SDR}$  which is done by performing matching:  $((Sk_{CS}^T \oplus Sk_{SDR}) \oplus Sk_{CS}^T) = Sk_{SDR}$ . Then, the *SDS* verifies whether it matches  $Sk_{SDS}$ . If they are equal, then the security of the E2E S2S communication session is proven. An S2S device can launch a session for secure E2E S2S message delivery in the IoT-cloud system. Thus, our scheme can prevent MITM attacks.

**Theorem 4.** The proposed scheme does not attract the attention of eavesdroppers to *MACLESS* by using double-stegging.

*Proof.* The advantage of hiding information over cryptography alone is that the intended secret data do not arouse interest during data transfers between the *SDS* and *SDR* in the IoT-cloud system. Encrypted messages are visible and can thus attract attraction. Encryption only protects the contents of the data. By contrast, steganography hides the fact that secret data are being sent as well as the contents of these data. In the proposed scheme, the sensitive data  $SDS_{Pack} = \{Msgl, MACLESS(Msgl) = \sum_{i=1}^L h(Msgl \| Sk_{CS}^T \| Sk_{SDi} \| Shk \| R^T)$  and  $R^T \in ST$  (Stego-image)} are hidden in a cover image by using double-stegging based on DWT steganography  $St(MACLESS(Msgl), R^T)$ . The double-stegging technique is used to increase the security of the concealed data. Therefore, the proposed scheme does not attract the attention of eavesdroppers, and the information remains unknown to possible attackers. Moreover, extracting data ( $Msgl, R^T$ ) from the stego-image is difficult because one selected coefficient carries *MACLESS*, and the concealment is performed twice. In addition, a distinct random number  $R^T$  is generated and used only once for each message delivery procedure.



TABLE 5. Comparison of security properties.

	Security features	Moh seni et al. [22]	Alizai et al. [23]	Adeel et al. [24]	Chen et al. [30]	Byou ngjin Seok et al. [31]	Our proposed work
1	Secure communication in IoT-cloud	No	No	No	No	No	Yes
2	Provides biometric key management	No	No	No	No	No	Yes
3	Provides biometric MAC	No	No	No	No	No	Yes
4	Provides authentication code anonymity for each session	Yes	Yes	Yes	Yes	Yes	Yes
5	Provides a temporary variable-length bio-salt key for each session	No	No	No	No	No	Yes
6	Provides mutual authentication	No	No	No	Yes	No	Yes
7	Using double-stegging to secure passing parameters	No	No	No	No	No	Yes
8	Prevents replay attacks	Yes	Yes	Yes	Yes	Yes	Yes
9	Prevents parallel session and forgery attacks	No	No	No	No	No	Yes
10	Prevents MITM attacks	No	No	No	Yes	Yes	Yes
11	Prevents reflection attack	Yes	No	Yes	Yes	No	Yes
12	Prevents key guessing attack	No	No	Yes	Yes	Yes	Yes
13	Prevents brute force and dictionary attacks	No	No	Yes	No	No	Yes

Consequently, our scheme remains robust by not attracting the attention of eavesdroppers.

**Theorem 5.** The proposed scheme uses nonce parameters to deflect reflection attacks.

*Proof.* When a rightful *SDS* sends a login request to an *SDR*, an attacker attempts to eavesdrop on the login request ( $Msg, Msgt, R^T$ ) and replies with the same MAC of the *SDS*,  $MACLESS(Msgt) = \sum_{i=1}^L h(Msg \| Sk_{CS}^T \| Sk_{SDS} \| Shk \| R^T)$ , to the *SDR*. In the proposed scheme, an attacker cannot deceive the *SDS* or *SDR* because they do not possess the knowledge of the bio-vector  $Rv$  generated in the registration phase and securely kept in the *CS*. Moreover, for each session,  $Sk_{SDS}$  and  $Sk_{SDR}$  are generated once and constantly updated for use in the next session by applying  $(Sk_{SDS} = (Sk_{SDS} \oplus Sk_{CS}^T) \gg \gg R^T)$  and  $(Sk_{SDR} = (Sk_{SDR} \oplus Sk_{CS}^T) \gg \gg R^T)$ , respectively. Hence,  $Sk_{SDi}$  and  $R^T$  are generated once to compute a one-time hashed value and a one-time *MACLESS* during secure message transmission for E2E S2S communication in the IoT-cloud system. In addition, an attacker does not acquire  $Rv$  to generate  $Sk_{SDi}$ , which was previously sent from the *CS* to the *SDS* and *SDR* through the cryptographically-strong approach of ECC. Our proposed scheme can strongly withstand insider and reflection attacks.

**Theorem 6.** The proposed scheme can withstand key guessing attacks.

*Proof.* The attacker may try to perform a guessing attack to guess the secret keys of both smart devices and the *CS*. Our work can prevent this type of attack in the registration phase by protecting the sensitive biometric parameters using ECC encryption, such as  $Enc_{PU_{CS}}(HS_{SDS}), Enc_{PU_{CS}}(HS_{SDR}), Enc_{PU_{CS}}(Rv), Enc_{PU_{CS}}(SHS), Enc_{PU_{CS}}(Shk)$ . It also protects sensitive keys by applying  $Enc_{PU_{CS}}((Sk_{CS}^T \oplus Sk_{SDS}) \| ID_{CS} \| ID_{SDS} \| ID_{SDR} \| Shk)$  and  $Enc_{PU_{CS}}((Sk_{CS}^T \oplus Sk_{SDR}) \| ID_{CS} \| ID_{SDS} \| ID_{SDR} \| Shk)$  for secure E2E S2S communication negotiation. For each session of E2E S2S communication in the IoT-cloud system,  $Sk_{SDS}$  and  $Sk_{SDR}$  are generated once and updated for use in the next session by applying  $(Sk_{SDS} = (Sk_{SDS} \oplus Sk_{CS}^T) \gg \gg R^T)$  and

$(Sk_{SDR} = (Sk_{SDR} \oplus Sk_{CS}^T) \gg \gg R^T)$ , respectively. These secret keys are derived based on the bio-shared parameters ( $Rv = Fx(SHS = HS_{SDS} \cup HS_{SDR})$ ). In addition, the *CS* generates a strong temporary key for each specific session  $T$  by computing  $(Sk_{CS}^T = d^{r^T} \text{ mod } lp)$ . Hence, an attacker cannot know the secret keys of the E2E S2S procedure ( $Sk_{SDS}$  and  $Sk_{SDR}$ ) or *CS*' key  $Sk_{CS}^T$  by trying various guessed keys.

**Theorem 7.** The proposed scheme can prevent online key guessing attacks.

*Proof.* To prevent this attack, we add some information to the session request during the secure E2E S2S communication negotiation phase. These operations,  $(Sk_{CS}^T \oplus Sk_{SDS})$  and  $(Sk_{CS}^T \oplus Sk_{SDR})$  are added for both negotiation requests  $Enc_{PU_{CS}}((Sk_{CS}^T \oplus Sk_{SDS}) \| ID_{CS} \| ID_{SDS} \| ID_{SDR} \| Shk)$  and  $Enc_{PU_{CS}}((Sk_{CS}^T \oplus Sk_{SDR}) \| ID_{CS} \| ID_{SDS} \| ID_{SDR} \| Shk)$  between E2E S2S devices in the IoT-cloud system.

Moreover, these keys are shared during the registration phase and protected using the ECC encryption operation of the *SDS* and *SDR*. When the attacker tries to use such an attack to obtain the secret keys of the *SDS* and *SDR*, the attacker must successfully pass the mutual authentication mechanism. In addition, the secret keys  $Sk_{CS}^T, Sk_{SDS}$  and  $Sk_{SDR}$  are only kept in the *CS* and corresponding smart devices (*SDS* and *SDR*) and are saved securely using ECC. Therefore, the proposed scheme can prevent online key guessing attacks.

**Theorem 8.** The proposed scheme can prevent brute force and dictionary attacks.

*Proof.* If we assume that the attacker attempts to damage our scheme by using possible combinations or an online guessing attack for obtaining the secret bio-key  $Sk_{SDi}$ , the attacker or adversary fails to apply this attack because he/she must try all possible combinations, totalling  $2^{3060}$ , to obtain the bio-key  $[(Sk_{SDi}) \in (Rv) \rightarrow I_i, E]$ ;  $2^{3060}$  is a very large number of trials (Table 3), where 3060 is the length of the feature vector  $Rv$ . Moreover,  $Sk_{SDi}$  is constantly changing and updated within a session  $T$  by  $(Sk_{SDi} = (Sk_{SDi} \oplus Sk_{CS}^T) \gg \gg R^T)$ . Our work obviously prevents these attacks.

### C. STEGANOGRAPHY ATTACKS

**Theorem 1.** The proposed scheme provides high-quality peak signal-to-noise ratios (PSNRs) for resisting visual attacks.

*Proof.* Notably, the nature of steganography is to hide or embed sensitive information ( $Msg^t$  and  $R^T$ ) by using a low-dimensional and minimally-complex cover image during a transmission between the  $SDS$  and  $SDR$  for E2E communication in the IoT-cloud system and vice versa. A visual attack attempts to extract the authentication and integrity value ( $Msg^t$ ) and random number  $R^T$  by comparing the differences between a source image and a cover image. In the proposed scheme, we embed 4 bytes, which are the summation of 40 hexadecimal codes  $MACLESS(Msg^t) = \sum_{i=1}^L h(Msg^t || Sk_{CS}^T || Sk_{SD_i} || Shk || R^T) = 4$  bytes, instead of embedding the whole hashed value, which is a 40 hexadecimal sum. Thus, our scheme can reconstruct an image after embedding 4 bytes to closely resemble the source image; afterwards, we can accurately demonstrate the superiority of the quality of the reconstructed image. The reconstructed image does not attract the attention of an eavesdropper when he/she compares the cover image  $ST(MACLESS(Msg^t), R^T)$  transmitted between the  $SDS$  and  $SDR$  with the source image in the IoT-cloud system. The proposed scheme enhances the capability of the system to maintain integrity and improves the visual quality of stego-images. The high PSNR of the stego-image demonstrates that an attacker cannot detect the hidden parameters ( $Msg^t$  and  $R^T$ ) (Table 4). Thus, our proposed scheme can strongly withstand visual attacks.

**Theorem 2.** The proposed scheme is impervious against statistical attacks.

*Proof.* A statistical attack is typically attempted to extract hidden critical data [ $MACLESS(Msg^t), R^T$ ] from a cover image ( $ST$ ) during E2E S2S transmission in the IoT-cloud system. Attackers attempt to statistically analyse the frequency of data in colour by using steganographic methods that work on stego-images. The DWT used to embed  $MACLESS$  in an image terminates statistical attacks [16], [29]. However, in the worst-case scenario, when an adversary successfully extracts critical data from the cover image via a statistical attack, the data in the new  $MACLESS$  encoding form cannot be understood or recovered. In addition,  $MACLESS$  is used only once for the message authentication code of each session. Thus, the expiration time is limited.

**Theorem 3.** The proposed scheme is robust against image-processing modifications and modification attacks.

*Proof.* Combining DWT with steganography to hide  $MACLESS$   $St(MACLESS(Msg^t), R^T)$  provides high robustness and imperceptibility [30]. Hence, we employ DWT in the proposed scheme to achieve robustness against different types of signal processing modifications, such as scaling, rotation, cropping, noise, or compression loss [29]. Thus, extracting or corrupting the secret data ( $(Msg^t), R^T$ ) becomes difficult for an attacker. In summary, our scheme simultaneously provides concealment, robustness, and imperceptibility to safeguard

$MACLESS$  in contrast with the schemes in previous works. Our proposed scheme can resist modification attacks.

## VI. RESULTS AND DISCUSSION

This section demonstrates a comparative security analysis in terms of security features and a performance evaluation based on the cost of one calculation of the two phases of our scheme compared with the costs of other schemes in existing studies.

### A. COMPARATIVE SECURITY ANALYSIS

This section provides a comparison of the security features presented and discussed before in Section V with those of recent related works, as shown in Table 5. Such a comparison is useful for judging the functionality and competence of the proposed method. Table 5, shows that the proposed method provides secure communication in the IoT-cloud system, biometric key management, biometric MACs, authentication code anonymity for each session, and a temporary variable-length bio-salt key for each session, while other methods do not. Additionally, only our method and the method of Chen et al. [30] provide mutual authentication, which is essential for preventing MITM and reply attacks; these attacks are threats to the proposed schemes in the works of Mohseni et al. [22], Alizai et al. [23], and Adeel et al. [24]. The proposed work can prevent parallel session, forgery, brute force and dictionary attacks, to which the schemes of Mohseni et al. [22], Alizai et al. [23], Adeel et al. [24], and Chen et al. [30] are vulnerable. Unlike the proposed work, the schemes of Mohseni et al. [22], Adeel et al. [24], and Chen et al. [30] lack multi-factor authentication, which is a strong aspect of authentication provided by the method of Alizai et al. [23]. In addition, our scheme uses a double-stepping mechanism to hide the important parameters for the communication process between smart devices in the IoT-cloud system, and this is not provided by other methods.

### B. PERFORMANCE AND IMPLEMENTATION ANALYSIS

A performance analysis of our work is estimated by comparing it with Byoungjin Seok et al. [31]'s scheme, as shown in Table 6. The notations used are illustrated at the end of this table along with their evaluated time costs in milliseconds. Although our scheme is less efficient than [31]'s scheme in the registration phase, our scheme overcomes that of [31] in terms of the computation time of the secure message delivery between D2D or E2E S2S devices in the IoT-cloud phase, as seen in Table 6. For the comparison to be fair, giving guaranteed security in the registration phase for our proposed method using asymmetric ECC, the computational cost is reasonable. In addition, as we explained previously, the registration phase is carried out only once. The secure lightweight E2E S2S communication negotiation mechanism costs additional time before the messages start to be sent between the two parties, but it is very effective in providing mutual authentication between devices that want to communicate with each other. Mutual authentication provides better security features, such as the prevention of illegal devices,

**TABLE 6. Comparison of computational time.**

		Registration and key negotiation phase			Secure message delivery in the IoT-cloud phase				
		Secure lightweight E2E S2S communication negotiation		Secure E2E S2S lightweight message delivery					
		SDS	SDR	IoT-cloud server	SDS	SDR	IoT-cloud server	SDS	SDR
1	Our proposed work	$T_{ASE} + T_{ASD}$ 522 ms	$T_{ASE} + T_{ASD}$ 522 ms	$2T_{ASD} + T_{bio-v} + T_{SkSDi}$ $4T_{ASE}$ 1.954 s	$2T_{ASD} + T_{ASE} + 4T_{Xor}$ 0.765 s	$2T_{ASD} + T_{ASE} + 4T_{Xor}$ 0.765 s	$2T_{ASD} + 3T_{ASE} + T_{SkCS}$ $8T_{Xor}$ 1.385 s	$T_h + T_{ST} + T_{Xor} + T_{shift}$ 0.0223 s	$T_h + T_{Ex} + T_{Xor} + T_{shift}$ 0.0210 s
	Estimated overall time (s)	2.998 s			2.951 s			0.0433 s	
2	Byoungjin Seok et al. [31]	0.702 s for the user registration in 5G network			3.7852 s for the whole process of secure D2D communication				

$T_{ASE}$ : time required to perform an asymmetric encryption operation;  $T_{ASD}$ : time required to perform an asymmetric decryption operation;  $T_{bio-v}$ : time required to perform a bio-shared feature extraction ( $R_v$ ) for use by the IoT-cloud server;  $T_{SkSDi}$ : time required to perform a bio-secret key generation for use by the SDS and SDR;  $T_{SkCS}$ : time required to perform a bio-secret key generation for use by the IoT-cloud server;  $T_{Xor}$ : time required to perform an exclusive-or operation;  $T_h$ : time required to perform a hash function operation;  $T_{shift}$ : time required to perform a shift operation;  $T_{ST}$ : time required to perform a low-complexity double-stepping operation;  $T_{Ex}$ : time required to perform a low-complexity extraction operation.  
According to [38], [39], [40],  $T_{ASE} \approx 300$  ms;  $T_{ASD} \approx 222$  ms;  $T_{Xor} \approx 0.005$  ms;  $T_h \approx 0.05$  s. Additionally, [41],  $T_{ST} \approx 0.06$  s;  $T_{Ex} \approx 0.04$  s;  $T_{shift} \approx 0.0001$  ms;  $T_{bio-v} \approx 0.3$  s;  $T_{SkSDi} = T_{SkCS} \approx 0.001$  ms

replay attacks, spoofing attacks, and MITM attacks, than the method of [31], see Table 5. for details. Additionally, such a negotiation mechanism is needed only once for each message delivery session; then, both parties can send an unlimited number of messages whenever they want during each session. Secure E2E S2S lightweight message delivery requires 0.0433 s, which is considered a reasonable time cost, while providing high security by using double-stepping to keep sensitive parameters confidential. Therefore, our scheme can be considered efficient for E2E S2S secure message delivery in IoT-cloud systems.

## VII. CONCLUSION

We present a lightweight E2E S2S communication scheme that differs from those of previous works to ensure secure message delivery in IoT-cloud systems. We develop our scheme based on two features. The first is secure, lightweight E2E S2S communication negotiation, which is important for providing mutual authentication and an organized, secure group of smart devices. The second is secure E2E S2S lightweight message delivery, which is used to securely send a message between a pair of smart devices. The proposed model can achieve higher efficiency than that of [31] because the time required for secure message delivery for E2E S2S devices in an IoT-cloud system is 0.0433 s. Thus, the secure message delivery process in this scheme requires minimal time consumption and is compatible with energy-constrained devices, which are practical choices for secure E2E S2S communication. Additionally, our work can provide mutual authentication for the prevention of MITM attacks and can prevent well-known threats such as replay, forgery, parallel session, reflection, offline guessing, online guessing, brute force, dictionary, statistical and visual attacks, as proven by the conducted security analysis. This technique can also be used to maintain message authentication, verify the integrity of received messages, and prove the origin or identity of the sender. Overall, our scheme is simple to use, and it is secure.

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**MUSTAFA ABDULAZEEZ MUTTLAQ AL-SIBAHEE** is an Researcher of Huazhong niversity of Science and Technology Shenzhen Institute, Shenzhen,China. Lecturer at Department of Communication Engineering at Iraq University College, Basrah, Iraq. Received his Bhd, (2018) from Huazhong University of Science and Technology, Wuhan-China. His research interests include Computer Networks and Information Security, Computer Network Measurements, Machine Learning Algorithms Applications, Wireless Sensor Network (WSN), Software Defined Networking (SDN), Embedded Systems and Cyber Physical Systems (CPS). You may contact him at I201522098@alumni.hust.edu.cn.



**SONGFENG LU** received the PhD degree from Huazhong University of Science and Technology, Wuhan, China, in (2001). From May 2009 to May (2010), he was a Visiting Research Scholar with the University of York, York, U.K. He is currently a Professor with the School of Cyber Science and Engineering, Huazhong University of Science and Technology. He has authored over (120) articles published in related international conference proceedings and journals and holds more than (20) patents. His current research interests include information security, quantum computing, and artificial intelligence. You may contact him at lusongfeng@hust.edu.cn.





**Zaid Ameen Abduljabbar** got his bachelor (2002) and master (2006) degrees of computer science from Basrah University, Iraq. Zaid received his PhD in computer engineering in 2017 from Computer Science and Technology, Huazhong University of Science and Technology, China. He is focused on cloud security, searchable encryption systems, similarity measures, Internet of Things, secure computation, biometric, and soft computing. He has published regular papers in many IEEE

International Conferences and High-quality papers in SCI journals, and has got the best paper award and published in the 11th International Conference on Green, Pervasive and Cloud Computing (*GPC16*), Xian, China, 6-8 May 2016. He has always served as a reviewer for several prestigious journals, and has served as a PC chair/PC member of more than 20 international conferences. You may contact him at [alsulamizaid@gmail.com](mailto:alsulamizaid@gmail.com).



**Zaid Alaa Hussien** is working as a Head of Information Technology Department in Management Technical College, Southern Technical University, Iraq. He received the B.Sc. degree in Computer Engineering from University of Basrah, Iraq in 2004 and the M.Tech degree in Computer Science and Engineering from Guru Gobind Singh Indraprastha University, India in 2009. Zaid got his PhD in Computer Engineering in 2017 from Computer Science and Technology, Huazhong U-

niversity of Science and Technology, China. He is focused on cloud security, searchable encryption systems, Authentication and Integration Data in Cloud, Internet of Things, and Network Security. Zaid is a reviewer for several journals and international conferences. You may contact him at [zaid.alaa@stu.edu.iq](mailto:zaid.alaa@stu.edu.iq).



**Xin Liu** is the Dean School of International Education at Neusoft Institute Guangdong, Guangdong, China. Director of International Communication and Cooperation Department Hong Kong, Macao and Taiwan Affairs Office. His research interests include Internet of Things, and Networks Information Security. You may contact him at [liuxin@nuit.edu.cn](mailto:liuxin@nuit.edu.cn).



**Hemn Barzan Abdalla** Holds a Ph.D. degree in the field of Communication and Information Engineering. He possesses one decade of experience in teaching and worked as a project assistant in various higher education places. Also, currently, he is working as a lecturer at Wenzhou-Kean University with a member of the Institute of training and development in Sulaimani (KRG). He is an Editorial board member/reviewer of International/ National Journals and Conferences. He has

more than 100 project systems for several places. His research interests include big data and data security, NoSQL, application. You may contact him at [habdalla@kean.edu](mailto:habdalla@kean.edu).



**Mudhafar Jalil Jassim Ghrabat** He received Ph.D. degree in computer science from, Huazhong University of Science and Technology, Wuhan, China in 2020. He received his master's degree in information technology from SRM Institute of Science and Technology, Chennai, India in 2015. He received his B.S. degree in computer science from the University of Al-Mustansiriyah University, Baghdad, Iraq, in 2006. His current research interests include machine learning, data

mining, image processing, and artificial intelligence. You may contact him at [mudhafarjalil@hust.edu.cn](mailto:mudhafarjalil@hust.edu.cn).

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**Mohammed Abdulridha Hussain** is a Lecturer in department of computer science, college of education for pure science at university of Basrah, Basrah, Iraq. He got his bachelor degree (2004) from department of computer engineer, college of engineering at university of Basrah, Iraq. He received his master degree (2009) in computer science and engineer from school of information technology at Guru Gobind Singh Indraprastha University, Delhi, India. He received

his PhD in computer engineer in 2017 from Computer Science and Technology, Huazhong University of Science and Technology, China. Research interest network security, data security, cloud security, networking. You may contact him at [mohsubber@gmail.com](mailto:mohsubber@gmail.com).